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Study on the Climate Adaption Planning for an Industrial Company with Regional Risk of the Water Supply System—A Case in Taiwan

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Abstract: Extreme uneven spatial and temporal distributions of rainfall pose the risk of water shortage to the industries in Taiwan, particularly during dry seasons, which may be worsen under climate change. This study aims to develop adaptation actions for an industrial company to reduce the risk of droughts. The Formosa Plastics Corporation (FPC) in Chuoshui River watershed is selected as a study case and an integrated risk assessment tool of water resources TaiWAP is used. The water shortage of FPC is mainly in the dry seasons because the water rights of public and agricultural uses are prioritized over industrial use. The considered adaptation options including water reuse, a desalination plant, smart agricultural water management, and rainwater harvesting. The results show that the waste-water reuse and sea-water desalination are the most effective adaptation options, which reduces the water shortage risks 33–44% per day in the return period of ten years. The results are generalized for the reference of other studies. The risk assessment and adaptation measure identification of the company require regional information. Moreover, some adaptation measures that the company implements help reduce the water shortage of the region and are consequently beneficial to the company, e.g., smart agricultural water management.

Keywords: water resources management; adaptation; an industrial company; climate change; risk assessment

1. Introduction

Drought is a slow and imperceptible phenomenon from continuous water shortage. According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), climate change increases the frequency of extreme rainfall events and intensifies the spatial and temporal contrast of wetness and dryness [1–3]. Little precipitation and snow for years caused severe droughts in California in 2009 and 2013–2016 [4]. In addition to agricultural and domestic use, industries such as manufacturing, golf, ski parks, and construction were strongly affected by the water rationing. Most places in Taiwan are vulnerable to droughts because of reservoir siltation, high water leakage rate, and low water price. Little precipitation in 2014 caused the most severe drought in 2015 over the past 67 years. It caused approximately 43 thousand acres of paddy fields to stop irrigation, 10% supply reduction on large industries, and phase-three water rationing for domestic use, i.e., two-day cut-off after five-day supply. These events indicate that the effects of droughts may show in meteorological, hydrological, agricultural, and social-economic aspects [5].

Industries are one of the sectors that experience more water stress because of increasing drought [6]. Droughts impose impacts on food and industrial production such as Coca Cola [7]. In Taiwan, the severe drought event in 2015 led to the rarely seen phase-two water rationing in Hsinchu Science Park. Under phase-three water rationing, the water supply will be reduced by 30% and that may need to shut down some production lines. To prevent the possible phase-three water rationing, various industries have actively invested in developing adaptation measures. For example, the United Microelectronics Corporation in Taiwan developed an early-warning system (United Microelectronics Corporation Drought Early Warning System, UMCDEWS) against droughts [8]. The tool has been proven able to predict the timing of water rationing, which helps the company order tank cars to deliver water in advance. Other adaptation measures include industrial water conservation and water recycling, which have been applied in Japan, Europe, and Latin America [6,9].

General procedures are proposed to assist climate-change-related adaptation decision-making. The concepts of the procedures are similar, which include analyses of the problems, assessment of the current and future risks, identification of the adaptation measures, implementation of the adaptation plan, and monitor and modification [10]. The main differences are in the classification of the steps and the consideration of monitor and modification. The adaptation procedures may be used by different potential users such as the professional team, government, industries, or general public. In fact, multi-level collaboration is essential to effective adaptation. Many studies have recognized the importance of clarifying the responsibilities of the regional, local, and individual actors [11–13]. However, most studies only elaborate the role of multi-level collaboration in adaptation instead of demonstrating the details of collaboration with a study case. This study focuses on adaptation planning from the perspective of an industrial company to identify the effective adaptation options to reduce the risk of droughts in future climate and social-economic scenarios. The significance of the study is in applying the adaptation planning framework to help recognize the adaptation measures that a company can implement to reduce the water shortage of the region and benefit the company itself. The existing adaptation planning of the government is treated as the boundary condition of the company's adaptation. If the regional adaptation planning is unavailable, the company must have more aggressive adaptation plan.

