Development of an integrated computational tool to assess climate change impacts on water supply–demand and flood inundation

Pao-Shan Yu, Tao-Chang Yang, Chen-Min Kuo and Shien-Tsung Chen

ABSTRACT

This paper aims to propose a decision support system (DSS) for evaluating the climate change impacts on water supply–demand and inundation; and assessing the risks for water shortage and inundation under future scenarios. The proposed DSS framework is universal and flexible, which comprises five modules integrated by a geographic information system platform, including the modules of (1) scenario rainfall and temperature projection under climate change, (2) impact assessment of water supply–demand, (3) impact assessment of inundation, (4) assessment of vulnerability and risk, and (5) adaptation strategy. A case study in southern Taiwan was performed to demonstrate how the DSS provides information on the climate change impacts and risks under future scenarios. The information is beneficial to the authorities of water resources management for understanding the spatial risks for water shortage and inundation, and planning suitable adaptation strategies for the locations with larger risks.

Key words | climate change, decision support system, inundation, risk, vulnerability, water shortage

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INTRODUCTION

According to the Fourth Assessment Report of Intergovernmental Panel on Climate Change (IPCC 2007), most of the observed temperature increase since the middle of the 20th century was caused by increasing concentrations of greenhouse gases. The annual mean temperature of Taiwan has increased by 1.4 $^{\circ}$C according to the statistical data of the past hundred years (1901–2000). Besides, the occurrence frequency and severity of extreme weather (e.g. droughts and storms) have been considerably raised. In Taiwan, typhoons often cause serious flood disasters. According to the statistics of the top 30 typhoons with extreme precipitation, which are identified based on the precipitation of the 198 typhoons striking the Taiwan area from 1970 to 2009, there is an increasing trend in the frequency of typhoons with extreme precipitation. The frequency of typhoons with extreme precipitation occurred once every two years before the year 2000, but it has increased to once a year since then (EPA 2009). The studies (Chen *et al.* 2009; Tseng *et al.* 2012) pertaining to climate change impacts on droughts point out that the occurrence frequency of meteorological droughts, the number of dry days, and the maximum consecutive dry days may increase obviously in the future, which will lead southern Taiwan facing a possible water shortage. Therefore, the residents of Taiwan should carefully deal with the climate change impacts since they live in a high risk area for flood and drought disasters (Dilley *et al.* 2005). Therefore, investigating the climate change impacts on water supply–demand and inundation, and assessing the risks for water shortage and inundation under future scenarios are requisite and helpful. The above information is beneficial to the authorities of water resources management for understanding the spatial risks for water shortage and inundation in the study area (via the risk maps) and planning suitable adaptation strategies for the locations with larger risks.

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In order to face a water shortage caused by droughts, various research groups in the world have been working in this scientific area on assessment of vulnerability and risk (e.g. Wilhite 2000; Garrote *et al.* 2007; Rossi *et al.* 2007; Cubillo & Garrote 2008; Tsakiris 2008; Iglesias *et al.* 2009; Karamouz *et al.* 2010; Tsakiris *et al.* 2010). Assessment of risk and vulnerability of water shortage under climate change is also an essential topic, especially for authorities of water resources management, and has been studied by many research groups (e.g. Kulshreshtha 1993; Yin 2006; Tonoyan & Harutyunyan 2009; Gober & Kirkwood 2010; Mawilmada 2010). For facing inundation caused by extreme rainfall events, the Federal Emergency Management Agency (FEMA 2009) proposed the 'Risk Mapping, Assessment, and Planning (Risk MAP) Multi-Year Plan: Fiscal Years 2010–2014,' which will deliver quality data that increase public awareness and leads to action that reduces flood risk to life and property. Recent scientific outputs also suggest that climate change is likely to cause shifts in the global pattern and intensity of flood events, in some regions increasing the exposure of life and property to severe inundation. Therefore, studies on assessment of inundation risk and vulnerability to changing climatic conditions (Few 2003; Mcleman & Smit 2006; Hebb & Mortsch 2007; Lawrence *et al.* 2011) are of much concern.

Recent trends in the solution of water management problems have been to aggregate several hydroinformatics models into an integrated decision support system (DSS). A DSS approach focuses on the interaction and interface between the user or analyst, and the data, models and computers. Many state-of-the-art literatures on the DSSs for solving water management problems can be found in this journal. For instance, Abebe & Price (2005) presented a DSS for flood warning and instantiation of restoration activities; Choi *et al.* (2005) proposed a web-based spatial DSS for hydrologic/water quality analysis for watershed management decision-makers and interested stakeholders; Cetinkaya *et al.* (2008) developed a consistent and well-integrated set of advanced but practical DSS for efficient 'optimal' water management strategies and policies of use; Cheong *et al.* (2010) integrated real-time monitoring, databases, optimization models and visualization tools into a DSS for optimal multi-objective reservoir operation rules; Wagenpfeil *et al.* (2013) proposed a DSS for optimized operational water management of artificial inland waterways; Pérez Urrestarazu *et al.* (2012) developed an integrated DSS to improve performance of irrigation districts. Werner *et al.* (2013) developed the Delft-FEWS flow forecasting system with the flexibility in open integration of models and data, which has additionally appealed to the research community.

Climate change is one of the major environmental issues for the coming years, both globally and regionally, and will affect all segments and sectors of society and the economy. Many governments over the world are extremely concerned about this essential issue and have invested heavily in meeting the challenge of climate change. For example, in the Netherlands, meeting the challenge of climate change calls for a major investment in knowledge development and knowledge infrastructure. For the period between 2005 and 2014, two large research programs have been initiated and funded in the Netherlands in response to this challenge: Climate changes Spatial Planning (CcSP) and Knowledge for Climate (KfC). Both programs are supported by the Dutch Government from a so-called Economic Structure Enhancing Fund, providing funding of 90 million euros, and by participating organizations and stakeholders, which add up an additional 110 million euros (www.climateresearchnetherlands.nl/research-programmes). The CcSP Program enhances joint-learning between communities and people in practice within spatial planning, with the themes of climate scenarios, mitigation, adaptation, integration and communication. The KfC Research Program develops knowledge and services, focusing on eight hotspots, enabling the climate proofing of the Netherlands. Moreover, a Consortium on Decision Support Tools was formed in 2010. This consortium research program aims at improving tools for design and evaluation of adaptation strategies with a special focus on spatial planning and cross cutting issues (www.climateresearchnetherlands.nl/research-themes/decision-support-tools). The developments of the decision support tools are essential and interesting. A similar development is going on in Taiwan and is introduced in the paper.

Since assessing the risks for water shortage and inundation under future scenarios is a big and essential issue, there is no individual model which can be used for this assessment in Taiwan. Many individual models for different estimation purposes have been well established by different research groups in Taiwan, e.g. the modified HBV rainfall-runoff model (Yu & Yang 2000), the Princeton Ocean Model by finite element method (Hsu *et al.* 1999), the land subsidence model based on the stochastic poroelastic theory and gray theory (Chen *et al.* 2012; Wang *et al.* 2012), the physiographic inundation-drainage model (Chen *et al.* 2006), etc. How to integrate them for solving a climate change issue has been raised and is developing in Taiwan. Moreover, effectively integrating individual models into a user-friendly DSS for this kind of assessment is helpful and attractive to the authorities of water resources management. For the above reason, the project funded by the Water Resources Agency (WRA), Ministry of Economic Affairs (MOEA), Taiwan, was proposed (WRA 2010, 2011). In the project, the work items include: (1) developing downscaling methods for future emission scenarios to obtain daily rainfalls and temperatures as the system input, (2) developing models of impact assessment for water supply–demand and inundation, (3) developing methods of vulnerability and risk assessment for water shortage and inundation, (4) constructing a database which includes adaptation strategies for preventing water shortage and inundation, (5) integrating all the former models, methods and database into a DSS with a geographic information system (GIS) interface, and (6) performing a case study to show how the DSS works and provides the information about climate change impacts on water supply–demand and inundation, and risks for water shortage and inundation under future scenarios. At present, the proposed DDS is designed to provide information on the impacts on water supply–demand and inundation, and the vulnerability and risk maps, which supports the consultative type of decisions. Based on the DSS results, the administrators may consider the locations with larger risks in priority for planning suitable adaptation strategies to reduce the risks for water shortage and inundation. The proposed DSS framework and the implementation results in the study area are introduced in this paper.

This paper is organized under two main topics. The first topic describes how the DSS is developed in the section 'The proposed approach', including a general overview of its main structure, procedures, components, and models. The second topic described in the section 'Case study' is the preliminary application of the DSS for a study area in southern Taiwan, which briefly introduces the study area and results of system performance. The conclusions and future work are finally presented.

THE PROPOSED APPROACH

In this paper, DSS is the proposed approach to address the issues of evaluating climate change impacts on water supply–demand and inundation, assessing risks for water shortage and inundation under future scenarios, and supporting decision makers (i.e. the authorities of water resources management) to plan suitable adaptation strategies for the locations with larger risks. The DSS constitutes a structured and instructive tool to help decision makers understand the spatial risks for water shortage and inundation in a study area and plan suitable adaptation strategies for the locations with larger risks. In order to describe the process of developing this approach, it is helpful to understand the main steps of the decision making process related to the exercise of developing suitable adaptation strategies for reducing the risks for water shortage and inundation.

