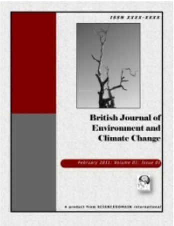

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Carrying Capacity and Sustainability Appraisals on Regional Water Supply Systems under Climate Change

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Authors' contributions

This work was carried out in collaboration between all authors. Author CPT designed the study and the framework. Author TML performed the model simulation, managed the analyses of the study and completed the draft of the manuscript. Author SWC performed the model programming and wrote the first draft of the manuscript. Authors KYK and MHL managed the literature searches and performed the statistical analyses. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

This study aims to appraise the carrying capacity and sustainability of four water supply systems which are in the same watershed under climate change. An integrated assessment tool, TaiWAP, which integrates the common procedures of impact assessment of climate change, i.e., downscaling, weather generation, hydrological model, and interface for linking system dynamics model, is used to evaluate the sustainability of regional water resources systems. The GWLF physical model is used to simulate surface water processes and Vensim (a specialized software tool) is used in a system dynamics approach to simulate Taiwan's Danshuei river watershed supply system to analyze climate impact on sustainable water resource utilization, which are both included in TaiWAP. To understand the sustainability of water supply systems, definition of a sustainable index are necessary to reveal the effects of response strategy and climate change. The results of this study could support making governmental strategies to enhance adaptive capacity, mitigate the impact of climate changes on water supplies and achieve sustainable and resilient water supply systems for the future.

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Keywords: Sustainable development; water resources; carrying capacity; system dynamics.

1. INTRODUCTION

In Taiwan, the average annual rainfall is up to 2500 mm, which is much higher than the world average of 834mm. However, most of the rainfall concentrates in the wet season (from May to October), and about 80% of the rainfall flows directly into the ocean due to the temporal and spatial non-uniform distribution [1,2]. As a result, in Taiwan, water shortages during the dry season do happen. In recent years, water shortages have seriously affected the availability of water supply. Under the future threat of climate change, efficient use of water resources becomes a vital area of study. To guard against climate change causing more extreme events with deleterious impacts on sustainable regional water resources development and increase drought risk, it is very important to consolidate visible water resource strategies and policy decisions with climate change assessment.

The impacts of climate change to water resources have been evaluated on many studies. The river flows may be changed due to climate change [3,4]. IPCC (Intergovernmental Panel on Climate Change) indicated that that flow seasonality increases, with higher flows in the peak flow season and either lower flow during the low flow season or extended dry periods [5]. It may cause more difficult on water resources management and challenge irrigation system [6].

With the threat of increasing dryness due to climate changes, finding more efficient ways to use water resources is becoming an important area of study. To estimate the sustainability of water resources under climate change, it is required to use an integrated model on assessment due to miscellaneous simulation steps and climate change scenarios. Liu et al.[7] developed an integrated assessment on water resources system to climate change, TaiWAP, which integrates the common procedures of climate change impact assessment, including scenarios of climate change released by IPCC [8], downscaling, weather generation, hydrological model , and interface for linking system dynamics model (SDM). This friendly tool merely requires users to set up a SDM for their own purpose and make a connection to the TaiWAP, the complex of assessing climate change impact is thus no longer a problem and can be download on TaiWAP Website [9].

Climate change refers to the long-term variation in climate trends that exacerbate short-term weather variability and possibly related extreme meteorological events, leading to significant impacts on both human society and the natural environment. Socioeconomic development depends on reliable water supply system, but climate change may affect the system, including changing available stream flow, groundwater, and irrigation requirement, etc. The purpose of this study is to define a sustainability indicator associated to evaluate climate change impacts on water supply systems. TaiWAP was used in this study to adopt the sustainability of regional water supply systems, and to strengthen adaptive capacity of risk management for water resources by proposing strategies for achieving sustainable development for the future.

2. STUDY AREA

The study area is the Danshuei River watershed, which crosses northern Taiwan and serves as the major water supply source for Taipei municipal areas and neighbor counties. Fig. 1 shows the Danshuei River watershed with three major tributaries, the Sindian River, the

Dahan River, and the Keelung River. The total length and area of the Danshuei River are 157.8 km and 2726 km^2, respectively. There are four main water supply districts, Taipei, Banshin, Taoyuan and Keelung. The Taipei district draws water from the Sindian River and the on-site Feitsui reservoir, while the neighboring water supply districts, Banshin and Taoyuan, utilize water from the Dahan River where the Shihmen reservoir is located. The Keelung River with only a few small reservoirs and hydraulic structures to hold water, is the source of Keelung water supply system. A conceptual diagrams of the water supply systems of the Danshuei River are given in Fig. 2 and Fig. 3.

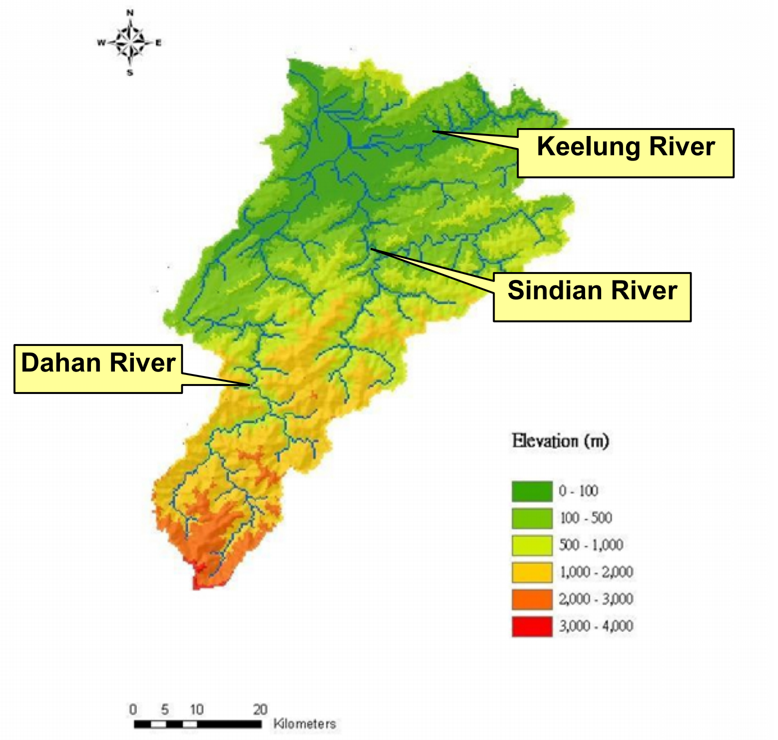

Fig. 1. The Danshuei River watershed with three tributaries

There are three water treatment plants, Chihtan, Chingtan and Gongguan, in the Taipei water supply district. Chihtan Weir delivers water to the Chihtan water treatment plant with a capacity of 2.70×106 m^3/ per day (CMD), while Chingtan Weirs store water for Changshin and Gongguan water treatment plants. Total capacity of the three major treatment plants and inlets are 3.82×10^6 and 3.80×10^6 CMD, respectively. These water treatment plants utilize water from the Nanshi River first. If this water supply is insufficient, a request will be sent to the Feitsui reservoir management bureau to release more stored water.

