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Drought mitigation under urbanization through an intelligent water allocation system

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ABSTRACT

Due to the uneven spatio-temporal distribution of water resources and increasing water demands driven by urbanization, making effective water allocation is a critical and challenging issue nowadays. This study proposes an intelligent water allocation system (IWAS) to reduce the water pressure of multiple sectors and enhance the resilience of the water allocation system under urbanization during droughts. We first make forecasts on future water demands in response to urbanization for Taoyuan City in Taiwan by using system dynamics (SD) based on historical agricultural and industrial data as well as population statistics. We next design six water supply scenarios formed by a combination of ten-day inflow data collected from the Shihmen Reservoir in two drought years and three initial reservoir storages. The non-dominated sorting genetic algorithm-II (NSGA-II) is then used to search the minimal modified shortage index (MSI) and the maximal ratio of water storage to reservoir capacity (RWS) subject to future water demand forecasts under six designed drought scenarios. M-5 rule curves take care of water shortage simulation and serve as a benchmark. The results of the NSGA-II indicate that the improvement rates of MSI and RWS can reach up to 24% and 9.6%, respectively, as compared to those of M-5 rule curves. Furthermore, when we incorporate a great number of irrigation ponds spreading over the study area into the NSGA-II model, the improvement rates of MSI and RWS can increase by at most 35.5% and 1.5%, respectively, as compared to those of the NSGA-II without incorporating irrigation ponds. The results demonstrate that the proposed IWAS can greatly improve the effectiveness and advantages of water allocation, especially when irrigation ponds are considered as a water supply source, in response to future urban water demands under drought scenarios, and therefore provide decision makers with apt reference guidelines for sustainable water resources management.

1. Introduction

Taiwan is situated in the subtropics and receives abundant rainfall. However, its uneven rainfall distribution and high mountains with rivers of steep slopes and short lengths inevitably cause most of river flow rushes into the ocean. Making effective use of water resources to meet the growing water demands is a great challenge. Therefore, building an intelligent water resources allocation system is essential and beneficial to decision makers for utilizing water resources aptly. In the last decades, the economic development in metropolitan areas has greatly increased the demands for various natural resources like water. Many studies showed that urbanization was a key factor affecting water scarcity (e.g., Bao and Fang, 2012; Kanta and Zechman, 2013; Song et al., 2016; Wu and Tan, 2012), which created serious problems in environmental, social and economic realms. Recent water resources planning and management methods have more focused on the interactions and feedbacks inside urban systems (e.g., Giacomoni et al., 2013). System dynamics (SD) is an approach to studying and managing complex feedback systems for building a model to give insight into the interactions among different components of the system, simulate dynamic system behaviors, evaluate alternative policies, and consequently choose a better management policy (Forrester, 2007). With the great capability of modeling the complex interrelation and dynamic features of nonlinear systems, the SD has been used in assessing resources consumption and city management (e.g. Ahmad and Simonovic, 2004; Bajracharya and Bhattarai, 2016; Eshtawi et al., 2016; Feng et al., 2013; Giordano et al., 2015; Jeong and Adamowski, 2016; Karami et al., 2017; Winz et al., 2009; Xi and Poh, 2013). However, there are limited attempts to take into account the dynamic natures of water resources together with economic and environmental effects as an important

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aspect of sustainability.

Urbanization with growing population in the last decades has greatly raised the pressure on water management, and irrigation water has usually been the first target to reduce when a drought condition had occurred. Facing the rigorous situation, it is desirable to make sustainable water resources management that optimizes multi-objective reservoir operation for balancing water demand and supply. To deal with multi-objective reservoir operation, many optimization approaches were proposed in the last decades, such as linear programming (LP), non-linear programming (NP), dynamic programming (DP) and genetic algorithm (GA) (e.g. Ahmad et al., 2014; Bai et al., 2015; Chang and Chang, 2001; Chang and Wang, 2013; Chaves et al., 2004; Jones et al., 2002; Yang et al., 2009; Yeh, 1985). Among these approaches, the GA embedded with an adaptive heuristic search algorithm for simulating the evolution process in nature is one of the most promising methods that produce many satisfactory results in water resources management (e.g. Cheng et al., 2008; Hassan-Esfahani et al., 2015; Wang et al., 2011; Xue et al., 2014). Being a modified version of the GA, the non-dominated sorting genetic algorithm (NSGA-II) proposed by Deb et al. (2002) is a branch of artificial intelligence (AI) and produces wide spread frontiers with fast convergence speed. Owing to the ability of visually presenting trade-offs between objectives, the NSGA-II has also been widely used in the field of water resources management (e.g. Ahmad et al., 2014; Chang and Chang, 2009; Chang et al., 2016; Farhadi et al., 2016; Makaremi et al., 2017; Tabari and Soltani, 2013; Tsai et al., 2015; Zhou et al., 2015).

In order to overcome the water scarcity problems driven by urbanization, this study proposes an intelligent water allocation system (IWAS) for reducing the water pressures of various sectors and improving the resilience of the water allocation system during drought periods (Fig. 1). We implement the SD not only to highlight the complex interrelations and dynamic characteristics of a metropolis but to simulate social impacts and forecast future water demands under urbanization. We then adopt the NSGA-II to optimize the multi-objective reservoir operation and search the non-dominated frontiers of the optimal water allocation. We also evaluate the benefit of incorporating a large number of irrigation ponds spreading over the study area into the multi-objective reservoir operation for improving water allocation during paddy-farming periods. The novelty of this research lies in adopting a system dynamics approach to simulating future water demands in response to urbanization and exploring the optimal strategies of future water allocation based on two water supply sources, i.e., a reservoir and a large number of irrigation ponds, through AI techniques for city sustainability management.

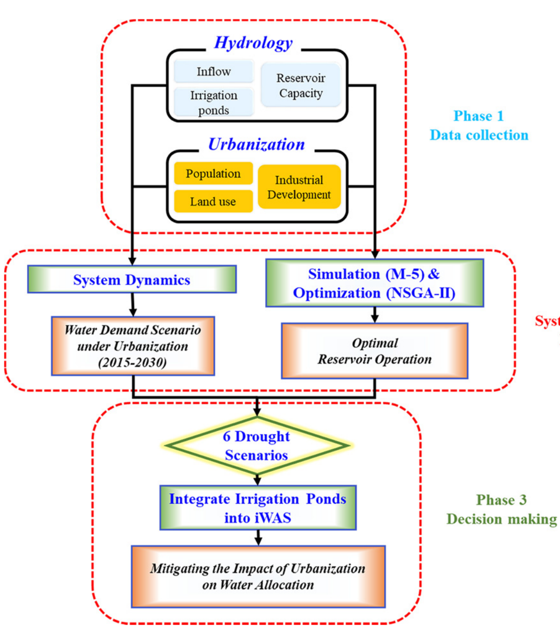


Fig. 1. Flow chart of the proposed intelligent water allocation system (IWAS) for apt water resources management under urbanization.