Main steps of decision making process

The process for supporting strategy development is shown in Figure 1. This process is organized into seven basic steps. Step 1 is to obtain the precipitation and temperature data of climate change scenario in a study area as the system input. Step 2 is to assess the impacts on water supply–demand and inundation in the study area. Given a climate change scenario, the precipitation and temperature data of climate change scenario are obtained and imported into the DSS, and then the impacts on water supply–demand and inundation are simulated. According to the impacts, simulation (i.e. potential hazards) by Step 2, Step 3 is to assess the vulnerabilities and risks for water shortage and inundation in the study area. Step 4 is to develop adaptation strategies for reducing the risks and Step 5 is to compare the performances of the adaptation strategies before and after adjustment. Based on the adaptation strategies by Step 4, impacts simulation (i.e. Step 2) and vulnerability and risk assessment (i.e. Step 3) should be performed again to see

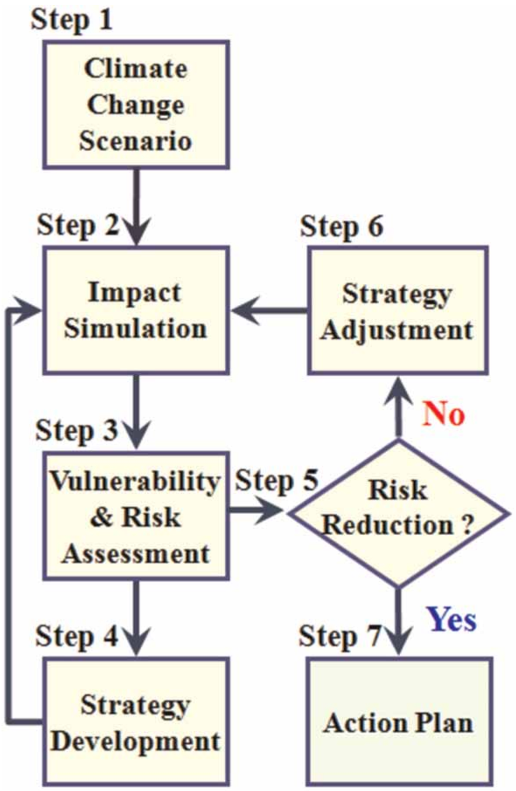

Figure 1 | Process for developing and adjusting strategies.

whether the adaptation strategies benefit reducing the risks or not (i.e. Step 5). If not, Step 6 is to adjust the adaptation strategies and then do impacts simulation (i.e. Step 2), vulnerability and risk assessment (i.e. Step 3), and compare the performances of the adaptation strategies before and after adjustment (i.e. Step 5) again. If yes, Step 7 is to make the action plan based on the adjusted adaptation strategies.

After considering the main steps of the former decision making process, the DSS procedures and structure are shown in Figure 2. The proposed DSS can be used to evaluate the climate change impacts on water supply–demand and inundation, and assess the vulnerabilities and risks for water shortage and inundation under different scenarios and adaptation strategies. All the information, especially the vulnerability and risk maps, provided by the DSS can help the decision makers to develop the suitable adaptation strategies for disaster prevention. The DSS comprising of five modules integrated by a GIS platform is presented, followed by a description of its structure, procedures, components, as well as the models included in the modules.

DSS structure and procedures

The DSS is structured using ESRI ArcGIS, Ventana Vensim, MODFLOW, Microsoft Visual Basic, Microsoft Fortran, SQL Server, and Autodesk MapGuide functionalities. The main procedures performed within the DSS are described as follows. Step 1 of the decision making process is supported mainly by a weather generation model and a frequency analysis model developed using Fortran codes which are packed into Module 1 of the DSS. Step 2 is supported by a continuous rainfall-runoff model developed using Fortran codes, a groundwater simulation model (i.e. MODFLOW), and a system dynamic model developed using Ventana Vensim. The three models are used to assess the climate change impacts on water supply–demand and packed into Module 2 of the DSS. Visual Basic functionalities are used in this stage to link the three models and develop the module interface. The other models used for assessing the climate change impacts on inundation in Step 2 are developed using Fortran codes, including a storm surge model, a land subsidence model, a physiographic inundation-drainage model, a flood routing model and a physiographic soil erosion-deposition model, which are packed into Module 3 of the DSS. In the module, the physiographic data are facilitated through the use of ArcGIS. The input data used for Step 1 and Step 2 are collected and stored in the database constructed by an SQL server. Step 3 is for assessing vulnerability and risk for water shortage and inundation and supported by the assessment methods developed using Fortran codes which are packed into Module 4 of the DSS. The field data used for Step 3 are investigated and stored in the database. Step 4 and Step 6 are to develop and adjust adaptation strategies, respectively. The adaptation strategies are stored in the strategy database (i.e. Module 5) constructed by SQL Server. Step 5 is for comparing the performances of the adaptation strategies before and after adjustment, which is coded and embedded in the GIS platform. The platform is supported by MapGuide, which integrates all the database and models, and has a user-friendly interface for operating the DSS and displaying the results of impact assessment, the

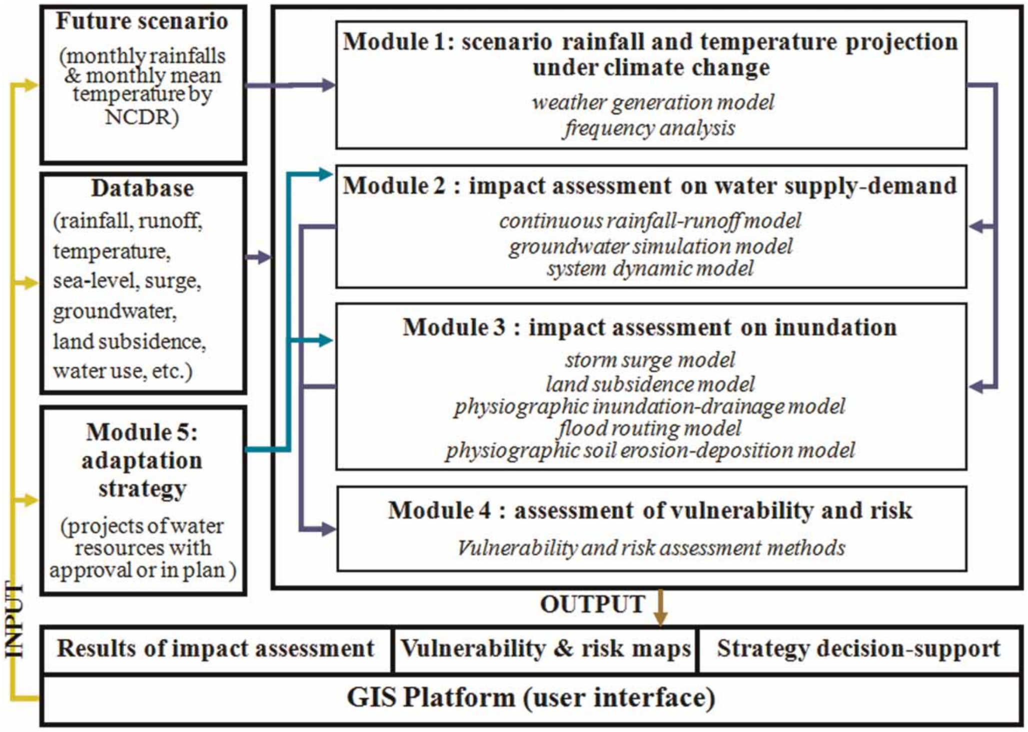

Figure 2 | Overview of DSS procedures.

vulnerability and risk maps during the baseline period and the future period under the emission scenarios for decision support. Step 7 is to make the action plan based on the adjusted adaptation strategies, which belongs to an ill structured task excluded in the DSS.

DSS components

The main components of the DSS are a database, five modules, and a GIS platform with a user-friendly interface. A description of the data base, the five modules, the GIS platform, as well as the models packed in the modules, follows.

Database

The database provides the input data to the models of the DSS. The input data include observed rainfall, runoff, temperature, sea-level, surge, groundwater, land subsidence, water use, etc.

Module 1: scenario rainfall and temperature projection under climate change

The module receives the data of monthly rainfall and monthly mean temperature under emission scenarios of climate change which are provided by the Taiwan Climate Change Projection and Information Platform Project (TCCIP) (National Science Council 2010). The module then performs a weather generation model to downscale the monthly data into the daily data as the system input for assessing the climate change impacts on water supply–demand and inundation. The weather generation model for daily rainfall generation is based on a first-order two-state Markov chain for wet/dry day transition and the probabilistic distribution of rainfall depth on a wet day (Yu *et al.* 2002). Regarding the daily temperature generation, a first-order autoregressive model was utilized to generate the daily temperature sequences in each month (Yu *et al.* 2002). The generated daily rainfall and temperature data are used for reservoir inflow simulation by a continuous rainfall-runoff model. Simulated reservoir inflows are further input into the system dynamic model for modeling the water supply–demand situation. Based on the generated daily rainfalls, the frequency analysis is performed to obtain 1-day and 2-day maximum rainfalls for different return periods (e.g. 25, 50, 100, 200 years), which are hourly distributed by the design hyetographs as the input for assessing impacts on inundation. In the frequency analysis, different probability distributions (including extreme value type-I, generalized extreme value, Pearson type-III, log-Pearson type-III, three-parameter log-normal) are used to fit the annual maximum series of the generated daily rainfalls, and the optimal probability distribution is decided based on the Kolmogorov–Smirnov test and the smallest root mean square error.