The major hydraulic facilities in the Dahan River include Shihmen reservoir, Houchi Weir, Yuanshan Weir, Sansia Weir, Shihmen major irrigation ditch, and Taoyuan major irrigation ditch. The Shihmen major ditch intake is located upstream of the Shihmen reservoir, while the intake of Taoyuan major ditch is installed in the Houchih Weir. The Taoyuan water supply system has four water treatment plants that withdraw water via Shihmen and Taoyuan ditches. The total capacity of water treatment plants and inlets are 1.27×10^6 and

1.35×10^6 CMD, respectively. The Banshin water treatment plant takes water from Sansia Weir first. If the water is insufficient, more water will be taken from Yuanshan Weir. The capacity of treatment and inlet for Banshin district are 1.20×10^6 and 2.10×10^6 CMD, respectively. The Banshin district also receives water supply from Taipei water supply district directly.

The Keelung water supply system includes two reservoirs, two pumping stations and seven weirs, as shown in Fig. 3. This supply system is more complicated than the other water supply systems. The Xishi and Xinshan reservoirs in the Keelung River watershed store water as much as possible and provide water without a discount water supply, which are different from reservoirs of the other water supply districts. Two pumping stations and seven weirs hold and send water to the water treatment plants to provide water to the whole Keelung district.