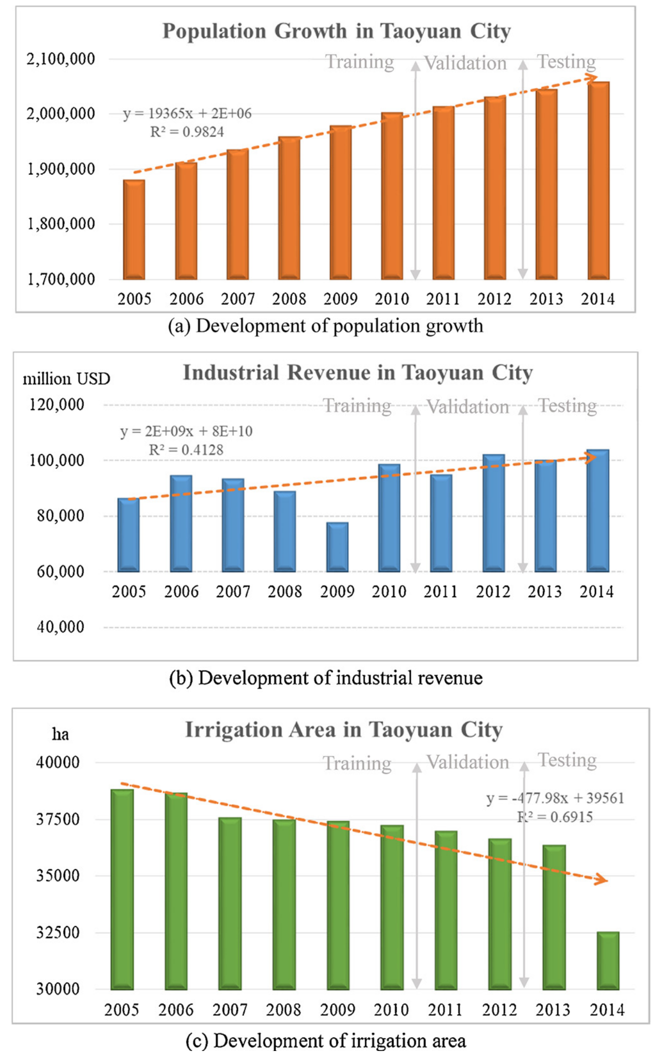


Fig. 2. Trends of (a) population growth, (b) industrial revenue and (c) irrigation area in Taoyuan City (2005–2014).

2. Study area and water supply system

2.1. Study area

In recent years, Taoyuan City in Taiwan serves as a transportation hub, and the accompanying career opportunities attract more and more people to reside in Taoyuan City. Therefore, the transportation hub has brought rapid growth in population and economic development such that the structure of economic development has transformed from agricultural production to industrial and commercial one. As shown in Fig. 2(a) and (b), the trends of population growth and industrial revenue are increasing since 2005.

The Shihmen Reservoir, located in the middle region of the Dahan River basin, is the pivotal reservoir in northern Taiwan. With an effective storage capacity of 202.3 million cubic meters (MCM) and a drainage area of 763.4 km^2, the Shihmen Reservoir operates to meet the municipal, industrial and agricultural water demands of both Taoyuan City and a part of Taipei metropolitan area. Owing to the Shihmen Reservoir and the comprehensive irrigation system, Taoyuan City once flourished in agriculture development and played a major role in rice productivity in Taiwan. However, urban development and the transformation of the economic structure in Taoyuan City in recent decades has caused a fact that newly built factories have encroached on irrigation farming lands, where a decrease in irrigation area from 38,778 ha to 32,498 ha has occurred during 2005 and 2014, as shown in Fig. 2(c). As a result, agricultural productivity has shrunk year by year in Taoyuan City.

Due to the smooth slope (1/40–1/120) of the terrain, Taoyuan City has the topographic advantage for harvesting rainwater in irrigation ponds such that pond water can be conveyed by gravity to irrigate the farms in downstream regions. There are a great number (683) of irrigation ponds spreading over the Shihmen and the Taoyuan irrigation areas with total storage capacities of 10 MCM and 46 MCM, respectively. However, more and more irrigation ponds have been abandoned or transferred into industrial use because of urbanization development in Taoyuan City. Therefore, this study also aims at analyzing the potential water availability derived from the joint operation of the multi-objective reservoir and irrigation ponds to tackle possible drought situations in the future.

2.2. Water supply system

The Shihmen Reservoir is a hydraulic facility that supplies water for the multiple purposes of irrigation, industrial and municipal uses, hydropower generation, and flood control in Taipei and Taoyuan Districts (Fig. 3). In the sector of public water supply, southern Taoyuan is supplied by the Shihmen Reservoir while northern Taoyuan is supplied jointly by the Shihmen Reservoir together with the Houchih Weir, Zhong Zhuang Weir and Yuan Shan Weir, respectively. The water supplied to irrigation areas supervised by the Shihmen and the Taoyuan Irrigation Associations is conveyed mainly through the Shihmen and Taoyuan Canals, respectively. The historical inflow of the Shihmen Reservoir and the historical water shortages in the study area during 1976 and 2008 are illustrated in Fig. 4. Due to the complexity of multi-objective reservoir operation, the designed rule curves of reservoir operation should be able to meliorate the effect of water supply for each objective. Fig. 5 shows the current operation rule curves (M-5) of the Shihmen Reservoir based on 36 ten-day periods. During the process of reservoir operation, the rule curves will be the guideline to judge droughts and flooding for dispatching water following different countermeasures.