Module 2: impact assessment on water supply–demand

The module includes: (1) a continuous rainfall-runoff model for simulating daily reservoir inflows (i.e. available surface water); (2) a groundwater simulation model for estimating the suitability yield amount (i.e. available groundwater); and (3) a system dynamic model for simulating the water supply–demand system of agriculture, industry and household. By inputting the generated results from Module 1, the continuous rainfall-runoff model and the groundwater simulation model can simulate the available surface water and the available groundwater, respectively, as the input data for the system dynamic model. In the module, the modified HBV rainfall-runoff model (Yu & Yang 2000) is used to simulate daily reservoir inflows, the groundwater simulation model, MODFLOW (McDonald & Harbaugh 1988), is used for estimating suitability yield as the available groundwater, and for constructing the system dynamic model, the simulation software, Vensim (Ventana Systems Inc. 2011), is adopted.

Module 3: impact assessment on inundation

The module includes: (1) a storm surge model for estimating sea-level hydrographs of different return periods as the downstream boundary condition for inundation-drainage simulation; (2) a land subsidence model for predicting the topographic change in the future as the topographic input data for inundation-drainage simulation; (3) a physiographic inundation-drainage model for simulating the spatial distribution of inundation caused by 1-/2-day maximum rainfalls for different return periods; (4) a flood routing model for calculating overflow of river system; and (5) a physiographic soil erosion-deposition model for calculating landscape evolution. The Princeton Ocean Model (Blumberg & Mellor 1983) by finite element method (Hsu *et al.* 1999) is adopted as the storm surge model for estimating sea-level hydrographs of different return periods as the downstream boundary condition for inundation-drainage simulation. The land subsidence model is based on the stochastic poroelastic theory (Wang & Hsu 2009; Hsu *et al.* 2013) and gray theory (Deng 1987) for estimating the topographic change in the future as the topographic input for inundation-drainage simulation. The physiographic soil erosion-deposition model, the flood routing model and the physiographic inundation-drainage model developed by Chen *et al.* (2006) are used in the module. The module can use the generated data from Module 1 (e.g. a design storm of 1-day maximum rainfall for 100-year return period under a given emission scenario) as the input; and use the future scenarios of sea-level and land subsidence calculated by the storm surge model and the land subsidence model, respectively, as the boundary conditions of the physiographic inundation-drainage model, the flood routing model and the physiographic soil erosion-deposition model for assessing the climate change impacts on inundation-drainage and soil erosion-deposition in the study area.

Module 4: assessment of vulnerability and risk

The module includes assessment methods of vulnerability and risk for water shortage and inundation, respectively. By inputting the generated results under climate change scenarios (Module 1), the system can assess the impacts on water supply–demand and inundation by Module 2 and Module 3, respectively. Then, the vulnerability and risk for each analysis unit can be assessed in this module for drawing the risk maps which can show the spatial distributions of risk for water shortage and inundation in the study area. The module mainly performs risk assessment based on the definition of United Nations Disaster Relief Office's report (UNDRO 1980) as follows:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \tag{1}$$

In the study, the risk which simultaneously considers agricultural, industrial, and household water shortages is defined as follows:

$$R_{\text{ws}} = H_{\text{ws}} \times V_{\text{ws}} \tag{2}$$

$$H_{\text{ws}} = (w_{H1}H_{a\text{ws}} + w_{H2}H_{i\text{ws}} + w_{H3}H_{h\text{ws}}) \tag{3}$$

$$V_{\text{ws}} = (w_{V1}V_{a\text{ws}} + w_{V2}V_{i\text{ws}} + w_{V3}V_{h\text{ws}}) \tag{4}$$

where R_{ws} is the risk of water shortage; H_{ws} is the multiple hazard factor of water shortage comprising three hazard factors ($H_{a\text{ws}}$, $H_{i\text{ws}}$, and $H_{h\text{ws}}$) which are defined as the rates (0–100%) of water shortage (i.e. the shortage amount divided by the demand amount) for agricultural, industrial, and household water consumptions, respectively; V_{ws} is the multiple vulnerability factor of water shortage comprising three vulnerability factors, $V_{a\text{ws}}$, $V_{i\text{ws}}$, and $V_{h\text{ws}}$, respectively, for agricultural, industrial, and household water shortages; and w denotes weight. The three vulnerability factors, $V_{a\text{ws}}$, $V_{i\text{ws}}$, and $V_{h\text{ws}}$, are further defined as follows:

$$V_{a\text{ws}} = w_{a\text{ws}1}V_{a\text{ws}1} + w_{a\text{ws}2}V_{a\text{ws}2} \tag{5}$$

$$V_{i\text{ws}} = w_{i\text{ws}1}V_{i\text{ws}1} + w_{i\text{ws}2}V_{i\text{ws}2} + w_{i\text{ws}3}V_{i\text{ws}3} \tag{6}$$

$$V_{h\text{ws}} = w_{h\text{ws}1}V_{h\text{ws}1} + w_{h\text{ws}2}V_{h\text{ws}2} + w_{h\text{ws}3}V_{h\text{ws}3} \tag{7}$$

where $V_{a\text{ws}1}$ and $V_{a\text{ws}2}$ are factors of vulnerability of agricultural water shortage (i.e., the agricultural area and the irrigation rate defined by the agricultural area per unit discharge, respectively); $V_{i\text{ws}1}$, $V_{i\text{ws}2}$, and $V_{i\text{ws}3}$ are factors of vulnerability of industrial water shortage (i.e. the water consumption per unit area, the number of factory, and industrial output value, respectively); $V_{h\text{ws}1}$, $V_{h\text{ws}2}$, and $V_{h\text{ws}3}$ are factors of vulnerability of household water shortage (i.e. the daily available water per capita, the number of population per unit area, and the number of population, respectively); and w denotes weight. Table 1 shows the list of the hazard and vulnerability factors for estimating the risk of water shortage.

Table 1 | The hazard and vulnerability factors for estimating the risk of water shortage

Hazard factors	Vulnerability factors
• The rate of water shortage for agricultural water consumption	• The agricultural area • The irrigation rate defined by the agricultural area per unit discharge
• The rate of water shortage for industrial water consumption	• The water consumption per unit area • The number of factory • Industrial output value
• The rate of water shortage for household water consumption	• The daily available water per capita • The number of population per unit area • The number of population

Four risks for inundation are considered in the study, including the risks of life, industry, agriculture and commerce (i.e. R_{lf}, R_{if}, R_{af}, and R_{cf}, respectively). They are defined as follows:

$$R_{lf} = H_f \times (V_{lf1} + V_{lf2}) \tag{8}$$

$$R_{if} = H_f \times V_{if} \tag{9}$$

$$R_{af} = H_f \times V_{af} \tag{10}$$

$$R_{cf} = H_f \times V_{cf} \tag{11}$$

where H_f is the inundation depth, which is defined as the hazard factor for life, industry, agriculture and commerce; V_{lf1} and V_{lf2} are factors of vulnerability of life (i.e. the whole population in an analysis unit and the number of elderly citizens, children and disabled people in an analysis unit, respectively); V_{if} is the vulnerability factor of industry and is defined as the ratio of the industrial area to the area of analysis unit; V_{af} is the vulnerability factor of agriculture and is defined as the ratio of the agricultural area to the area

Table 2 | The hazard and vulnerability factors for estimating the risks for inundation

Risks for inundation	Hazard factor	Vulnerability factors
Life	• The inundation depth	• The whole population in an analysis unit • The number of elderly citizen, children and disabled persons
Industry	• The inundation depth	• The ratio of the industrial area to the area of analysis unit
Agriculture	• The inundation depth	• The ratio of the agricultural area to the area of analysis unit
Commerce	• The inundation depth	• The ratio of the commercial area to the area of analysis unit

of analysis unit; and V_{cf} is the vulnerability factor of commerce and is defined as the ratio of the commercial area to the area of analysis unit. Table 2 shows the list of the hazard and vulnerability factors for estimating the risks for inundation.

The module uses the concept of relative risk (i.e. the risk value by the cross analysis of risk matrix) proposed by Anbalagan & Singh (1996) to calculate the degree of risk. Based on the risk matrix, the risk level can be decided for each analysis unit and the risk maps in the study area can be plotted.

Module 5: adaptation strategy

The module comprises a database which includes adaptation strategies for reducing the risks for water shortage and inundation. Based on the database, the module can drive Modules 1–4 to carry out the risk assessment for different adaptation strategies to understand their performances of risk reduction.