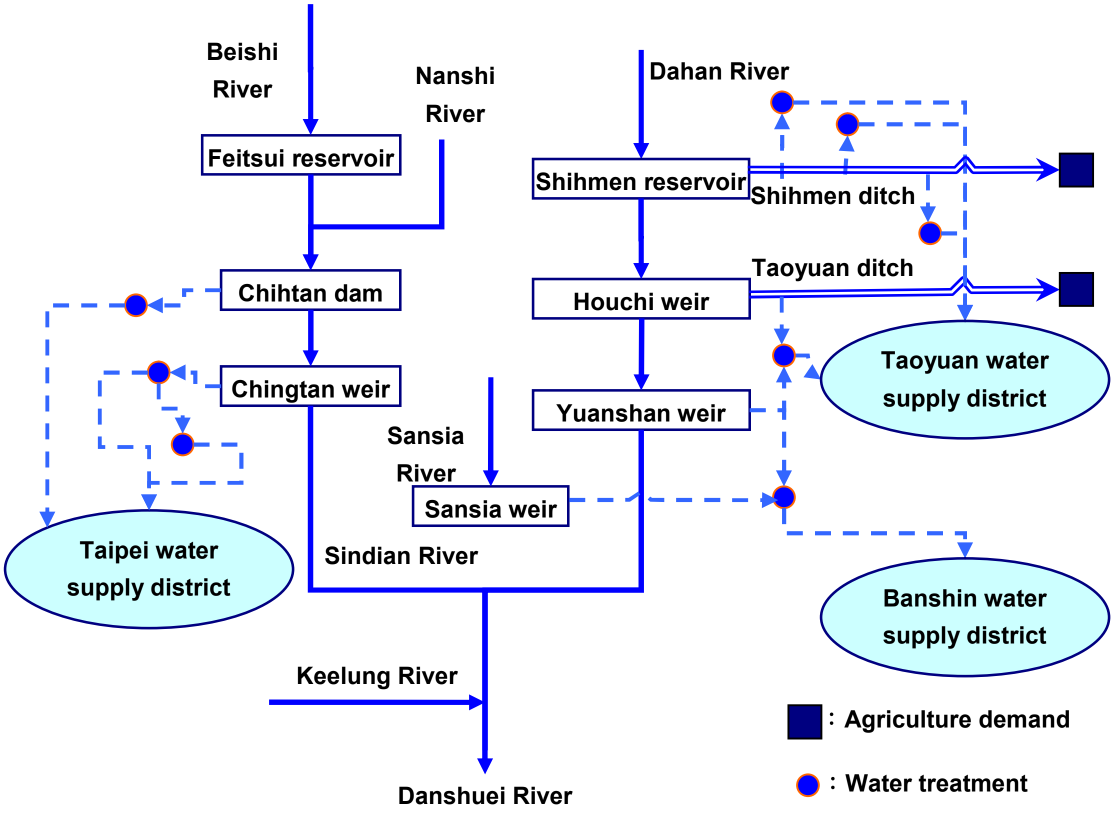

Fig. 2. Taipei, Taoyuan and Banshin water supply systems

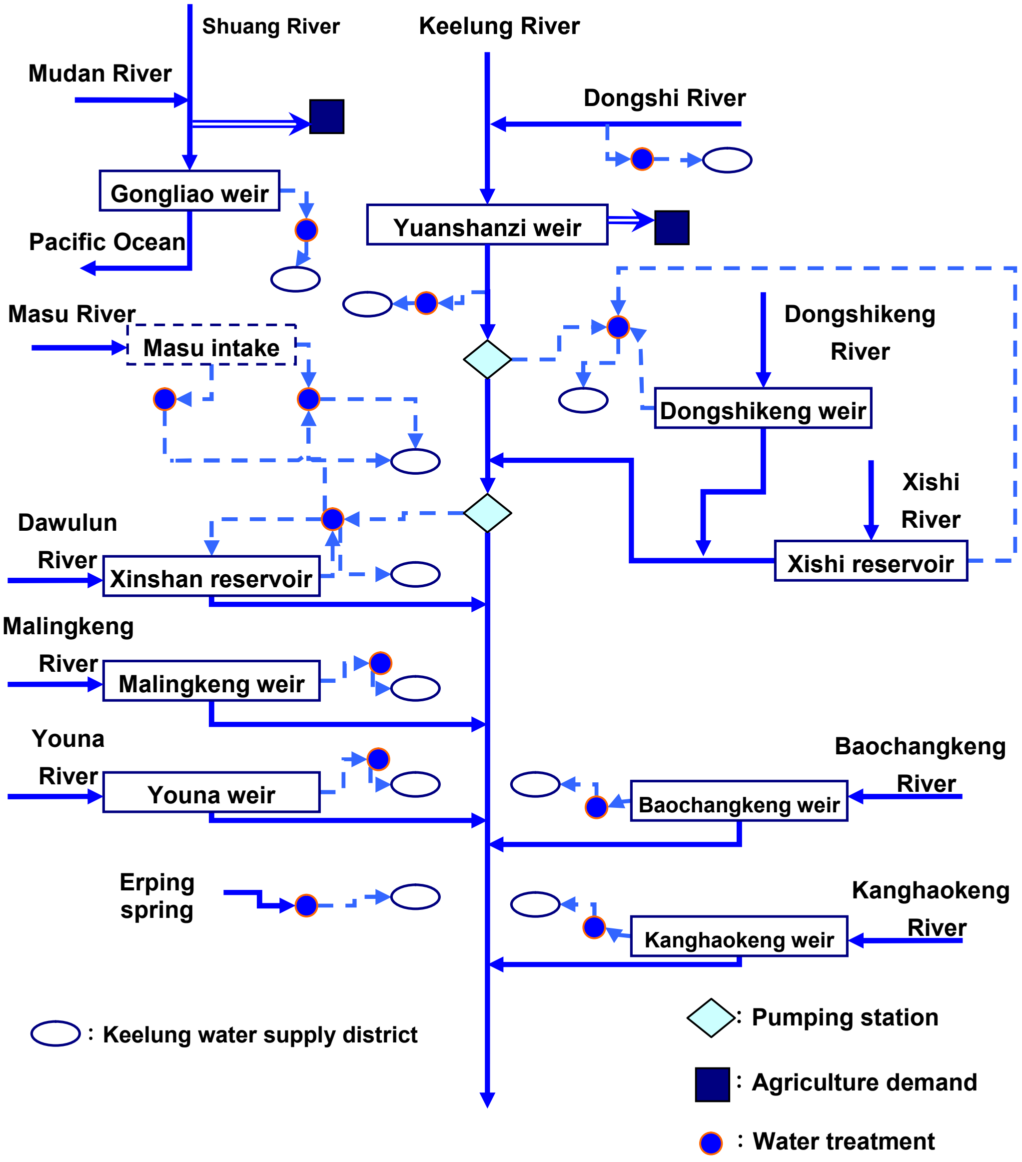

Fig. 3. Keelung water supply system

3. METHODOLOGY

The procedure of assessment was divided into five steps, as shown in Fig. 4. First, current and future weather data are prepared, which means climate scenarios are derived based on several General Circulation Models (GCMs) with downscaling skills. Then these scenarios consisting of monthly climate statistics are used to create different weather data sets by a weather generation model in the second step. The third step is to input weather data into a hydrological model to simulate the inflow discharge in the water supply system. Fourth, a water supply system dynamics model is employed for the water supply simulation and sustainability appraisal of a water supply system. In the end, determination of a sustainable index which improves understanding the status of a water supply system was applied. The whole process were included in TaiWAP which was developed to assess the vulnerability of the water resources systems in but not limited to Taiwan. It involved the climate change scenarios of precipitation and air temperature which were released by IPCC. In addition, the weather generator, hydrological model(GWLF model), and water resources system dynamics model(package built by Vensim) are within. The assessment steps as the components of TaiWAP are described below.

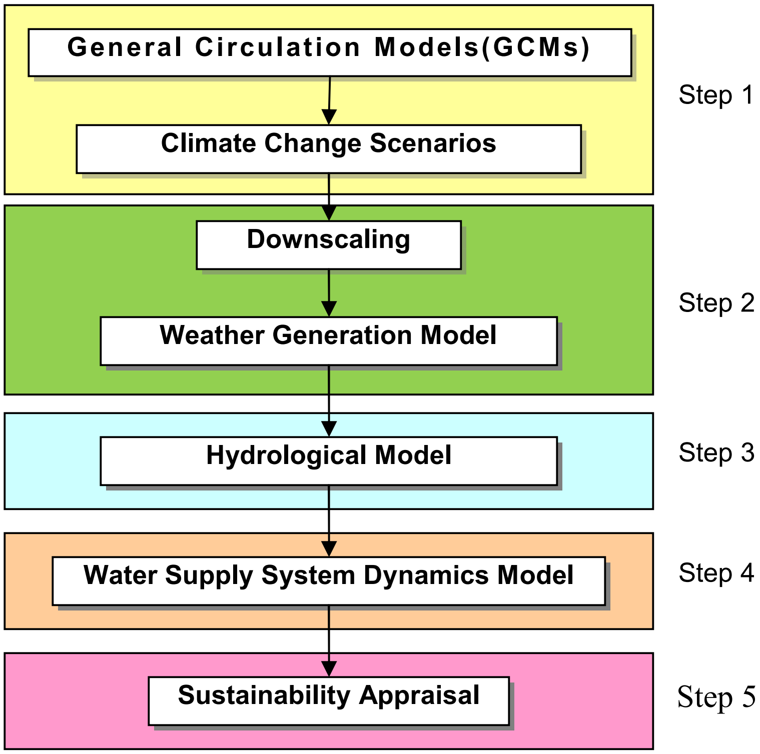

Fig. 4. The methodology diagram

3.1 Climate Change Scenarios

Research on climate change impacts are based mainly on the results of GCMs. However GCMs are global-scale simulations with uncertain validity for local-scale application. For impact assessment, the predictions of GCMs can only be used to establish climate change scenarios, and to generate input data for assessment model with the weather generator. The predictions of GCMs are large-scale results and should be transformed by downscaling to obtain local climate characteristics.

For the analysis of future climate scenarios, the A2, A1B, and B1 scenario of Special Report on Emissions Scenarios (SRES) [10] are adopted in this research. This study applies different GCMs scenarios and discusses the variation by the changes of precipitation and mean temperature in short-term (2010-2039). A downscaling method named “Simple Downscaling” was adopted herein.

Simple downscaling method directly uses the forecast data of the nearest GCMs grid and assumes the changes of temperature and precipitation will be equal in the same zone. Accordingly, the first step is getting the meteorological data, such as temperature and precipitation, of future climate-change scenarios derived from GCM predictions. To reduce the uncertainty of GCMs, it is recommended to adopt the better skill GCMs. In this study, six GCMs, MRI-CGCM2.3.2, GFDL-CM2.1, UKMO-HADCM3, MPIM-ECHAM5, INM-CM3 and NCAR-CCSM3 [4] were chose due to high correlated precipitation pattern to study area. When TaiWAP was developed, there were only ten GCMs released with three scenarios, A2, A1B, and B1. Table 1 shows the correlation coefficients of monthly mean precipitation between simulated precipitations from these ten GCMs and historical observations in study area. The six higher correlation GCMs were marked with bold font in Table 1 and the brief of 6 GCMs were shown as Table 2.