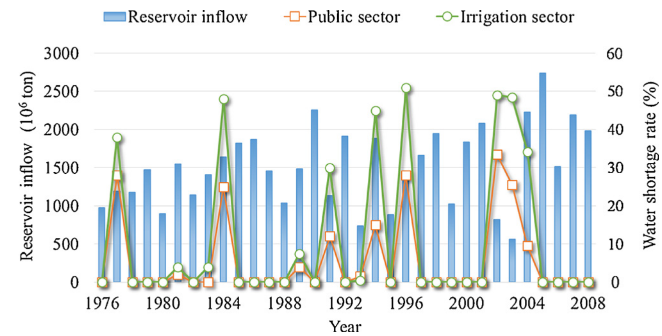


Fig. 4. Inflow of the Shihmen Reservoir and water shortage rates of irrigation and public sectors in the study area, respectively (1976–2008).

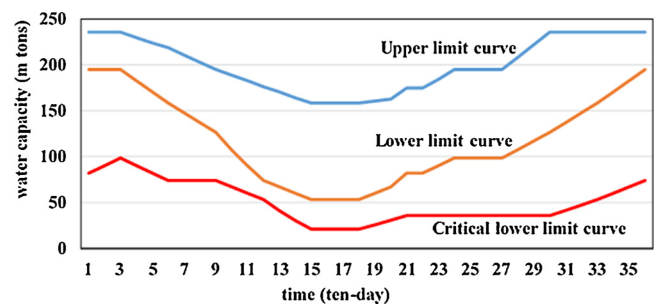


Fig. 5. M-5 operation rule curves of the Shihmen Reservoir.

3. Methodology

In this study, we propose an intelligent water allocation system (IWAS) that embraces modern techniques of the SD and the NSGA-II and incorporates irrigation pond water as a new water supply source for mitigating the tense condition of water management during drought periods under urbanization. We first use the SD to analyze the dynamic

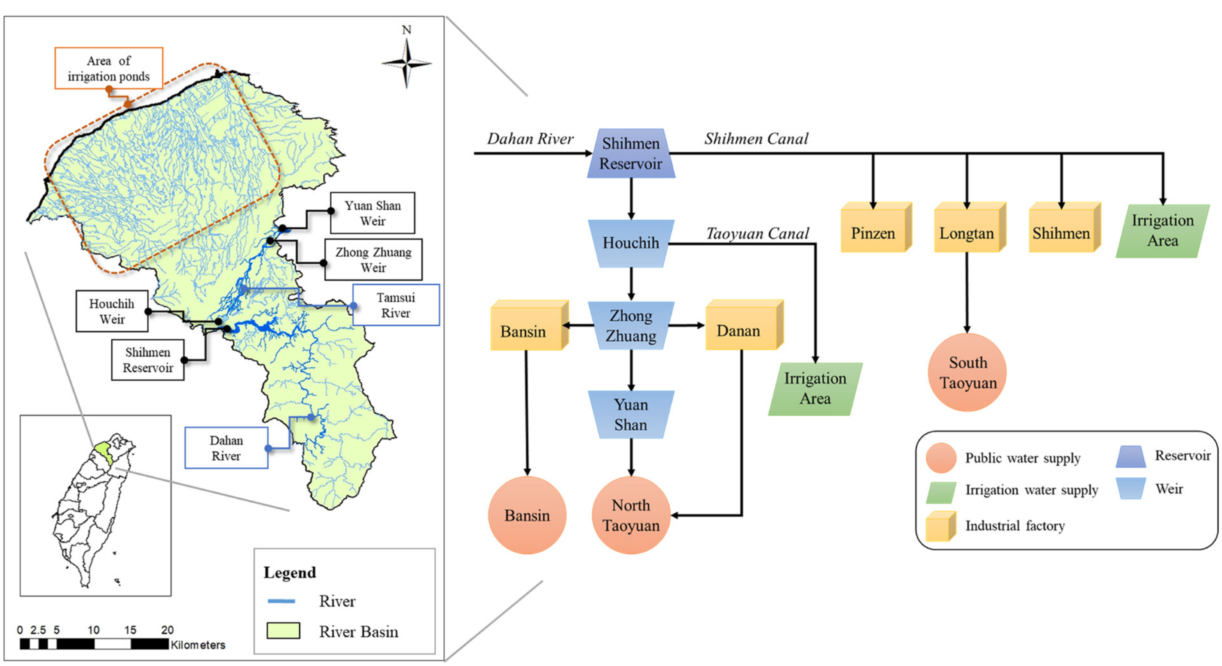


Fig. 3. Schematic diagram of the Shihmen Reservoir Water Supply System.

water consumption in consideration of the urban development in the study area and then construct a model to simulate the sequential changes of water demands in response to urbanization during 2015 and 2030. We next build an optimization model to minimize the water shortages of various sectors by using the NSGA-II for dealing with drought events, where future water demands are projected by the SD and the drought events are formed by two serious drought years in the past decades. Finally, we assess the benefit of the optimal multi-objective operation of the reservoir incorporating a large number of irrigation ponds as another water source, especially for water intensive periods (i.e. paddy-farming periods in this study). The flow chart of the proposed IWAS for achieving apt water resources management under urbanization is shown in Fig. 1, and the brief introduction of the SD and the NSGA-II is given as follows.

3.1. System dynamics (SD)

SD models are causal mathematical models to deal with the uncertainty and complexity problems, and they aspire to explore the understanding and improvement of systems (Barlas, 1996; Forrester, 1994). The SD is one of the contemporary models that enjoy flexibility to construct a system of interest and simulate the trends of the complex linkages among factors. It has been widely used in different applications for understanding social, economic, agricultural and environmental systems (e.g., Dace et al., 2015; Kotir et al., 2016; Marzouk and Azab, 2014). Once the initial conditions (inputs) are set, SD models are capable of synthesizing component-level knowledge into system behaviors and well simulating the system condition within the preset time interval.

3.1.1. Forecast future water demands under urbanization by using the SD

In this study, the SD is used to simulate (forecast) future water demands under urbanization based on key factors including population growth, industrial revenue, and land use, where three water demanding sectors (irrigation, industrial and municipal) are investigated (Fig. 6). The basic components of the SD consist of flows, stocks, and connectors, as shown in Fig. 6(a) and (b). The stock (box) denotes physical and non-physical accumulations. The flow (curve) denotes an action in a stock, which transport quantities into or out of a stock over time. The connector (blue arrow) is used to connect two variables on a sketch. All the parameters and data used to build the SD model were extracted from the open-access sources of governmental statistics and corporate annual reports (Table 1). These credible data sources provided the verification of the future prediction and have significantly enhanced the validity of the SD model.