GIS platform

The platform integrates the former five modules and has a user-friendly interface for controlling all the module functions and displaying results of impact assessment and maps of vulnerability and risk under different scenarios. Moreover, the impact assessment for different adaptation strategies can be performed on the platform, which can support the authorities of water resources management to develop suitable adaptation strategies.

CASE STUDY

A case study was performed by the proposed DSS for simulations of climate change impacts in a study area in southern Taiwan, including Tsengwen River Basin, Chianan Irrigation Area and the Sixth District of Taiwan Water Corporation. All the models used in the DSS have been calibrated and validated in the project. The descriptions of the study area and the results of system performance are presented as follows.

Study area

For assessing the climate change impacts on inundation, the simulation area was chosen in southern Taiwan from the southern embankment of the Bazhang River to the Yanshuei River basin, which includes the Jishuei River basin, the Jiungyun River basin, the Cigu River basin, the Tsengwen River basin and the Yanshuei River basin, but excludes the upstream catchment of Tsengwen Reservoir. The simulation area has an area around 2,048 km^2. The study area is shown in Figure 3.

For assessing the climate change impacts on water supply–demand, the Sixth District of Taiwan Water Corporation and Chianan Irrigation Area in southern Taiwan were chosen as the simulation area. The Sixth District of Taiwan Water Corporation is the main source of water supply in Tainan, Taiwan. Its operation region spans from the south of Bazhang River to the north of Erren River with an area of 2,218 km^2. There are seven water treatment plants in the district. The Chianan Irrigation Area is bounded by Taiwan Central Mountain (east), Peikang River (north), Erren River (south) and Taiwan Strait (west). The management area covers Chiayi County and Tainan City with an area of 780.41 km^2.

The former simulation areas for assessing the climate change impacts on water supply–demand have two main reservoirs for supplying surface water, that is, Tsengwen Reservoir and Nanhua Reservoir, as shown in Figure 3.

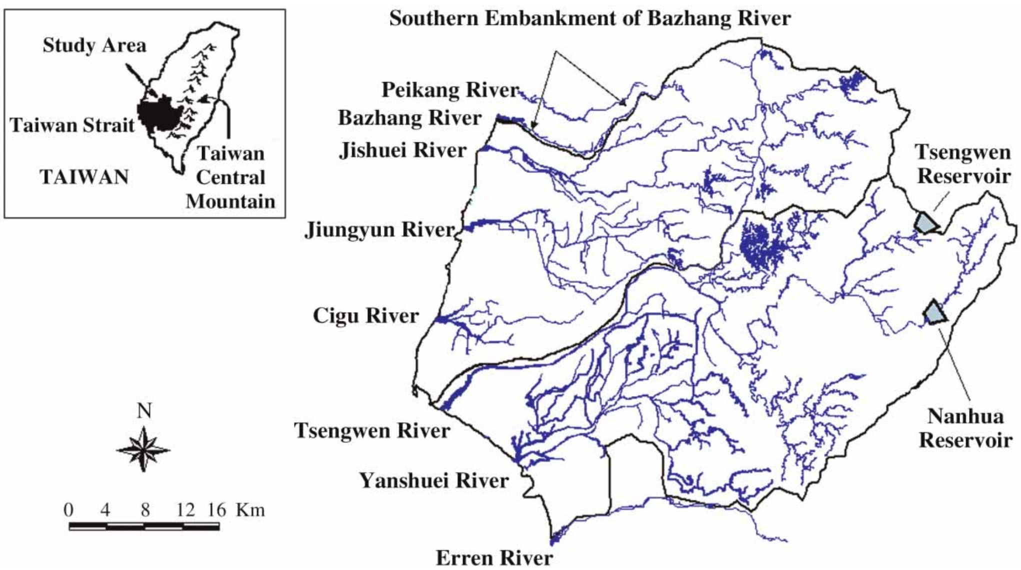

Figure 3 | Study area.

Tsengwen Reservoir, with a storage capacity of about $7.8 \times 10^8\,m^3$, is the largest reservoir in Taiwan. The Tsengwen Reservoir was completed in 1973, having multifunction of the water demands for agriculture, domestic use, flood control and hydropower generation with a storage capacity of around $6.1 \times 10^8\,m^3$ and an area of 481 km^2. The catchment of Tsengwen Reservoir is at an elevation of 157–3,514 m above sea level. Nanhua Reservoir began to store water in 1993 with a storage capacity of about $1.5 \times 10^8\,m^3$ and an area of 103.5 km^2, and is at an elevation of 250–900 m above sea level.

Results of system performance

Emission scenario under climate change

In the case study, the future period is set to 2020–2039 and the baseline period is set to 1980–1999. TCCIP provides the downscaling projections of monthly rainfall and monthly mean temperature from the 24 general circulation models (GCMs) for each node of a 25×25 km grid (covering Taiwan) under A1B, B1, and A2 emission scenarios. Besides, for each GCM, each grid node and each month, the change rates (%) of monthly rainfall and monthly mean temperature from the baseline period to the future period are also provided. The original data of the 24 GCMs are collected from the Program for Climate Model Diagnosis and Intercomparison (PCMDI, www-pcmdi.llnl.gov/ipcc/about_ipcc.php), reported by the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC 2007).

The downscaling results from each emission scenario of each GCM can be chosen in the DSS for the following analysis. However, in the case study, only the A1B emission scenario was chosen and a multi-model ensemble approach by using the downscaling results from the 24 GCMs was adopted. Based on the multi-model ensemble approach, two climate impact conditions (CICs) were hypothesized for evaluating the climate change impacts on water supply–demand and inundation, respectively. The two CICs are described as follows.

Module 1 of the DSS received the change rates (%) of monthly rainfall and monthly mean temperature from the baseline period to the future period under A1B emission scenario for each GCM, each grid node and each month. For each grid node and each month, the mean change rate and its standard deviation of monthly rainfall of the 24 GCMs, and the mean change rate of monthly mean temperature of the 24 GCMs were calculated. The CIC for evaluating the impact on water supply–demand (denoted as CIC-1) is that the mean change rate of monthly rainfall subtracts a standard deviation for each month. This CIC-1 is worse than the mean condition of the 24 GCMs. The other CIC for evaluating the impact on inundation (denoted as CIC-2) is that the mean change rate adds a standard deviation for each month during the May–October wet season and the mean change rate subtracts a standard deviation for each month during the November–April dry season. The CIC-2 hypothesized condition, i.e. larger rainfall during the wet season and less rainfall during the dry season, makes it more temporally heterogeneous than the mean condition of the 24 GCMs.

The change rates of monthly rainfall at a raingauge were determined by the change rates of the grid node closest to the raingauge. Therefore, the change rates of monthly rainfall for all the raingauges in the study area were decided. Using the observed monthly rainfalls during the baseline period and the change rates of monthly rainfall for the two CICs, a first-order two-state Markov chain for wet/dry day transition and the probabilistic distribution of rainfall depth on a wet day were performed to transform the monthly rainfalls into the daily rainfalls at each raingauge for the future period as the system input. The change rates of monthly mean temperature at a meteorological station were determined by the change rates of the grid node closest to the meteorological station. Based on the mean change rates of monthly mean temperature and the observed monthly mean temperatures during the baseline period, the daily temperatures at each meteorological station for the future period were generated by using a first-order autoregressive equation.

After the former weather generation model was run, two sets of 200-year daily rainfalls and daily temperatures for CIC-1 and CIC-2, respectively, were generated for further impact analysis on water supply–demand and inundation. Figure 4 illustrates the mean values of monthly precipitation for CIC-1, CIC-2 and the baseline condition, respectively, for each month in the catchment of the Tsengwen Reservoir.

Different climate change scenarios result in different potential impacts. In the case study, two CICs based on the multi-model ensemble approach were hypothesized for evaluating the climate change impacts on water supply–demand and inundation under A1B emission scenarios, respectively. Uncertainty from all the GCMs and emission scenarios is not considered in the proposed DSS. Coupling each uncertainty source, such as hydrological model parameter sets, GCMs, and emission scenarios for uncertainty assessment of climate change impacts (Jung *et al.* 2012), provides our future research directions.

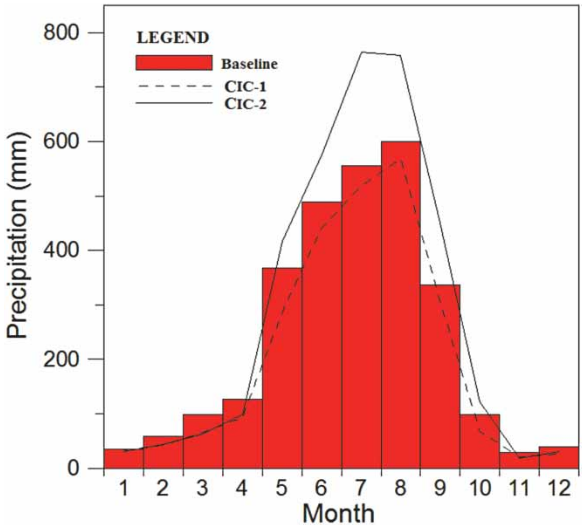

Figure 4 | Precipitation depths for each month during the baseline period and under CIC-1 and CIC-2, respectively.