The study uses the Sixth Naphtha Cracker Complex Park of Formosa Plastics Corporation (FPC) and the Chuoshui River watershed in Taiwan as a study case. The goal of adaptation for the entire watershed includes enhancing the water resource management, increasing the function of water retention, maintaining the quantity and quality of the groundwater, and facilitating the responding mechanism of irrigation during droughts. Moreover, the goal of the company includes reducing the amount of water shortage, increasing the resilience, and maintaining the availability of the water supply for industrial water use. Risk is a function of hazard, exposure, and vulnerability, as defined in AR5 [1]. The definition of hazard is the climate-related events leading to impact to the system the adaptation aiming at protecting. Moving the concerned system to place with less hazard is considered eliminating the exposure. Moreover, the vulnerability can be divided into the sensitivity and adaptive capacity. The former is the inherent characteristics to determine how susceptible the protecting systems are to water shortages, whereas the latter represents the ability of the systems to adapt to water shortages. Increasing the adaptive capacity or decreasing the sensitivity reduce the vulnerability, which can be evaluated concerning the wealth, technology, information, skills, infrastructure, institutions, and equity aspects. The paper is organized as follows: the methods to evaluate climate risk and identify the adaptation options are elaborated in Section 2; the study case is introduced in Section 3; the results are shown in Section 4; the discussions and conclusion are shown in Section 5.

2. Materials and Methods

This study applies the methodology of evaluating climate risk and identifying the adaptation options to the general adaptation planning framework, to assist an industrial company in the decision-making of climate change adaptation. The climate change risk assessment and adaptation option identification are conducted based on the viewpoint of an industrial company, which is different from the studies that focus on the regional or governmental viewpoint. Because the water resources of the company are also affected by other water users, the company needs the information of the risk assessments and adaptation measures of the entire watershed. The company has its own objective of the adaptation to minimize the risk of water shortage, and the adaptive capacity for the entire watershed is treated as the boundary condition. Government has already a procedure in adaptation planning. However, the results of regional risk assessment and adaptation option identification and evaluation for a company may not be provided by the governmental agency, as the case of FPC is. Therefore, the company must conduct risk assessment and evaluate whether it should invest in existing adaptation options or implement additional measures. The following sections are categorized as model verification and indicator definition, risk assessment, and identifying and assessing the adaptation options.

2.1. Model Verification and Indicator Definition

2.1.1. Verification of Assessment Models

Verifying the assessment models helps provide reasonable results. The observed weather data and streamflow are used to verify the hydrological component of the Generalized Watershed Loading Function (GWLF) [14] and water supply system dynamics model, respectively. This study uses the GWLF to simulate streamflows and inputs the flows into a water supply system dynamics model to allocate regional water resources. The results are used to estimate the risk of water shortage.

The GWLF is selected because it provides reasonable estimates of the monthly streamflow in the Chuoshui River watershed. It is a conceptual lump model which calculates the water balance at the surface layer and the non-saturated aquifer, which reflects the effects of the weather, types of land use, and drainage characteristics of soils on the streamflows. This study simulates the stream-flows based on the concept of GWLF but calculates the daily and ten-day flows. The streamflow (SF_t) is estimated by summing the surface runoff (Q_t) and the baseflow discharged from the shallow saturated zone (G_t), as shown in Equation (1). The surface runoff is calculated using the Curve Number Method [15], whereas the ground water discharge is modeled as a linear reservoir. The input parameters are the Curve Number (CN), daylight hours, maximum water-holding capacity of the soil, coefficient of evapotranspiration, cover coefficient, and recession coefficient of the shallow non-saturated aquifer. The flowchart is shown in Figure 1, and more descriptions of the GWLF can be found in [14].

$$SF_t = Q_t + G_t, \tag{1}$$

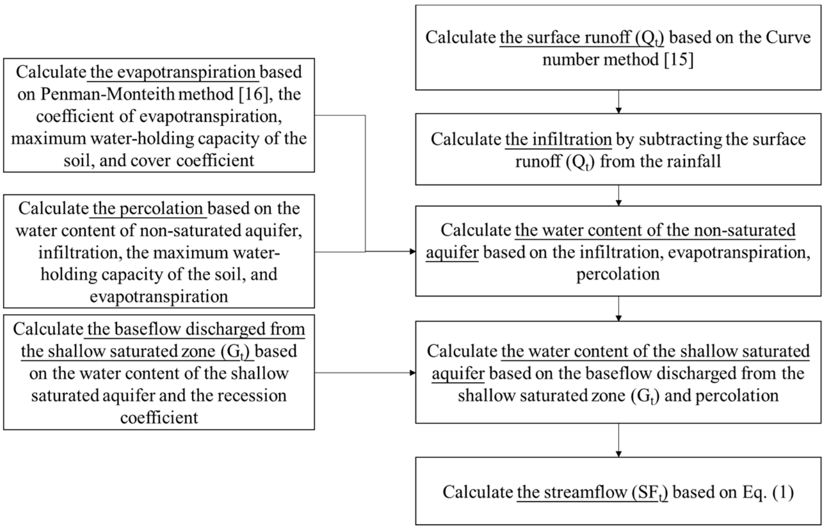

Figure 1. Flowchart of the derivation process of the streamflow from weather data [16].