The industrial and municipal water demands are formulated mainly by Eqs. (1) and (2).

$$\mathrm{D_{ind}} = \mathrm{W_{ind}} \times \mathrm{R_{ind}} \times \mathrm{d} \tag{1}$$

where $\mathrm{D_{ind}}$, $\mathrm{W_{ind}}$, $\mathrm{R_{ind}}$, and d are the industrial water demand per year, the industrial water quota per year, the industrial revenue per year, and working days per year, respectively.

$$\mathrm{D_{dom}} = \mathrm{N} \times \mathrm{PR} \times \mathrm{W_{dom}}/\mathrm{R} \tag{2}$$

where $\mathrm{D_{dom}}$, N, PR, $\mathrm{W_{dom}}$, and R are the municipal water demand per year, the number of population per year, the water supply penetration rate, the municipal water quota per year, and the percentage of actual meter readings, respectively.

The agricultural water demand is formulated mainly by Eq. (3).

$$D_{ir} = A_{ir} \times R_{ir} \times \frac{100}{100 - R_{loss}} \tag{3}$$

where $\mathrm{D_{ir}}$, $\mathrm{A_{ir}}$, $\mathrm{R_{ir}}$, and R_{loss} are the agricultural water demand per year, agricultural area size, irrigation rate, and the rate of water conveyance loss, respectively.

After defining the key factors of each water demanding sector, all the factors are configured and fused into the SD model. The adjustment value of each factor is presented in green color at the SD simulation stages in Fig. 6. With the proposed SD methodology, we can construct an intricate water demand model to clearly express the interactions among factors without implementing complicated computer programming.

3.2. Optimize multi-objective reservoir operation by using the NSGA-II

The NSGA-II, an evolutionary algorithm, is one of the commonly used methods for the optimization of multi-objective systems and is widely applied in many engineering fields (e.g., Dong et al., 2015; Ghodsi et al., 2016; Li et al., 2017). There are three main features of the NSGA-II: elitist principle; non-dominated solutions; and explicit diversity preserving mechanism. In this study, the NSGA-II is used to optimize the water allocation in response to future hydrological conditions coupled with growing water demands for figuring out adaptive water allocation strategies. More details of the NSGA-II can be found in Chang and Chang (2000) and Chang et al. (2016).

4. Case study

Water shortage has been a critical problem in Taoyuan City for many years; and furthermore, urbanization has further enlarged industrial and municipal water demands. Under the condition of hydrological uncertainty and urbanization, aptly and jointly utilizing local hydraulic facilities, such as the reservoir and irrigation ponds, will be an important means to tackle droughts in the future. We develop three models to simulate and/or optimize the water allocation in the study area, introduced as follows.

4.1. Simulation model of future water demands, constructed by M-5 rule curves

We develop a simulation model of future water demands that are projected by the SD based on agricultural and industrial data as well as population statistics collected during 2005 and 2014. The relationships between the water release (R) and storage capacity of the Shihmen Reservoir can be presented by the following equations.

$$R_{IR}(t) = D_{IR}(t)^{*}\alpha_{IR}^{S} \tag{4}$$

$$R_{PUB}(t) = D_{PUB}(t)^{*}\alpha_{PUB}^{S} \tag{5}$$

$$R_{total}(t) = R_{IR}(t) + R_{PUB}(t) + e(t) \tag{6}$$

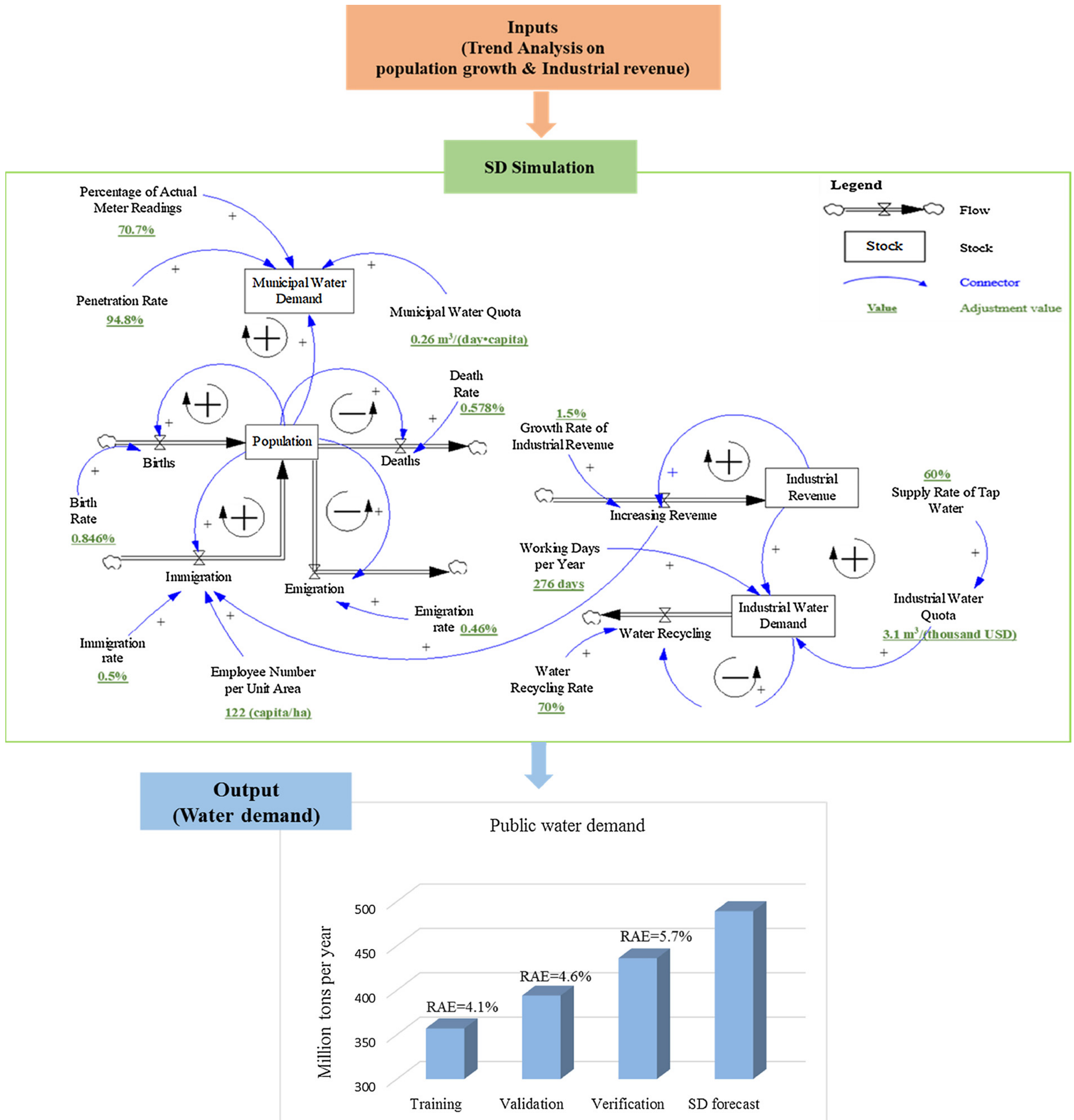
$$S(t+1) = S(t) + I(t) - R_{total}(t) \tag{7}$$