Impact assessment for water supply–demand

After Module 1 generated the daily rainfalls and daily temperatures for CIC-1, Module 2 performed the modified HBV rainfall-runoff model to simulate the reservoir inflows (i.e. available surface water) for Tsengwen Reservoir and Nanhua Reservoir which are the main suppliers of surface water in the study area. By the reservoir operations, the outflows of these two reservoirs can be estimated and then distributed by the water treatment plants for agricultural, industrial and household water demands. Meanwhile, Module 2 started up the groundwater simulation model, MODFLOW, for estimating suitability yield for CIC-1 as the available groundwater. The zero groundwater change method was used to evaluate available groundwater. The estimated results for CIC-1 reveal that the available groundwater will decrease $1.9 \times 10^6\ m^3$/year. The decreased amount is about 2.7% of the available groundwater during the baseline period ($70.4 \times 10^6\ m^3$/year). These estimated results of available groundwater for the baseline period and CIC-1 were used for further impact assessment of water supply–demand.

Module 2 continued to start up the system dynamic model, Vensim, to simulate the supply–demand conditions of industrial, domestic and agricultural water in the study area by inputting the results of reservoir inflows and available groundwater. The analysis results of the system dynamic model for CIC-1 reveal that water shortages (including duration and magnitude) of agriculture, industry, and household will increase, which means the serious impact of climate change on water shortages will occur. The total amount of water shortage in 2039 for the study area will reach $64.5 \times 10^6\,m^3$/year. Figure 5 shows the rates of water shortage (i.e. the supply amount divided by the demand amount) for agricultural, industrial, and household water consumptions, respectively, for each analysis unit (i.e. district: a city is delineated into many districts for administrative purpose in Taiwan) under CIC-1, which were used to be the hazard factors for risk assessment in Module 4.

As for the continuous rainfall-runoff model, the study uses the HBV-based hydrological model due to its simple lumped model structure, few input variables (i.e. daily rainfall and temperature), and successful applications in many catchments of Taiwan for reservoir inflow simulation. Historical daily rainfall and inflow data in the catchments of Tsengwen Reservoir and Nanhua Reservoir were used for model calibration and validation. Figure 6 illustrates the calibration and verification results of Tsengwen Reservoir. These results reveal the HBV-based hydrological model is able to simulate the rainfall-runoff behavior over the reservoir catchments.

Conceptual hydrological models are widely used for climate change impact assessment. The implicit assumption in most such work (including the study herein) is that the parameters calibrated from observations remain valid for future climatic conditions. Evaluation of the transferability and uncertainty of hydrological model parameters for simulations under changed climatic conditions has been emphasized and on-going in many studies (e.g. Vaze et al. 2010; Bastola et al. 2011a, 2011b). In the future, greater effort should be invested in improving the model robustness and considering the transferability and uncertainty of hydrological model parameters for climate change impact studies.

As for the groundwater simulation model (i.e. MODFLOW) used herein, it can handle models with up to 1,000 stress periods, 80 layers and 250,000 cells in each layer (Chiang & Kinzelbach 2005). This limitation should be cautioned if a larger area with the number of cells exceeding 250,000 is chosen for modeling. The area can be divided into several smaller ones for solving the limitation.

In the aspect of system dynamic model (i.e. Vensim) for a water resources system, the data of water demand, operation rules of reservoir/dam, and principles of withdrawing water from weirs are important and affect the accuracy of water budget simulation. Herein, the projections of water demand under different future scenarios are set to be the same, but should be different in fact, which has to be studied further. Moreover, the operation rules of a reservoir/dam, and principles of withdrawing water from weirs, are also set to be the same during both the baseline period and the future period in the proposed DSS. These operation rules and principles can be further optimized under future scenarios as adaptation strategies for reducing the risk of water shortage (e.g. Kim et al. 2009; Raje & Mujumdar 2010; Donia 2013).

Impact assessment for inundation

Module 3 started up the storm surge model (i.e. the Princeton Ocean Model by finite element method) to estimate sea-level hydrographs for different return periods as the downstream boundary condition for inundation-drainage simulation. The rate of sea level rise around Taiwan was

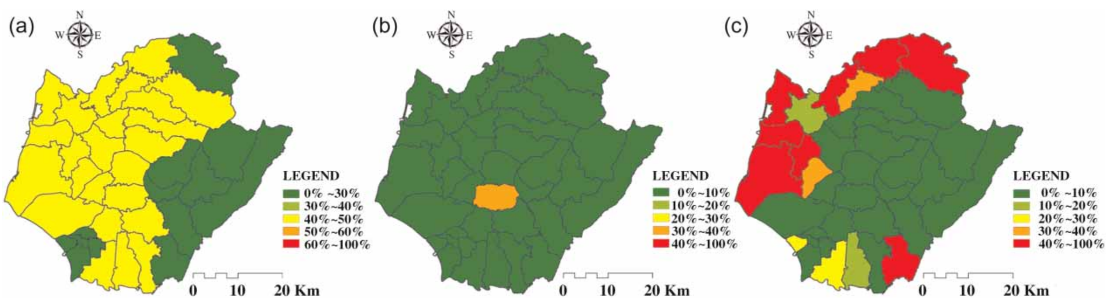

Figure 5 | Rates of water shortage for (a) agricultural, (b) industrial, and (c) household water consumptions under CIC-1.

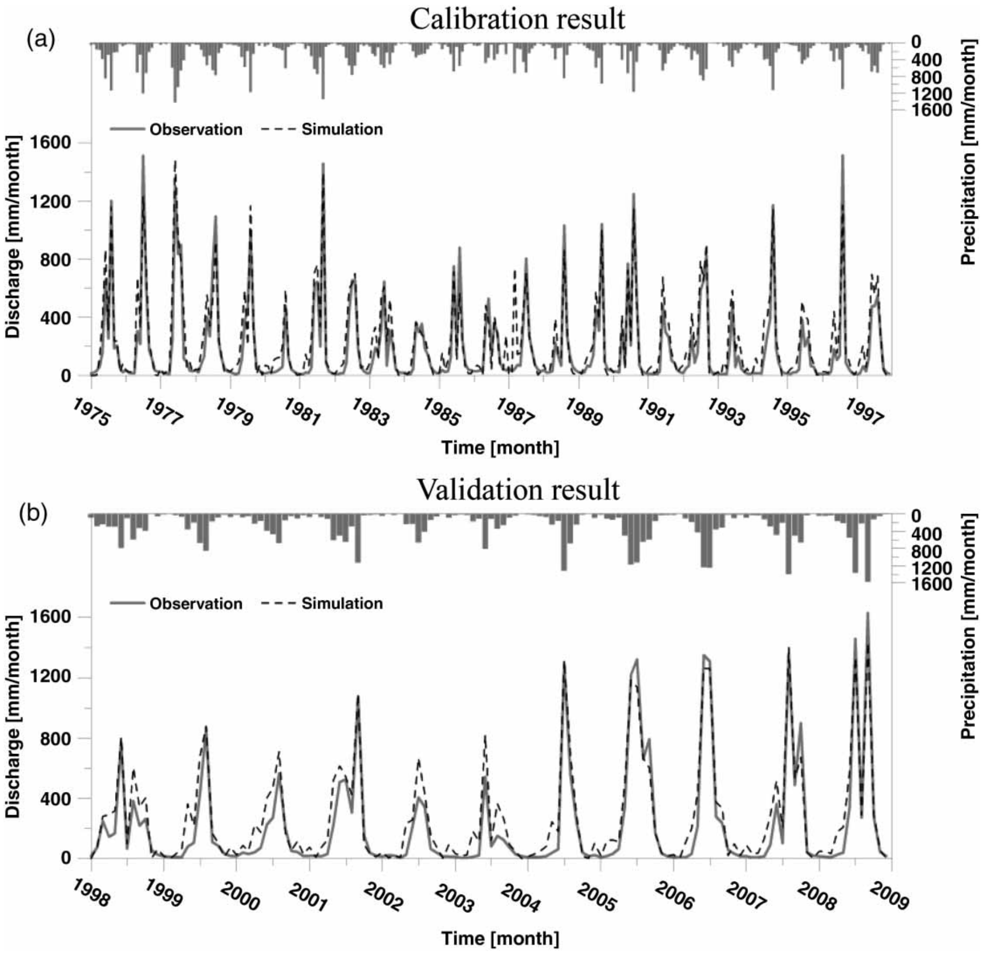

Figure 6 | (a) Calibration and (b) validation results of the HBV-based hydrological model for Tsengwen Reservoir.

found to be 3.2–4.4 mm per year. The land subsidence model based on the stochastic poroelastic theory and gray theory was started up for estimating the topographic change in the future as the topographic input for inundation-drainage simulation. The result reveals that the value of land subsidence will reach a maximum of 1.03 m in 2039 (i.e. the last year of the future period). Figure 7 illustrates land subsidence prediction in 2039 in the study area.