Table 1. Correlation coefficients of monthly mean precipitation between baseline of GCMs and historical observations in study area. Six higher correlation GCMs are in bold font

GCM / **Station**	**CSIRO-MK3**	**GFDL-CM2.0**	**GFDL-CM2.1**	**INM-CM3**	**IPSL-CM4**	**NIES: MIROC3.2-MED**	**MPIM-ECHAM5**	**MRI-CGCM2.3.2**	**NCAR-CCSM3**	**UKMO-HADCM3**
Fusan	0.451	0.150	0.648	0.565	-0.041	-0.067	0.811	0.523	0.722	0.453
Gaoyi	0.369	0.062	0.563	0.552	-0.016	-0.123	0.811	0.518	0.640	0.397
Baling	0.377	0.062	0.590	0.566	0.042	-0.086	0.815	0.483	0.586	0.376
Bihu	0.630	0.071	0.752	0.593	0.204	0.095	0.820	0.370	0.619	0.375

Table 2. The brief of six GCMs which were used in this study (IPCC, Data Distribution Center [8])

Center	**Center Acronym**	**GCM**	**Atmospheric resolution (longitude x latitude)**
Max-Planck-Institut for Meteorology(Germany)	MPIM	ECHAM5	Approximate 1.9 x 1.9 degrees
Geophysical Fluid Dynamics Laboratory(USA)	GFDL	CM2.1	Approximate 2.5 x 2 degrees
Institute for Numerical Mathematics(Russia)	INM	CM3	5 x 4 degrees
Meteorological Research Institute(Japan)	MRI	CGCM2.3.2	Approximate 2.8 x 2.8 degrees
National Centre for Atmospheric Research(USA)	NCAR	CCSM3	Approximate 1.4 x 1.4 degrees
UK Met. Office(UK)	UKMO	HadCM3	3.75 x 2.75 degrees

3.2 Weather Generation Model

The weather generation model [7] is required in the impact assessment of climate change to generate daily air temperature and precipitation based on different climate scenarios. To reproduce the statistic of precipitation and temperature of the observation, a quite number of generation data, at least 100years, is required [7]. Therefore, sequences of 100 years of daily precipitation and air temperature data were generated for current and future climate scenarios in this study.

In the weather generation model, the daily temperature is generated using one-order Markov Chains as equation (1).

$$T_i = \mu_{Tm} + \rho_m (T_{i-1} - \mu_{Tm}) + \nu_i \sigma_{Tm} \sqrt{1 - \rho_m{}^2} \tag{1}$$

where T_i is the temperature in day I,μ_{Tm} is the mean temperature of the target month, $\rho_m$is the correlation coefficient of T_i and T_{i-1} of the target month called the first order serial correlation coefficient, ν_i is the normal sampling deviate which is the number between 0 and 1 generated randomly for each day and σ_{Tm} is the standard deviation of the observed temperature of target month respectively. The temperature of the first day in simulation uses the mean temperature of the first month and of the rest following days can be generated day by day.

The daily rainfall is generated in two steps, generating occurrence and generating amount. For generating occurrence, a random number, *RN*, between 0 and 1 is generated. *P(W|W)* and *P(W|D)* which are the conditional probability of a wet day following a wet day and the conditional probability of a wet day following a dry day are adopted by the historical data and used to generate the occurrence. If day (*i-1*) is a wet day and $RN \le P(W/W)$, then the day *i* will be a wet day. Otherwise, it will be a dry day. If day (*i-1*) is a dry day and $RN \le P(W/D)$, then the day *i* will be a wet day. Otherwise, it will be a dry day. When the occurrence is simulated as a wet day in the first step, the rainfall amount will be produced by using a formula in the next step：

$$P = \mu_P(I) \times [-\ln(1 - RN)] \tag{2}$$

The distribution of precipitation is assumed as an exponential distribution. Therefore the rainfall amount can be generated with a uniform distributed random number RN which is between 0 and 1.

3.3 Hydrology Simulation Model

The hydrology simulation model GWLF [11-13] was used in this study to simulate the water budget of the watershed. In the model, the streamflow was calculated from runoff and groundwater. In water balance, rainfall brings the water into the watershed. When rainfall reaches to the ground, some of the rainfall infiltrates to the soil and the rest becomes surface runoff and flows into the river. The rainfall will supply the water content of the unsaturated zone. When the soil moisture content in the unsaturated zone is more than the field capacity, because of gravity, the water will percolate down into the shallow saturated zone and can then enter the stream as underground drainage. Streamflow contains runoff and underground drainage. The water balance in the watershed is mainly divided into three categories: surface, unsaturated zone and the shallow saturated zone. GWLF was used in this study due to its simple input requirement, i.e., only rainfall and temperature. Readers can refer to Haith et al. [14] for more details of GWLF.

3.4 The Water supply System Dynamics Model

Systems dynamics was started from simulating urban dynamics describing development of a city that finally collapses due to resource exhaustion [15]. It studies how the behavior of complex system changes through time and has been applied to many research areas. Simonovic [16] mentioned that systematic planning for water resources is complicate and requires computer programming. System dynamics modeling is a powerful measure to develop a simulation model. Forrester [17] developed a system dynamics model to describe urban dynamics, and Meadows et al. [18] used system dynamics to describe limits to growth. Many researchers have also developed their system dynamics model and applied to water resources systems (e.g., Guo et al. [19]).This study uses system dynamics in a simulation model to evaluate sustainability of water supply systems.

A system consists of many components and functions to describe the relationships between components. System dynamics modeling has three major components that include level, rate, and auxiliary and uses arrow to link components. Thus, system dynamics modeling can be applied to develop a simulation model more intuitively, especially for water resources systems. For example, a reservoir can be represented by a level component, and its inflows and outflows can be described by the rate components. Besides operational rules of a reservoir, principles of withdrawing water from a weir or other management strategies can be stated by the auxiliary component.