$$S_{min} \leqq S(t) \leqq S_{max} \tag{8}$$

where $R_{IR}(t)$, $R_{PUB}(t)$, and $R_{total}(t)$ are the water release of the reservoir for irrigation and public sectors, and the total water release of the reservoir in the tth ten-day period, respectively; $D_{\mathrm{IR}}(t)$ and $D_{\mathrm{PUB}}(t)$ are the water demands of irrigation and public sectors in the tth ten-day period, respectively; α_{IR}^{S} and α_{PUB}^{S} are the ratios of water releasing from the reservoir to irrigation and public sectors, respectively, which will be determined by the M-5 rule curves; $e(t)$ is the basic ecoflow of the Dahan River in the tth ten-day period; and $S(t)$ and $I(t)$ are the storage and inflow of the reservoir in the tth ten-day period, respectively.

The operation strategies of the Shihmen Reservoir based on M-5 rule curves are shown below.

(a) The water allocation system will fully meet water demands if reservoir storage capacity exceeds the lower limit curve;
(b) α_{IR}^{S} and α_{PUB}^{S} are set as 0.75, 0.9, respectively, if reservoir storage capacity falls between the lower limit curve and the critical lower limit curve; and



(a) Industrial and municipal water demands

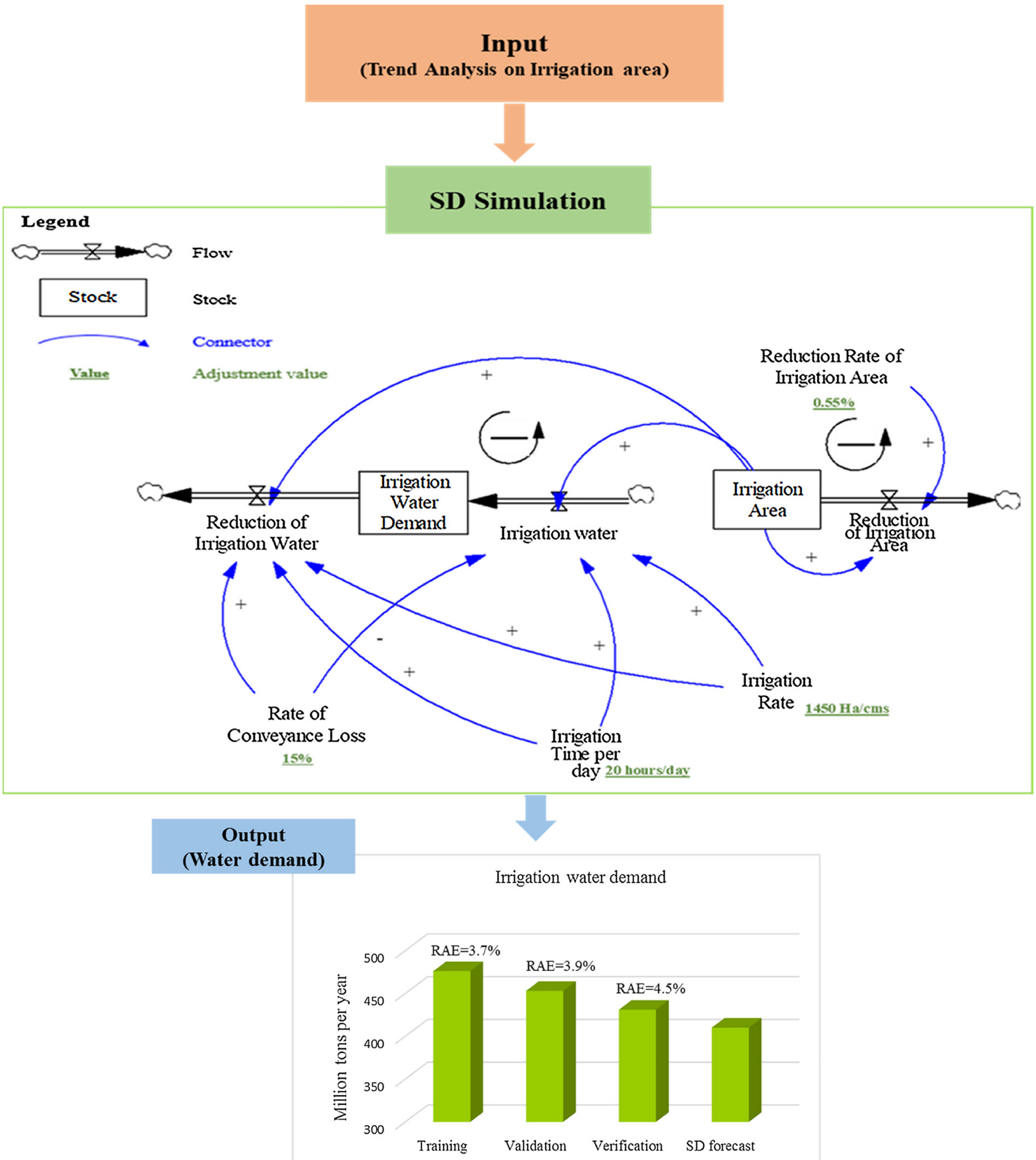
Fig. 6. Flow charts of system dynamics simulation models for forecasting future water demands in (a) industrial and municipal sectors; and (b) irrigation sectors in Taoyuan City, respectively. RAE stands for the Relative Absolute Error, which is formulated as follows.

$$\text{RAE} = \frac{|\text{Historical water demand} - \text{Simulated water demand}|}{\text{Historical water demand}} \times 100\%$$

(c) α_{IR}^{S} and α_{PUB}^{S} are set as 0.5, 0.8, respectively, if reservoir storage capacity falls below the critical lower limit curve.