The physiographic soil erosion-deposition model, the physiographic inundation-drainage model, and the flood routing model were performed to assess climate change impacts (under CIC-2) on landscape evolution and inundation caused by 1-day maximum rainfalls for the 100-year return period. The area and amount of inundation caused by 1-day maximum rainfalls for the 100-year return period under CIC-2 were found to be more severe than during the baseline period. Figure 8 illustrated the maximum inundation depth caused by 1-day maximum rainfall for the 100-year return period under CIC-2. The maximum inundation depth of each analysis unit was taken as the hazard factors for risk assessment for inundation in Module 4.

The Princeton Ocean Model (POM) is applied to simulate storm surges in the coastal water of river outlets. It requires the wind field as input, which is estimated by the Rankin–Vortex Model (Chang & Anthes 1978) with the central pressure of typhoon/hurricane as input. The wind and pressure distributions of a prototypical typhoon/hurricane provided by Holland (1980) are used. For applying the POM under climate change scenarios, the projected central pressure of typhoon/hurricane directly affects the estimation accuracy of storm surges and much uncertainty remains. At present, the studies on simulation of storm surges under

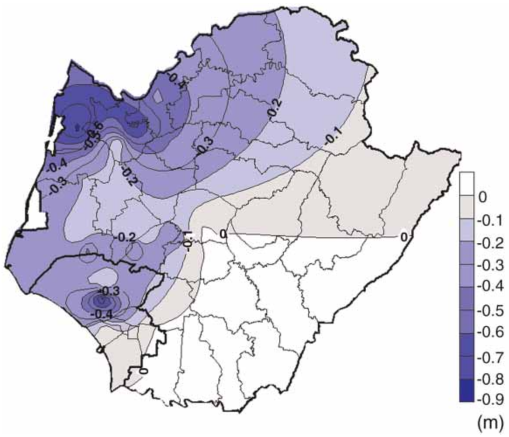

Figure 7 | Land subsidence prediction in 2039.

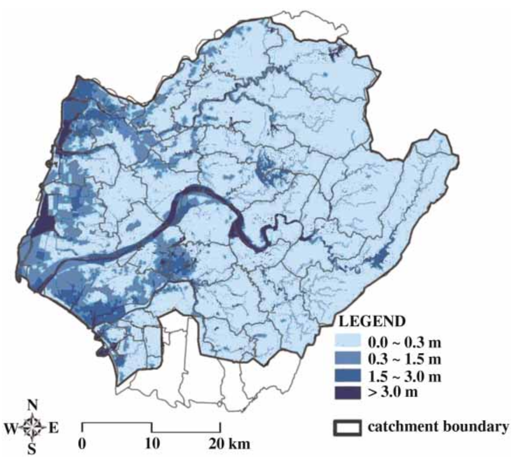

Figure 8 | Maximum inundation depths for 1-day maximum rainfall with 100-year under CIC-2.

climate change scenarios in Taiwan are on-going. In this case study, the simulations of storm surges under different emission scenarios in the future are assumed to be the same as those during the baseline period. As GCMs cannot simulate storm surges directly, alternative approaches to simulate synthetic surge events under projected climates have been proposed (e.g. Lin *et al.* 2012; Wah *et al.* 2012).

The land subsidence model is based on the poroelastic theory (Castelletto *et al.* 2008; Wang & Hsu 2009; Teatini *et al.* 2010; Hsu *et al.* 2013) and gray theory (Deng 1987). The poroelastic model is a physically-based model whose physical parameters have to be observed by soil permeability tests on the location of subsidence well. The calibrated parameters (i.e. loading and pumping) during the observation period can be obtained through fitting the simulated and observed settlements from subsidence well. The gray system model, a black-box-based model, only requires the observed settlements of benchmark for model calibration. In the study area, there are only four subsidence wells but 169 benchmarks where leveling is performed every two years. Therefore, combining these two models is a good approach for estimating the spatial distribution of land subsidence (Chen *et al.* 2012). The model validation in the study area can be seen in the study of Wang *et al.* (2012). The limitation of poroelastic model for climate change research is that the pumping amount (i.e. usage amount of groundwater) under climate change scenarios is difficult to estimate. In the case study, the historical trend of groundwater usage is used to extrapolate the usage amount of groundwater (around 30% increase) during the future period as the scenario of potential groundwater usage. In the future work of our study, establishing more suitable scenarios of potential groundwater usage is required and has to be invested by more effort.

To construct the physiographic soil erosion-deposition model, the physiographic inundation-drainage model, and the flood routing model in this DSS, GIS was used to partition the study area into computed cells according to the topography and landform. The computed cells were classified as either land cells or river cells. After defining the main river channels, the width of river cells are assigned based on the measured cross-sections in the field. In addition, land cells are assigned according to soil type, land use, land cover and road system. The physiographic and hydrological data of each cell were obtained through GIS analysis. Therefore, appropriate discretization of cells is essential for modeling accuracy and too many cells may reduce the computational efficiency (Chen *et al.* 2006, 2011). Land use and land cover (LULC) of the catchment affect the value of Manning's n in calculations. Digitized land utilization maps, coupled with GIS, are useful for illustrating the state of LULC in each computed cell. However, limitations of its application for climate change research are that the changes of LULC in catchments under future scenarios cannot be considered due to the difficulty in predicting the future situations of LULC. Scenarios of potential future LULC change are required in order to better manage potential impacts on climate change. This issue is essential and on-going by many research groups (Rounsevell et al. 2006; Sohl & Sleeter 2012; Rodrguez et al. 2013).

Moreover, validation of flood inundation modeling heavily depends on the accurate inundation depths at the flood margin of historical storm events. In the case study, only the inundation extent by field investigation is used to validate the flood inundation modeling. For example, Figure 9 illustrates the inundation modeling result for Typhoon Haitang in 2005 and the inundation areas by field investigation. This rough validation shows the modeling result seems reasonable. In the future, great effort must be made to obtain more accurate inundation depths at the flood margin for storm events. Advanced techniques (e.g. remote sensing) on this issue have been developed (Mason et al. 2011; Stephens et al. 2012).

Vulnerability and risk assessment for water shortage

After Module 2 performed an impact assessment on water supply–demand, Module 4 started up to perform assessment of vulnerability and risk for water shortage. The risks for water shortages (including agricultural, industrial, and household water shortages) are considered in the case study, as defined in Equation (2). Three hazard factors in Equation (3) were calculated by Vensim for each analysis unit (i.e. district) in the study area, which are shown in Figure 5. Equal weights of the three hazard factors in Equation (3) were used to calculate the multiple hazard factor of water shortage as shown in Figure 10. In this figure, the five levels (i.e. very

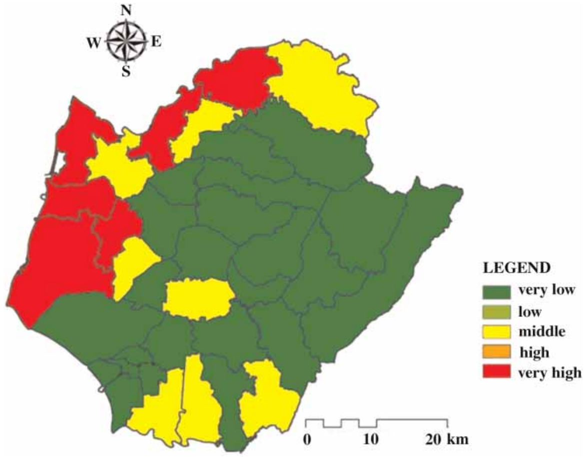

Figure 10 | Hazard map for water shortage.

low, low, middle, high and very high) were classified by the five intervals of the multiple hazard factor (i.e. 0–10, 10–20, 20–30, 30–40 and 40–100%, respectively).

For calculating the multiple vulnerability factor in Equation (4), the three vulnerability factors of agricultural, industrial and household water shortage, respectively, defined in Equations (5)–(7), have to be calculated. The factors at the right-hand side of the equal sign in Equations (5)–(7) were calculated and predicted by data collection for each district in the study area, and then the values of each factor for all districts were standardized into the range of 0.0–1.0. Equal weights were considered in the study for Equations (4)–(7). After the values of the multiple vulnerability factors in Equation (4) for each district were calculated, the vulnerability map for water shortage in the study area was plotted.

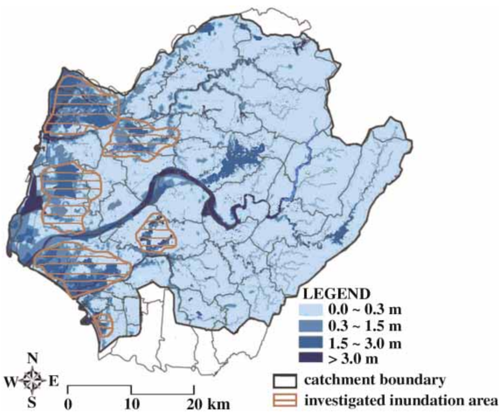

Figure 9 | Inundation modeling result for Typhoon Haitang in 2005 and inundation areas by field investigation.