In this study, the system dynamics model was used to build the Danhsuei River water supply system and to evaluate the sustainability of water supply systems. This model is divided into several sub models, including three water supply systems for the Sindian, Dahan and Keelung River and water demand sub models for four water supply districts. The model was developed by using Vensim software. The water supply system dynamics model needs two kinds of input data which are upstream flow and total water demand. For the reservoir component in this model, its outflows are determined according to total water demand, inflow, and the operation rules. For the water supply to the domestic and industrial water, the water is determined by the outflow from the river or the reservoir, water demand and the capacity of the water treatment plant. The complicated water supply system is composed by many components like water treatment plants, reservoirs or dams and supply or demand components. However, the system dynamics model can simulate the realistic water supply with considering all the components and make the complex system a modular model.

3.5 Sustainable Appraisal Index

There are three steps to make a sustainable appraisal. The first is defining an environmental carrying capacity which is referred to water supply capacity in this study. According to the definition of sustainable development, “Meets the needs of the present generation without compromising the ability of future generations to meet their own needs”, it needs a critical limit to avoid degrading the environment and meet needs of future generations, which is called environmental carrying capacity. The water supply capacity is the ability of water supply and the main constraint on development, or it will lead to degraded environment. The ability of water supply is evaluated based on the goals of shortage index (SI)of 0.1, 0.5, 0.5, and 0.5 for Taipei, Banxin, Taoyuan and Keelung, respectively. Second, the cumulative impact is identified. The cumulative impact means the impact on the environment resulted from incremental effects of the project in addition to other past, present, and reasonably foreseeable future projects regardless of what person undertakes the other projects. The cumulative impact in this study is total water demands. The third step is to get a sustainable index by comparing the carrying capacity with total water demands and it helps to clarify the sustainability of water supply. A water supply system which meets sustainability needs total water demands less than the carrying capacity. On the other hand, if total water demands are beyond the carrying capacity, which means water supply cannot meet demand, continuous economic and social development will be stopped or new water resources, which normally cause impacts on ecosystems, are needed. Therefore, a good index should be able to represent above principles and can be designed as Eq.3 and shown as Fig. 5.

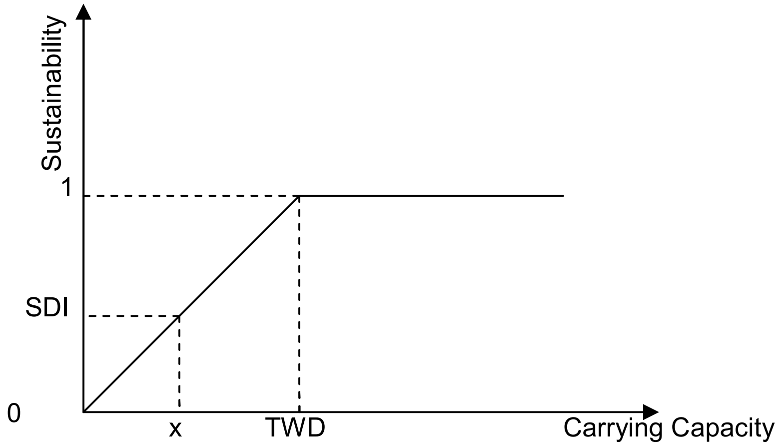

Fig. 5. The sketch of sustainable appraisal index

$$SDI = \begin{cases} 1 & \text{if } x \geq TWD \\ \dfrac{1}{TWD}x & \text{if } x < C \end{cases} \tag{3}$$

Where SDI is a sustainable index, TWD is total water demands. When the index equals one, it means that carrying capacity is more than total water demands and the water supply system is sustainable. However, if carrying capacity is less than total water demands, the index will decrease from one to zero, a nil carrying capacity condition. A lower index value implies less sustainable water supply.

4. VALIDATION STUDY

The water supply system dynamics model was validated by assessing practical predictions for the Sindian, Dahan and Keelung River. To verify whether the proposed model can reasonably describe the management strategies and reservoir operational rules, three sets of historical stream flows recorded in the period of 1991 through 2000 were used. Upstream flows were entered into the model to simulate downstream flows which were compared with the observed flows recorded in the Hsiulung, Sanying bridge and Wudu gauge stations located downstream in the Sindian, Dahan and Keelung Rivers, respectively. The results are shown in Figs. 6 to 8, which indicate the reasonable predictions by the water supply system dynamics model. There is a significant error on 96th month (i.e., October of 1998) noted. This is likely explained by a strong typhoon with heavy rainfall that increased stream flows that month. The system dynamics model developed in this study lacks ability to describe reservoir operational rules for flood mitigation. Besides, the model assumes lateral flow proportional to its drainage area. This assumption may not be hold for a typhoon event. However, this study is mainly concerned about the ability of water supply system and its vulnerability under climate change, and hence flood mitigation is less relevant.

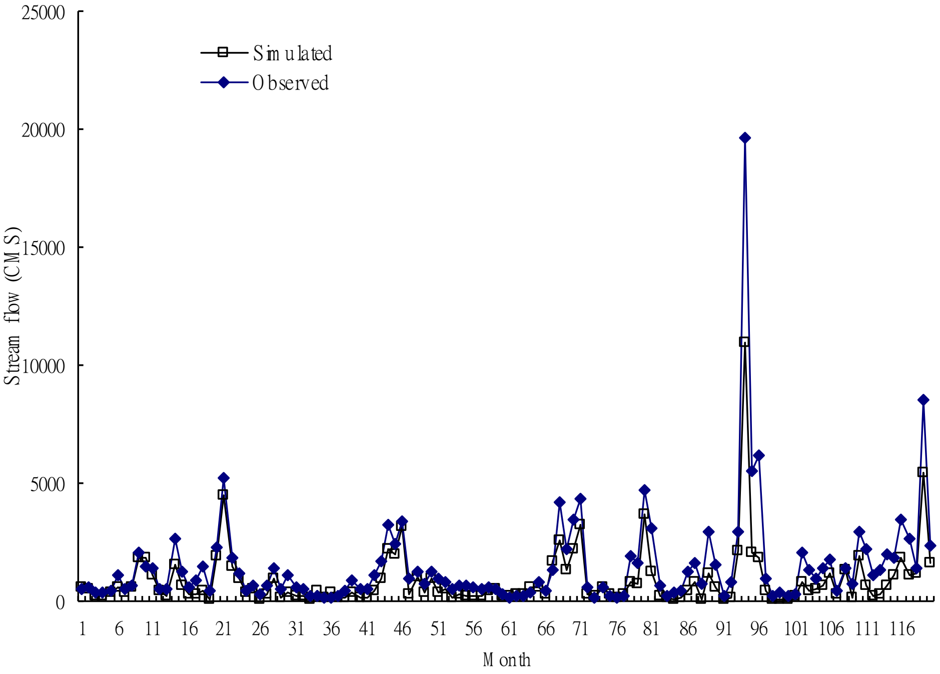

Fig. 6. Validation study – observed version simulated monthly streamflows of the Sindian River. (Correlation coefficient=0.95)