4.2. Optimization model of multi-objective reservoir operation, constructed by the NSGA-II

In the study area, public water demands always gain high priority than irrigation ones. In order to make suitable water supply regulations in consideration of a flexible transfer of water from irrigation sectors to industrial and municipal sectors, we use the NSGA-II to search the optimal ratios, $\alpha_{IR\_opt}^{S}$ and $\alpha_{PUB\_opt}^{S}$, of water release to water demand every ten-days for irritation and public sectors, respectively. For alleviating water shortages and enhancing the resilience of the water allocation system, the water supply reliability (i.e. 1 − the modified shortage index (*MSI*, Tsai et al., 2015)) and the ratio of water storage to reservoir capacity (*RWS*) are adopted as the criteria for evaluating the performance of reservoir operation. As a result, the objectives of the NSGA-II are to maximize the water supply reliability (=1-*MSI*) and *RWS*, for implementation purpose.



(b) Irrigation water demand

Fig. 6. (*continued*)

$$Maximize \quad 1 - MSI = 1 - \frac{10000}{n} \sum_{t=1}^{n} \left(\frac{ST(t)}{DT(t)}\right)^2 (\equiv Minimize \quad MSI) \tag{9}$$

$$Maximize \quad RWS = \frac{100}{n} \sum_{t=1}^{n} \left(\frac{S(t)}{V}\right) \tag{10}$$

where $ST(t)$ is the total water shortage in the tth ten-day period; $DT(t)$ is the total water demand in the tth ten-day period; n is the number of ten-day periods investigated (i.e. 36 ten-day periods in this study); $S(t)$ is the reservoir storage in the ith ten-day period; and V is the maximum reservoir capacity (i.e. 209.7 million tons). Two drought years (1977 and 2002) are selected for operation purpose. The constraints of the NSGA-II follow those mentioned in Section 4.1.

4.3. Optimization model incorporated with irrigation ponds

The purposes of incorporating irrigation ponds into the optimization model are to alleviate the irrigation water shortage and enhance the resilience of the water allocation system, especially during water-intensive periods (e.g., paddy-farming periods in our case). Two simple guiding rules are set to facilitate the effectual use of irrigation pond water: (1) when the ratio of water releasing from the Shihmen Reservoir to the water demands in irrigation sectors is less than 50%, irrigation ponds will fulfill the unsatisfied water demand of irrigation sectors, and the operation policy of irrigation ponds will follow Eq. (12); and (2) if such ratio exceeds 50%, irrigation ponds will only meet

Table 1
Sources of SD parameters.

SD parameters	Sources
Industrial demands	
• Initial industrial area	Department of Budget, Accounting and Statistics, Taoyuan City, R.O.C.
• Growth rate of the industrial area (growth rate of industrial revenue)	
• Working days per year	Directorate-General of Budget, Accounting and Statistics, Executive Yuan, R.O.C.
• Daily water use per hectare (industrial water quota)	Water Resources Agency, Ministry of Economic Affairs, R.O.C. Department of Budget, Accounting and Statistics, Taoyuan City, R.O.C.
• Rate of water recycle	Ministry of Economic Affairs, R.O.C.
• Rate of water supply	Water Resources Agency, Ministry of Economic Affairs, R.O.C.
Municipal demands	
• Initial population	Department of Civil Affairs, Taoyuan City, R.O.C.
• Birth rate	
• Death rate	
• Migration rate	
• Municipal water quota	Environmental Protection Administration, Executive Yuan, R.O.C.
• Percentage of water supply	Taiwan Water Corporation
• Percentage of actual meter reading	
• Penetration rate	
• Industrial labors per hectare (employee number per unit area)	Department of Budget, Accounting and Statistics, Taoyuan City, R.O.C.
Agricultural demands	
• Initial irrigation area	Department of Budget, Accounting and Statistics, Taoyuan City, R.O.C.
• Reduction rate of irrigation area	
• Irrigation rate	Water Resources Agency, Ministry of Economic Affairs, R.O.C
• Irrigation duration per day	
• Rate of conveyance loss	

half of the unsatisfied water demand of irrigation sectors so as not to quickly consume pond water and the operation policy of irrigation ponds will follow Eq. (13).

The water allocation equations of irrigation ponds are shown below.

$$P(t+1) = P(t) - PR(t) \tag{11}$$

(1) If the ratio of water releasing from the Shihmen Reservoir to the water demands in irrigation sectors is lower than 50%:

$$PR(t) = D_{IR}(t) - D_{IR}(t)^{*}\alpha^{S}_{IR\_opt} \tag{12}$$

(2) If the ratio of water released from the Shihmen Reservoir to the water demands in irrigation sectors exceeds 50%:

$$PR(t) = (D_{IR}(t) - D_{IR}(t)^{*}\alpha^{S}_{IR\_opt})^{*}0.5 \tag{13}$$

$$3 < t < 10 \tag{14}$$

$$PR(t), P(t) \geqq 0 \tag{15}$$

where *P(t)* and *PR(t)* are the total impoundments of irrigation ponds and the water supply of irrigation ponds in the t^{th} ten-day period, respectively. Eq. (14) indicates the joint operation of the reservoir with irrigation ponds will focus on the paddy-farming period starting from February to March (i.e. 6 ten-day periods).

5. Results

To systematically build up an intelligent water allocation system, a meaningful and sequential research conception is essential. This study first uses the SD to explore future water demands under urbanization and then uses the NSGA-II to optimize the water allocation in response to future hydrological conditions coupled with growing water demands for figuring out adaptive water allocation strategies. The results are divided into three parts. The first part makes forecasts on the water demands of Taoyuan City for the period between 2015 and 2030 by using the SD theory. The second part searches for the optimal water allocation strategy by using the NSGA-II based on the obtained future water demands, and the optimal outcomes are compared with those simulated by M-5 rule curves. The third part integrates irrigation ponds into reservoir operation to alleviate the irrigation water intensive conditions during paddy-farming periods. The results are summarized as follows.