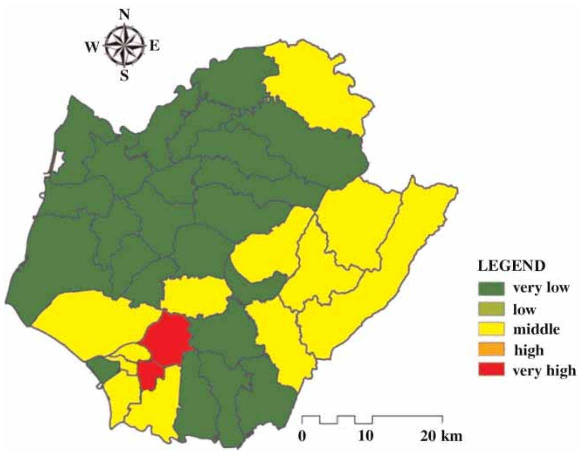

Figure 11 | Vulnerability map for water shortage.

Figure 11 displays the vulnerability map for water shortage in the study area. In this figure, the five levels (i.e. very low, low, middle, high and very high) were classified by the five intervals of the multiple vulnerability factor (i.e. 0–20, 20–40, 40–60, 60–80, and 80–100%, respectively).

The risk matrix of water shortage (5×5 matrix in Table 3) was established based on the classified levels of the multiple hazard factor and the multiple vulnerability factor. For the risk matrix, five levels of risk (i.e. very low, low, middle, high, and very high) were defined and the risk level for each element of matrix was decided. Based on the risk matrix, the risk levels of water shortages were decided for each district and the risk map of water shortages was plotted. Figure 12 illustrates the risk map for water shortage in the study area. From this risk map, the risk level of water shortage for each district can be seen.

For assessment of water-shortage risk, the vulnerability and hazard factors have to be carefully defined. Different research groups (e.g. Kulshreshtha 1993; Yin 2006; Tonoyan & Harutyunyan 2009; Gober & Kirkwood 2010; Mawilmada 2010) have different definitions and numbers of vulnerability and hazard factors for risk assessment of water shortage under climate change. So far, there are no standard definitions and numbers of vulnerability and hazard factors, which remains an essential research topic in the future. In the paper, the vulnerability and hazard factors are preliminarily defined for this project. Future work will comprehensively investigate the reasonability of these factors and add more social and economic vulnerability factors (e.g. insurance, education, GDP, income, government expenditure, etc.) in the proposed DSS. Moreover, the level classification of hazard and vulnerability factors is important and should be reasonably implemented for easily experiencing the severity degree through the five or four levels. However, different levels of classification may lead to different risk assessments.

Table 3 | The risk matrix of water shortage

	Vulnerability (%)				
Hazard (%)	**0–20**	**20–40**	**40–60**	**60–80**	**80–100**
0–10	Very low	Very low	Low	Low	Middle
10–20	Very low	Low	Low	Middle	Middle
20–30	Low	Low	Middle	High	High
30–40	Low	Middle	High	High	Very high
40–100	Middle	High	High	Very high	Very high

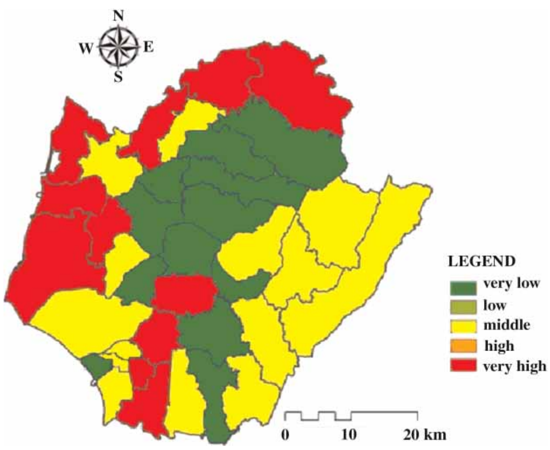

Figure 12 | Risk map for water shortage.

Vulnerability and risk assessment for inundation

After Module 3 performed impact assessment on inundation, Module 4 started up to perform assessment of vulnerability and risk for inundation. Four risks for inundation were considered in the case study, including the risks of life, industry, agriculture and commerce, as defined in Equations (8)–(11), respectively. Herein, the analysis unit adopts 'village' which is the basic unit for city administration and is smaller than 'district' in Taiwan. The hazard factor for life, industry, agriculture and commerce is defined as the inundation depth, which was calculated from the former inundation simulation in Figure 8. In this case study, four levels of inundation depth were used for assessing the risk of life. They are 0.0–0.3, 0.3–1.5, 1.5–3.0 and above 3.0 m, respectively. Three levels of inundation depth were used for assessing the risk of agriculture, industry and commerce, which are 0.0–0.5, 0.5–1.5, and above 1.5 m, respectively.

The vulnerability of life in Equation (8) was classified to five levels according to the summation of the former two factors. The five levels are 0–600, 600–2400, 2400–4200, 4200–6000, and above 6000, respectively. The vulnerability factors in Equations (9)–(11) for industry, agriculture and commerce, respectively, were then standardized to the range of 0–100% for classification. Four levels were classified as 0–25, 25–50, 50–75, and 75–100% for the vulnerability of industry and commerce. For the vulnerability of agriculture, five levels were classified as 0–20, 20–40, 40–60, 60–80 and 80–100%.

According to the classified levels of hazard factor and vulnerability factors of life, industry, agriculture and commerce, four risk matrixes of life (4×5 matrix in Table 4), agriculture (3×5 matrix in Table 5), industry (3×4 matrix in Table 6) and commerce (3×4 matrix in Table 6) were made. For the risk matrix of life, five levels of risk (i.e. very low, low, middle, middle-high, and high) were defined and the risk level for each element of matrix was decided. For the risk matrixes of agriculture, industry and commerce, three levels of risk (low, middle, and high) were defined and the risk level for each element of matrix was decided. Based on these four risk matrixes, the risk levels of life, agriculture, industry and commerce were decided for each village and the risk maps of life, agriculture, industry and commerce in the study area were plotted as shown in Figure 13. From these risk maps for inundation, the risk levels of life, industry, agriculture and commerce for each village can be seen.

For assessment of inundation risk, the vulnerability and hazard factors have to be carefully defined. Different research groups (e.g. Few 2003; Mcleman & Smit 2006; Hebb & Mortsch 2007; Lawrence et al. 2011) have different definitions and numbers of vulnerability and hazard factors for risk assessment of inundation under climate change. So far, there are no standard definitions and numbers of vulnerability and hazard factors, which remains an essential research topic in the future. In the paper, the vulnerability and hazard factors are preliminarily defined for this project. Future work may consider adding more social and economic vulnerability factors (e.g. insurance, education, GDP, property value (vehicles, furniture, electric equipment, etc.), house types, occupation, debt, low income household, house prices, government expenditure, etc.) in the DSS. Moreover, the level classification of hazard and vulnerability factors is important and should be reasonably implemented for easily experiencing the severity degree through the five or four levels. Different levels of classification may lead to different risk assessment, which should be paid attention to.

Table 4 | The risk matrix of life

	Vulnerability (population/village)				
Hazard (m)	0–600	600–2,400	2,400–4,200	4,200–6,000	> 6,000
0.0–0.3	Very low	Very low	Very low	Very low	Very low
0.3–1.5	Low	Low	Low	Middle	Middle
1.5–3.0	Middle	Middle	Middle	Middle-high	Middle-high
> 3.0	Middle-high	Middle-high	High	High	High

Table 5 | The risk matrix of agriculture

	Vulnerability (%)				
Hazard (m)	0–20	20–40	40–60	60–80	80–100
0.0–0.5	Low	Low	Low	Middle	High
0.5–1.5	Low	Middle	Middle	High	High
> 1.5	Middle	High	High	High	High

Table 6 | The risk matrix of industry and commerce

	Vulnerability (%)			
Hazard (m)	0–25	25–50	50–75	75–100
0.0–0.5	Low	Low	Low	Middle
0.5–1.5	Low	Middle	Middle	High
> 1.5	Middle	High	High	High

Adaptation strategy

Module 5 comprises a database which includes adaptation strategies for reducing the risks for water shortage and inundation. In the case study, five adaptation strategies for reducing the risks for water shortage, such as recycle of industrial water usage (e.g. 20% of recycle rate), development of alternative water resources (e.g. a desalination plant that can provide freshwater around $1 \times 10\ m^3$/day), reduction of household water usage (e.g. 10% off, 20% off of present water usage, and 250 L/day per capita) were preliminarily considered in the DSS. Each individual adaptation strategy is independent. The DSS reran the impact and risk assessments for each strategy to see the performance of impact and risk reduction. In the case study, the