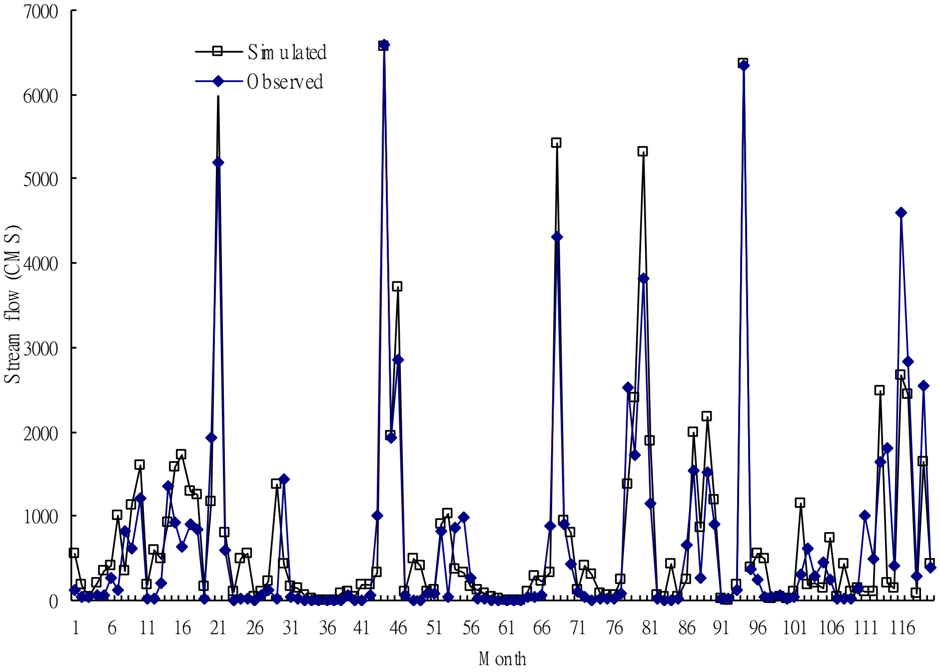

Fig. 7. Validation study – observed version simulated monthly streamflows of the Dahan river. (Correlation coefficient=0.92)

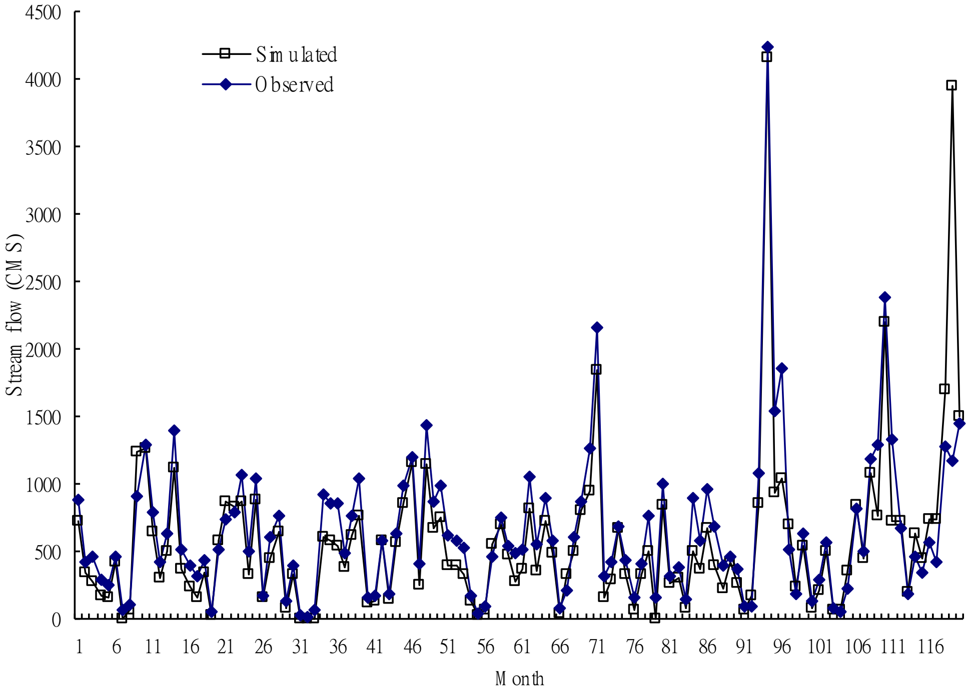

Fig. 8. Validation study – observed version simulated monthly streamflows of the Keelung River. (correlation coefficient=0.85)

5. RESULTS

There are three parts in this section to appraise the sustainability of the water supply systems, i.e. the baseline assessment, the future projection without climate change impact and the future projection with climate change impact.

5.1 Baseline Study

Baseline study is the assessment for the period of 1991 to 2001. In 2001, a water supply project which is called the First Stage of Water Supply Improvement Project for Banxin District was carried out and accomplished in 2003. The purpose of this project is to improve the water supply in Banxin district as the amount of water supported by Taipei water supply system reaches 530,000 CMD. To evaluate the effectiveness of the First Stage of Water Supply Improvement Project for Banxin District, two cases were proposed for baseline study. Case I does not consider the First Stage of Water Supply Improvement Project for Banxin District, while Case II does.

By using SDI index to indicate the sustainability of a water supply system, Table 3 shows that all water supply systems are sustainable except Banxin water supply system in the Case I, which is consistent to the real case. Because the Banxin water supply system shares the same water source from TaHan river with Taoyuan located upstream of TaHan river. Therefore, Banxin has more water shortage risk because of the lack of water intake. That’s why the government undertook the water supply improvement project for Banxin District to enhance the water supply capacity of Taipei and transfer water from Taipei to Banxin. Case

II shows the benefit of the improvement project because the sustainable index in Banxin becomes 1. Also, after the accomplishment of the First Stage of Water Supply Improvement Project for Banxin District, the water supply capacity raised from 282.0 × 10^4 CMD to 348.7 × 10^4 CMD. It not just made Taipei with higher water supply capacity but also solved the water shortage problem of Banxin.