5.1. Future water demand forecasts

The trends of population growth, the total industrial revenue and the total irrigation area during 2005 and 2014 are shown in Fig. 2, respectively. We notice that the trends of population growth and the total industrial revenue are almost linearly increasing while the trend of the total irrigation is linearly decreasing. These results point out the impacts of urbanization on water allocation, i.e. people migrate to main cities and pursue industries with high economic profits (abandon industries with low economic profits, such as agriculture). These impacts also result in water demand alteration. According to the statistical data of water supply allocated by the Shihmen Reservoir from 2009 to 2013, irrigation sectors consumed 490 million tons of water per year in average while the industrial and municipal sectors consumed 400 million tons of water per year in average. A total of 10-year data (2005–2014) were used to build the model in this study, where 6-year data (2005–2010) were for model training, 2-year data (2011 and 2012) were for model validation, and 2-year data (2013 and 2014) were for model testing, respectively. In terms of the values of Relative Absolute Error (RAE) indicator, it is noted that the SD model has a good fitting in accuracy between predicted (or simulated) and historical water demands in all the three (training, validation and verification) stages (Fig. 6). The results demonstrate that the constructed SD model can well fit the water demands in all three cases (i.e., training, validation and testing stages). According to the SD results shown in Fig. 6, the future water demands of municipal and industrial sectors will be 486 million tons per year in average, which increases 21.5%, as compared with historical one (the output stage of Fig. 6(a)). On the other hand, the future irrigation water demand will be 410 million tons per year in average, which is less than the historical one by 10.42% (the output stage of Fig. 6(b)). The SD results indicate that even though the future irrigation water demand decreases under urbanization, the total water demand of the study area still increases with population growth. Thus, it is essential to build a reliable and intelligent water allocation system for mitigating the impacts of urbanization on water shortages in various sectors.

5.2. Optimal water allocation strategies

For optimizing water allocation in response to water deficit, we set up six scenarios as hydrological conditions, which are a combination of three initial reservoir storages (i.e., 50%, 40%, and 30%) with daily reservoir flow series of two most drought years (1977 and 2002) in the past 30 years. The NSGA-II is implemented to search the optimal Pareto Front for water supply reliability (1-MSI) and RWS under the six designed scenarios, respectively. Table 2 shows the parameter setting of the NSGA-II model, and Table 3 illustrates the optimal results of the NSGA-II. As shown in Table 3, it is easy to identify that the NSGA-II produces much better performances (smaller MSI and larger RWS) than the M-5 rule curves in all six scenarios, which demonstrates the solutions searched by the NSGA-II can efficiently ameliorate water shortage situations. It appears that the NSGA-II can greatly improve the MSI by as high as 35.5%. We also notice that a higher ratio of initial reservoir storage will lead to higher improvement rates in both objectives, subject to the same water demands.

Table 2
Parameter setting of the NSGA-II.

Parameters	Setting
Generation	300
Population size	300
Coding	Real-coded
Selection	tournament
Crossover	intermediate
Mutation	Gaussian distributed
Number of objective functions	2
Number of constraints	5
Number of decision variables	36

Fig. 7 presents the NSGA-II results under the Scenario of [reservoir inflow of year 2002, initial reservoir storage capacity = 50% ($S_{50\%}$)], where the optimal Pareto Front converged at the 300th generation. The results show that the conflicts of the two objectives occur, where higher RWS is accompanied with lower water supply reliability (1-MSI), and vice versa. It explicitly indicates that high reservoir water release will lead to high water supply reliability. The results also point out the best RWS (44.7%), the best water supply reliability (0.9) and compromise solutions, which can help decision makers to choose the most suitable strategy (reservoir operation) from the diverse solutions for better tackling the concerns about water allocation.

In brief, water shortages in public sectors can be mitigated through transferring water from irrigation sectors to public sectors, and a flexible dispatch of irrigation water to replenish public water demands can greatly improve the efficiency of traditional water supply strategies made by M-5 rule curves.

5.3. Results of the optimal water allocation strategy in consideration of irrigation ponds

As shown above, the NSGA-II indeed provides the optimal solutions to solve the problem of water deficit. However, we should keep seeking for as many water resources as possible to keep reducing the impacts of urbanization on water allocation. In this study, we consider the geographical conditions of Taoyuan City and regard irrigation ponds spreading over Taoyuan City as a potential water supply source. Table 3 shows the comparative results between two NSGA-II models (i.e. integrated w/ or w/o irrigation ponds) under six scenarios. Owing to the potential water volume supplied by the great number of irrigation ponds, the results show that obvious improvements in MSI can be made for most of the scenarios as irrigation ponds are incorporated into reservoir operation. This is especially obvious for the Scenarios of 1977, where the improvement rates over the original optimization models can increase by 13.3%, 23.9% and 35.5% when the initial reservoirs storages are 30%, 40%, and 50%, respectively. The results demonstrate that irrigation ponds do make a significant and satisfactory contribution to water shortage mitigation, especially for paddy-farming periods (February–March).

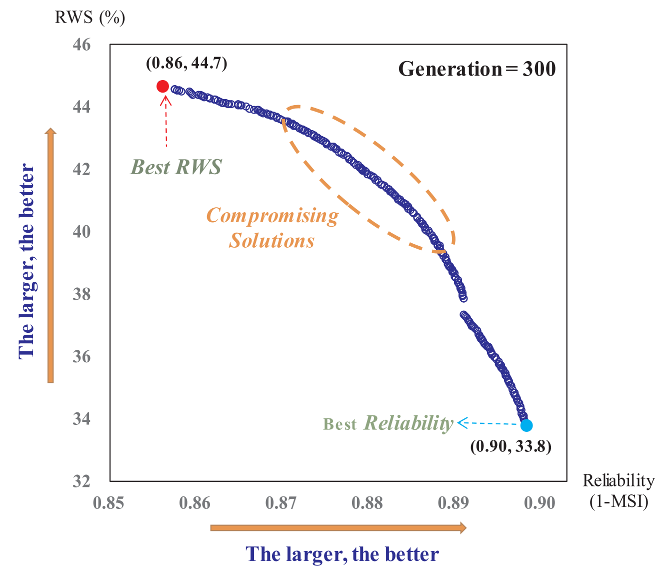


Fig. 7. Pareto Front of the NSGA-II with respect to the ration of water storage to reservoir capacity (RWS) and water supply reliability (=1-MSI) under the Scenario with reservoir inflow of year 2002 and initial reservoir storage capacity = 50% ($S_{50\%}$), which converges at the 300th generation.