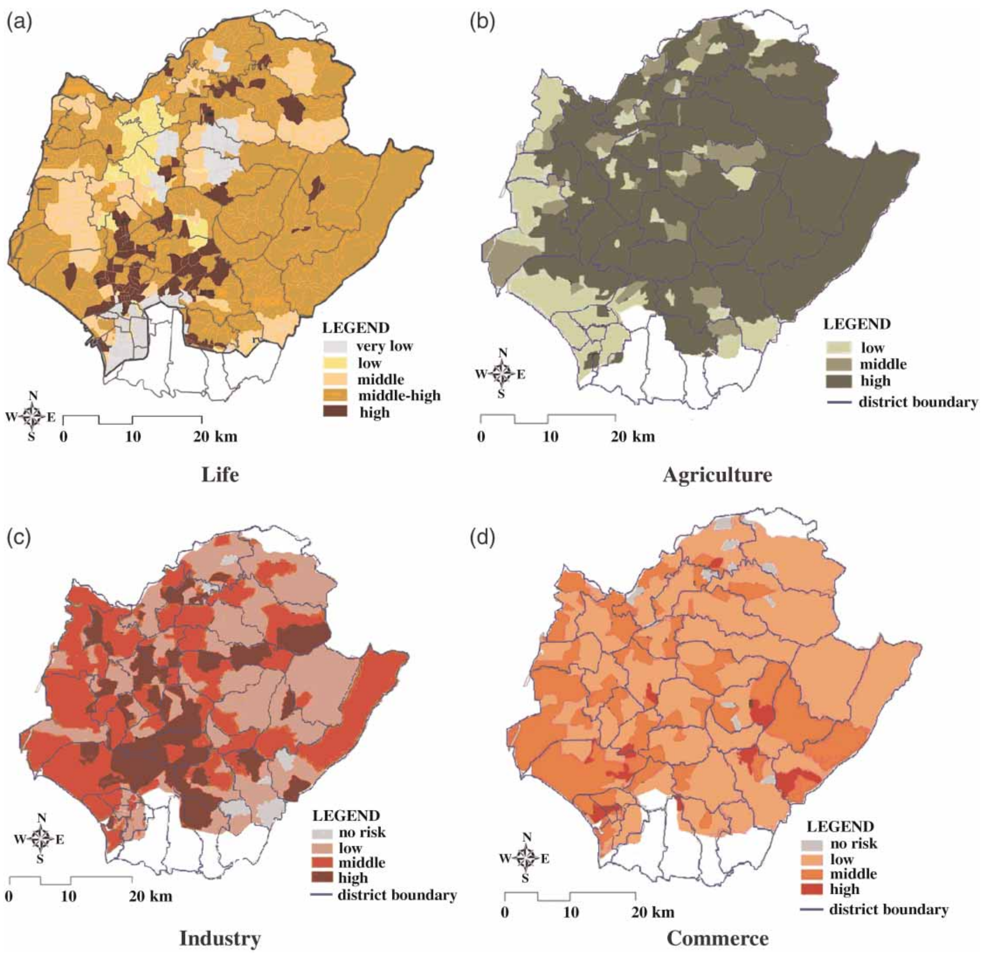

Figure 13 | Risk maps of (a) life, (b) agriculture, (c) industry, and (d) commerce.

strategy of reduction of household water usage to 250 L/day per capita was found to be the best among the five adaptation strategies. For the locations with larger risks of life, industry, agriculture and commerce, some structural and non-structural strategies have been preliminarily suggested for reducing the risk for inundation, including constructing a detention pond, enhancing drainage facilities, controlling land develop, changing land use, enhancing flood warning, planning evacuation of inhabitants, etc.

The limitation of using the database of adaptation strategy is as follows. For assessing an adaptation strategy, users have to judge whether the adjustment of model parameters can represent the adaptation strategy or not. If yes, the adaptations can drive the changes to the model through the adjustment of model parameter. If no, the adaption strategy cannot be assessed in the proposed DSS. For example, if users want to assess an adaptation strategy, such as recycling of industrial water usage (e.g. 20% of recycle rate), to see its performance on reducing the risk for water shortage, they can adjust the industrial water demand (i.e. one parameter of system dynamic model in Module 2) to 80% of the original value for rerunning the related modules (i.e. Modules 2 and 4) in the DSS.

CONCLUSIONS AND FUTURE STUDIES

Since assessing the risks for water shortage and inundation under future scenarios is a large and essential issue, integrating individual models into a user-friendly DSS for this type of assessment is helpful and attractive to the authorities of water resources management. This paper mainly introduces a DSS approach for evaluating the climate change impacts on water supply–demand and inundation; and assessing the risks for water shortage and inundation under future scenarios. As demonstrated in this paper, the DSS comprises five modules integrated by a GIS platform with a user-friendly interface which provides easy access to information and interaction. The evaluation results from the DSS are beneficial to the authorities of water resources management for understanding the spatial risks of water shortage and inundation in the study area and planning suitable adaptation strategies for the locations with larger risks. The proposed framework of the DSS used to address the presented issue is the main innovation proposed with this study.

In the case study, the projections of monthly rainfall and monthly mean temperature from 24 GCMs under A1B emission scenario were used and the multi-model ensemble approach was adopted to hypothesize two CICs for evaluating the climate change impacts on water supply–demand and inundation, respectively. The DSS used them to generate the daily rainfall and temperature data, and performed the frequency analysis for assessing impacts on water supply–demand and inundation, respectively.

The results of impact assessment on water supply–demand reveal that water shortages (including the duration and magnitude) of agriculture, industry, and household will increase. From the results of impact assessment on inundation, it is found that the area and amount of inundation caused by 1-day maximum rainfalls for the 100-year return period under the A1B emission scenario will be larger than the area and amount during the baseline period. After these impact assessments, the vulnerability and risk assessments for water shortage and inundation were performed. The vulnerability and risk maps were plotted by the DSS. From the risk maps, the risk levels of water shortage and inundation for each analysis unit can be seen. The locations with larger risks have to be considered as a priority for planning suitable adaptation strategies to reduce the risks for water shortage and inundation.

At the present stage, a user-friendly interface has been made for users to input the data and receive the information of model output. Since the interface is designed in Chinese and its improvement is on-going, the figures of the interface are not shown in the paper. The present DSS is a prototype, further improvements are needed. Moreover, the established DSS is limited for use in southern Taiwan. If this DSS is applied to other locations, all the individual models in the DSS have to be recalibrated. It requires much time and effort to collect the analysis data and recalibrate all the individual models. The new 2-year project for the other location, central Taiwan, is now in progress. The other limitation is that the DSS itself cannot predict the future land use, water demand, and vulnerability factors which have to be collected from the estimations of the other studies or projects. The proposed approach is universal and flexible. Each individual model can be substituted by the other models with similar functionality.

The presented study mainly demonstrates a DSS approach as the method to support the decision process of strategy planning for reducing the risks for water shortage and inundation. The importance of integration between models in the DSS is more stressed than the description of each model. Therefore, the models used in the DSS were briefly described in the study. More details on the models including their mathematical formulations, relevant model parameters, and even their calibrated and verified results are not shown in the present paper due to the page limitation but can be found in the cited literature for readers to further explore them. So far, the DSS has been established for southern Taiwan and performed for the moderate A1B emission scenario under the instruction of WRA, MOEA, Taiwan. The implementation for a wider range of spatial locations and climate scenarios will be considered as our future work. Moreover, the aforementioned adaptation strategies have been preliminarily planned and stored in the database for the case study. Future work may establish more strategies for running simulation in the DSS to see their performances.

Moreover, in the Netherlands, the Consortium research programme on Decision Support Tools (Theme 8 of KfC programme, http://knowledgeforclimate.climateresearchnetherlands.nl/decisionsupporttools) is on-going, and it aims at improving tools for design and evaluation of adaptation strategies with a special focus on spatial planning and cross cutting issues. The program focuses on three core elements:

(1) tools for formulation of the adaptation task, based on climate scenarios and economic development; (2) tools for development and visualization of adaptation strategies in general, and in particular related to hotspots and case study areas; and (3) evaluation and monitoring tools for assessing adaptation strategies in terms of various indicators such as costs and benefits, side effects, equity issues, efficiency and temporal and spatial scales. Seven work packages (WPs) are included in the program: (1) WP1: Integrating and downscaling national socio-economic scenarios; (2) WP2: Assessing the economic impacts of flood risks; (3) WP3: Interactive development of spatial adaptation strategies; (4) WP4: Visualization and simulation of impacts and strategies; (5) WP5: Economic modeling and assessment of the impacts of climate change and adaptation strategies on freshwater resources; (6) WP6: Optimal timing, cost benefit analysis and adaptation strategies; and (7) WP7: Monitoring and evaluation of climate change impacts, vulnerability and adaptation policies at different spatial scales. The aforementioned work packages include all the scientific and societal aspects in developments of decision support tools for climate change challenge. In the proposed approach of the study, integrating and downscaling national socio-economic scenarios, assessing the economic impacts of flood and water shortage risks, and the cost benefit analysis for adaptation strategies have to be developed and included in future work.

Due to administrators of water resources management being confronted with the need to draw up long-term plans with regard to climate change and being faced with major uncertainties, the major improvements that still need to be carried out are to integrate all facets of uncertainty in the proposed DSS in the future. However, the integrated uncertainty approach in climate change research is not easy and is still an important issue. For example, the Institute for Mathematics Applied to Geosciences (IMAGe) held a meeting in 2012 with the theme of 'Uncertainty in climate change research: an integrated approach' (IMAGe 2012) and the website of the Consortium research programme on Decision Support Tools in the Netherlands (www.climateresearchnetherlands.nl/research-themes/decision-support-tools) also mentions the importance. Besides, integrating and downscaling national socio-economic scenarios, assessing the economic impacts of flood and water shortage risks, and the cost benefit analysis for adaptation strategies have to be developed and included in the future work.

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