Table 3. The sustainability assessment of two cases for baseline (Unit: 10^4 CMD)

Water supply system	**Case I. Disregarding the First Stage of Water Supply Improvement Project for Banxin District**			**Case II. Considering the First Stage of Water Supply Improvement Project for Banxin District**		
	Average water demand	**Water supply capacity**	**SDI**	**Average water demand**	**Water supply capacity**	**SDI**
Taipei	220.9	282.0	1	220.9 52.6 (Supporting Banxin)	348.7	1
Banxin	70.6	52.2	0.74	52.6 (Supported by Taipei) 18.0	69.3	1
Taoyuan	66.8	108.9	1	66.8	108.9	1
Keelung	22.9	36.3	1	22.9	36.3	1

5.2 Future Projection without Climate Change Impact

In order to meet the future water demand in 2021, some water resources facilities and allocation have been planned to raise water supply capacity. To understand the future water resources sustainability, the carrying capacities of water supply systems conditioned on current and future water supply systems are appraised. The input data of baseline are based on historical upstream flow and water demand. The upstream flow in the future is assumed statistically identical as baseline. The projected future water demand data is obtained from the government's published reports. Further, the SDI index and water supply capacity of baseline and future condition were discovered for each water supply system.

In Table 4, the projected future water supply appraisal without climate change was compared with the baseline result. Based on the government's published reports, water demand in Taipei district doesn't increase too much, but water demand in Banxin, Taoyuan, and Keelung district rise significantly. Note that the Banxin supply plus a supply of 53×10^4CMD from Taipei just met total water demand in Banxin. As a result, the sustainability indices of water uses for Taoyuan and Keelung in the short-term are 0.88 and 0.84 respectively. It means that these areas will likely be unsustainable in the future. To solve the water shortfall, the government is undertaking a master plan of water resources management to enhance the stability of water supply and reduce the existing vulnerability.

5.3 Future Projection with Climate Change Impact

To estimate the climate change effects on water supply system in various future scenarios, a sequence of 100 years of daily precipitation and air temperature is generated by weather generation model for current and future climate scenarios and were input to GWLF model to simulate the flow discharge for baseline and future climate scenarios. Because of the uncertainty of GCMs [20], different GCM has different projection for the same climate change scenario. Figs. 9 to 11 shows the results of the number of GCMs for different change ratio of the water supply capacity for SRES-A2, SRES-A1B, SRES-B1, respectively. Because of the uncertainty of GCMs, it is not recommended to have quantitative assessment from GCMs. Using categories of change ratio is a better way to appraise the carrying capacity. Six categories, ">10%", "5%~10%", "0%~5%", "0%~-5%", "-5%~-10%" and "<-10%", are adopted to classify the water capacity tendency of future.

Table 4. The comparison of the sustainability of water supply system without climate change impact between the present and future (Unit: 10^4 CMD)

Water supply system	**Baseline**			**Future**		
	Average water demand during 1991 to 2001	**Water supply capacity**	**SDI**	**Average water demand in 2021**	**Water supply capacity**	**SDI**
Taipei	273.5	348.7	1	277.6	377.9	1
Banxin	18.0	69.3	1	39.2	66.7	1
Taoyuan	66.8	108.9	1	145.2	127.8	0.88
Keelung	22.9	36.3	1	48.4	40.4	0.84

In Taipei, three scenarios have the same change ratio among 6 GCMs which showed that the water supply capacity of Taipei will slightly increase under climate change. Banxin, Taoyuan and Keelung water supply systems don't have the consistent trend under climate change. In SRES-A2 scenario, Banxin water supply system has three GCMs on the "increase side" and three GCMs on the "decrease side". It implies no obvious trend from the result. Taoyuan and Keelung water supply systems both have four GCMs on the "decrease side" which shows that the water supply capacity might decrease under SRES-A2 scenario. In SRES-A1B scenario, Banxin, Taoyuan and Keelung water supply systems all have the trend of decreasing water supply capacity by the results of more than three GCMs on the "decrease side". In SRES-B1 scenario, Banxin has three GCMs on the "increase side" and three GCMs on the "decrease side". However, two GCMs are in ">10%" category which means it has more probability to have increasing water supply capacity due to climate change. Taoyuan water supply system might have slight increasing water supply capacity because of 4 GCMs in "0%~5%" category. Keelung has equal GCMs on both sides but slightly trend to decreasing water supply capacity due to 3 GCMs in the "0%~-5%" category.

From the results of three scenarios, it is obviously that Taipei water supply system will slightly gain more capacity from climate change. Banxin, Taoyuan and Keelung water supply systems couldn't have the consistent result from different scenarios. From the definition of each scenario, SRES-A1B is more like the path where the world is going to, which means the result of SRES-A1B will be more like our future. If that is so, then Banxin, Taoyuan and Keelung water supply systems could have the risk of decreasing water supply capacity under climate change. From the result of SDI index shown as Fig. 12, even though the carrying capacity will decrease in Banxin water supply system, the SDI index still remains 1 which means Banxin water supply system is still sustainable in the future. Otherwise, Taoyuan and Keelung water supply systems will have more water shortage risk in the future because of unsustainable water supply systems. The strategies to enhance the adaptive capacity and achieve sustainability of these two water supply systems will be needed for the future.

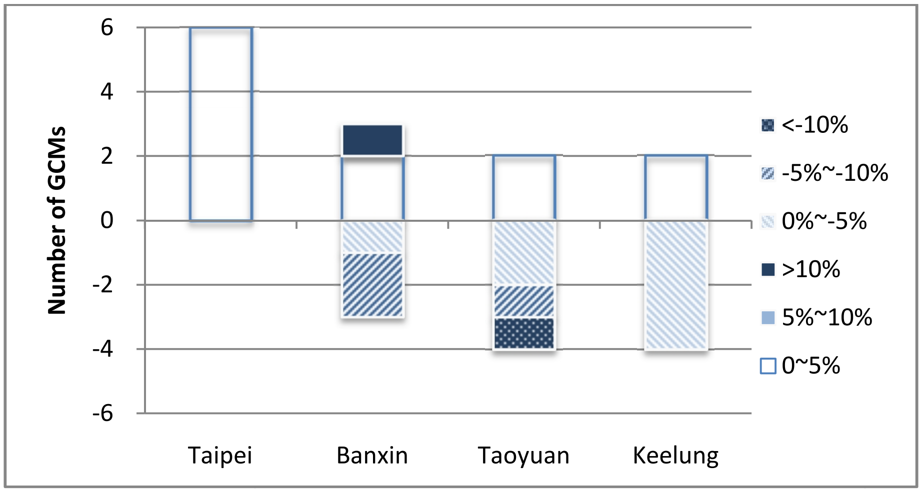

Fig. 9. Number of GCMs for different change ratio of the water supply capacity in A2 scenario