In Fig. 8, the orange line presents the water supplied only from the Shihmen Reservoir (i.e. no irrigation ponds involved) while the blue line presents the water supplied from both the Shihmen Reservoir and irrigation ponds. That is to say, the difference between orange and blue lines demonstrates that the joint operation of the reservoir with irrigation ponds could significantly mitigate irrigation water shortage in general, and this is especially obvious during the 4th and the 9th ten-day periods (i.e., paddy-farming period ranging from Feb. 1 to March 30) under the Scenario of 1997 [reservoir inflow of year 1977, initial reservoir storage capacity = 50% ($S_{50\%}$)]. As known, water shortage could result in a decrease in agricultural production. The water shortage rates of irrigation sectors would significantly decrease in general (only slightly increase in the 11th and the 12th ten-day periods) in a very drought year (i.e., 1977 in this study case) if irrigation ponds cold be incorporated into reservoir operation. The analyzed results demonstrate that the NSGA-II could efficiently ameliorate water shortage situations and keep water supply sufficient in the consequent

Table 3
Results of water allocation obtained from M5 rule curves simulation (benchmark), NSGA-II optimization, and NSGA-II optimization incorporated with irrigation ponds under six scenarios, respectively.

Scenario		RWS[a]			MSI[b]		
Year	Ratio of initial reservoir storage	M-5 rule curves	NSGA-II	NSGA-II considering irrigation ponds	M-5 rule curves	NSGA-II	NSGA-II considering irrigation ponds
1977	50%	46.5	**50.0** [c] (7.5[d])	**50.0** (0.0[e])	10.0	7.6 (24.0[d])	**4.9** (35.5[e])
	40%	44.7	47.5 (6.3)	**47.9** (0.8)	11.9	9.2 (22.7)	**7.0** (23.9)
	30%	43.7	45.5 (4.1)	**46.2** (1.5)	13.7	11.3 (17.5)	**9.8** (13.3)
2002	50%	40.8	44.7 (9.6)	**45.3** (1.3)	15.7	12.8 (18.5)	**10.3** (19.5)
	40%	39.5	41.6 (5.3)	**42.2** (1.4)	17.3	14.9 (13.9)	**13.5** (9.4)
	30%	37.5	**38.9** (3.7)	**38.9** (0.0)	19.5	**16.9** (13.3)	**16.9** (0.0)

[a] Ratio of water storage to reservoir capacity (%).
[b] Modified shortage index (%).
[c] Model with the best performance under each scenario is shown in bold.
[d] Improvement rate over the results of M5 rule curves (%).
[e] Improvement rate over the results of the NSGA-II (%).

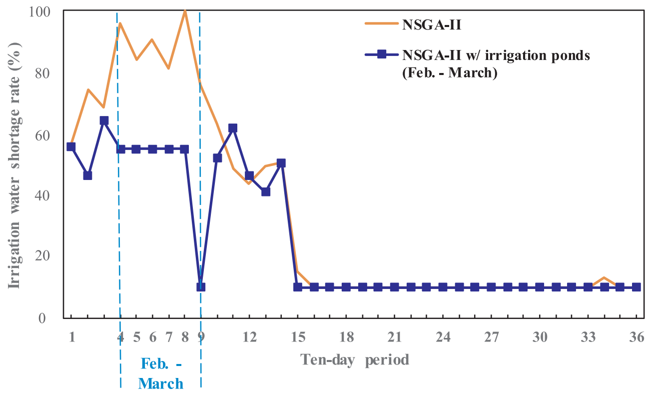


Fig. 8. Improvement of drought mitigation under the Scenario with reservoir inflow of year 1977 and initial reservoir storage capacity = 50% ($S_{50\%}$).

irrigation periods. This again provides a clear evidence that the large number of irrigation ponds in the study area could be a valuable facility for promoting the effective use of water resources and have the merit of significant mitigation on water deficit during drought periods.

From the perspective of practice in reality, the realization of incorporating irrigation ponds into reservoir operation still lies on the minor engineering approaches to keeping the connection between the Shihmen Reservoir and each pond, such as through irrigation channels, open channels and underdrains. Besides, irrigation ponds should store water as much as possible before dry seasons. According to the joint operation rules of the Shihmen Reservoir and irrigation ponds, if water shortage occurs, the Shihmen Reservoir will focus on supplying water to industrial and municipal sectors while irrigation ponds can afford to meet the water demands of irrigation use or local areas flexibly. In this way, the impact of water shortages on both public and agricultural demands could be mitigated. The proposed approach could benefit both irrigation associations (the authority responsible for irrigation sectors) and the Water Resource Agency (WRA) in Taiwan (authority responsible for public and industry water supply).

6. Conclusions

The fast development of urbanization and industrialization in recent years has brought huge impacts on water demands. Following the direction of environmental protection and sustainable city development, this study demonstrates how to use the existing water resources efficiently in an adaptive manner for water allocation and how to overcome water deficit under urbanization. We propose the IWAS, which consists of three major modules: (1) projecting the future water demands in response to urbanization by using the SD method; (2) optimizing water allocation by using the NSGA-II method based on the projected future water demands; and (3) mitigating water shortages through an incorporation of a great number of irrigation ponds into the water allocation system. The results of the SD models show that urbanization may change the water demands of different sectors, whereas it still cannot change the fact that water resource shortage remains critical in the future. Previous studies indicated that the NSGA-II could be a powerful and flexible tool to effectively build complex and dynamic water allocation systems in an adaptive manner for obtaining satisfactorily counterbalanced solutions. For the NSGA-II optimization model, we consider two objectives, maximizing water supply reliability and the ratio of water storage to reservoir capacity, for assessing the impacts of urbanization on irrigation water supply when irrigation water is dispatched to replenish public water demands. The results indicate that the IWAS can significantly decrease public water shortages but just slightly affect irrigation water shortages during drought periods in response to urbanization. The improvement rates of the MSI and the RWS can reach up to 24% and 9.6%, respectively, as compared to those of M-5 rule curves. Moreover, on account of a great number of irrigation ponds located in Taoyuan City, we consider them as another viable water source that bears great potential in enhancing water supply reliability and decreasing water pressure. The results show that water shortage conditions can be effectively alleviated as the IWAS is integrated with irrigation ponds, especially during paddy-farming periods. The improvement rates of the MSI and the RWS can enhance by up to 35.5% and 1.5%, respectively, as compared to those of the NSGA-II without incorporating irrigation ponds. Our results show that even though the optimal strategy of water supply is to dispatch irrigation water to satisfy public water demands, we still can satisfy irrigation water demands to ensure food security through IWAS (coupled with irrigation ponds).

We conclude that the flexibility on water resources management is the sticking point for drought mitigation, especially at the moment of rapid urbanization and growing water demands. The water transfer strategies and the idea of incorporating irrigation ponds into reservoir operation could provide a nice alternative for decision makers to make better water management with a sustainable utilization of water resources.

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