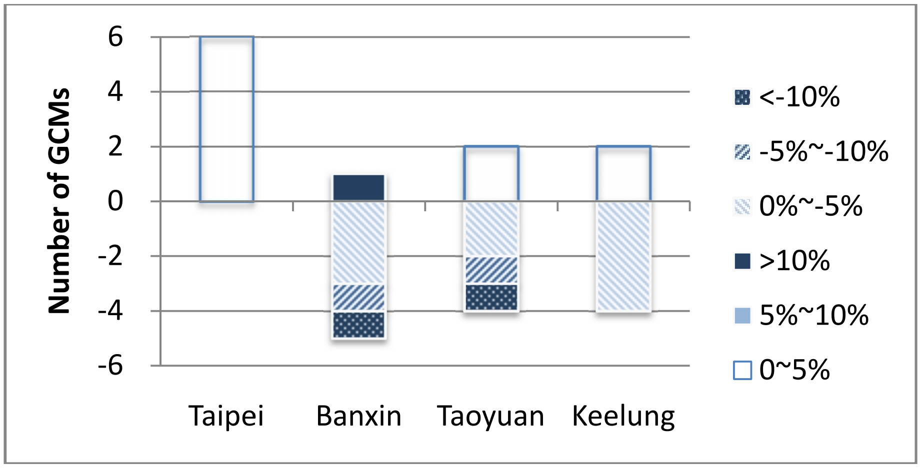

Fig. 10. Number of GCMs for different change ratio of the water supply capacity in A1B scenario

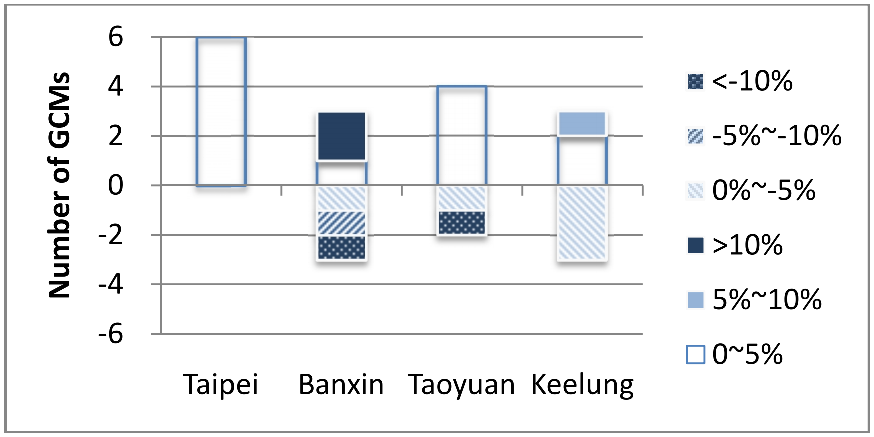

Fig. 11. Number of GCMs for different change ratio of the water supply capacity in B1 scenario

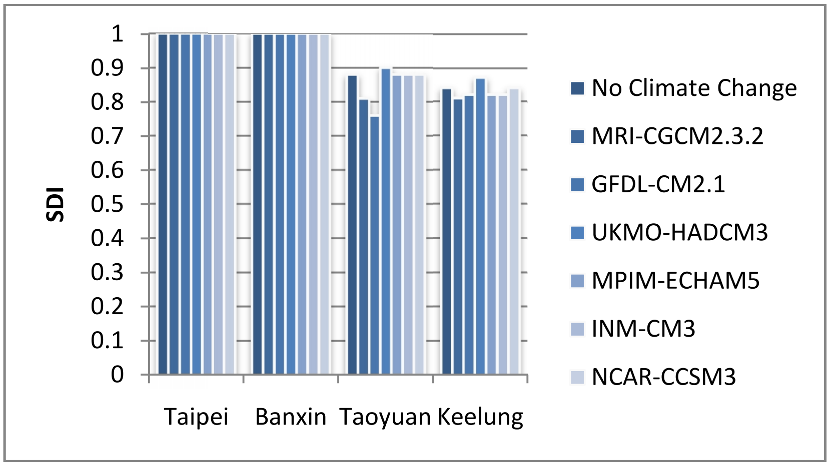

Fig. 12. Sustainable Index (SDI) of each water supply system from different result of GCM conditioned on no climate change and six GCMs' results of SRES-A1B

6. CONCLUSIONS

Under the threat of climate change, it is important to appraise the sustainability of water supply system, find whether the water supply can meet the water demand or not and make the strategies for the future. This study assesses the carrying capacity and sustainability of four water supply systems under climate change. From climate change scenario data to model programming, modeling integration, and sustainability appraisal, the whole process is very complex. Therefore, an integrated assessment tool, TaiWAP, was used to integrate the common procedures of impact assessment of climate change to evaluate the sustainability of regional water resources systems in this study. There are some major conclusions listed below:

1. For current situation, Taipei, Banxin, Taoyuan and Keelung are all sustainable water supply systems after the First Stage of Water Supply Improvement Project for

Banxin District was applied and the water shortage risk in Banxin water supply system was thus solved. In 2021, Taoyuan and Keelung water supply systems will turn into unsustainable because of raising water demand.

2. Due to the uncertainty of climate change simulation, as more as possible GCMs is recommended to be used in assessment. This study employed six GCMs for three climate change scenarios to evaluate the carrying capacity and sustainability of water supply systems. Six GCMs refer to MRI-CGCM2.3.2, GFDL-CM2.1, UKMO-HADCM3, MPIM-ECHAM5, INM-CM3 and NCAR-CCSM3. Because of the uncertainty of GCMs, it is not recommended to have quantitative assessment from GCMs. Using categories of change ratio is a better way to appraise the carrying capacity. In this study, six categories are adopted to classify the water capacity tendency of future. The more number of GCMs in the same category shows the more likely tendency of future.
3. Three climate change scenarios refer to SRES-A2, A1B and B1 scenario, which has different path for the future. Among three scenarios, SRES-A1B is more like the path where the world is heading and is recommended to choose if there is only one scenario can be used to reduce the uncertainty of climate change scenario.
4. To discover the most likely future of water supply systems, the sustainability appraisals for SRES-A1B scenario are adopted to reveal the sustainability of four water supply systems. Taipei and Banxin water supply systems will remain sustainable under climate change, otherwise Taoyuan and Keelung water supply systems will remain unsustainable. Climate change may slightly decrease their carrying capacity so that the effectiveness of strengthening water adaptive capacity might be affected by climate change. It is recommended further evaluation for future strategies under climate change.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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