The stream flows are used as the inputs of the water supply system dynamics model. The system dynamics model is developed to simulate the allocation of regional water resources. The relationship between the water use of a company and that of the regional system can be clearly identified using the system dynamics model. It is of great use for a company to recognize whether the source of water resources is affected by the concerned hazard and which users have large water demands. This study uses the modeling tool of Vensim [17] to build the water supply system dynamics model based on the layout of the hydraulic facilities and operation rules of the reservoirs and weirs, which define the amount of power generation and water rights of different users. The water supply system dynamics model of the water allocation in the Chuoshui River watershed is shown in Figure 2.

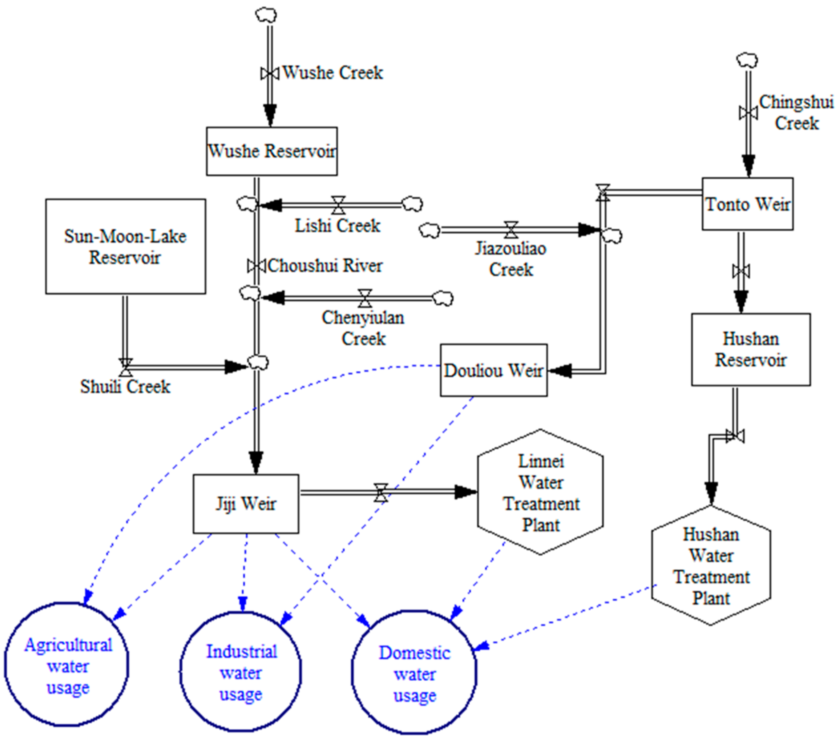

Figure 2. The water supply system dynamics model for the water resources allocation in Chuoshui River watershed.

In this study, the maximum water supply within the tolerable risk of water shortage is defined as the carrying capacity of the water supply system. The tolerable risk of water shortage is set as the Shortage Index (SI) [18] of 1. SI is commonly used to estimate the capacity of a water supply system and is calculated using Equation (2).

$$\mathrm{SI} = \frac{100}{N} \times \sum_{i=1}^{N} \left(\frac{D_i}{S_i}\right)^2, \tag{2}$$

where N is the total number of years of simulation; D_i and S_i are the amount of water shortage and planned amount of water supply, respectively.

The study estimates the carrying capacity of the water supply system in different climate and social-economic scenarios using the system dynamics model. The iterative estimating process used to determine the maximum water supply without exceeding the threshold of SI is described as follows. The total water demand of different users is first estimated to be the initial design of the water demand; then, the water supply and demand are compared to calculate the value of SI. If SI is less than the threshold, the designed water demand is increased; otherwise, it is reduced. The process is stopped when the value of SI approaches the threshold. Then, the designed water demand is the carrying capacity of the water supply system.

2.1.2. Indicators for Risk Assessments

The most concerned aspect of drought risks is the amount of water shortage. However, a company is more concerned about the details that affect its economic loss and may hope that the duration of allowable water deficit is less than a given number of days to ensure the production work. These details may include the recovering time and average functioning performance of the system. The water shortage ratio is commonly used to describe the amount of water shortage. Proposed in 1977 by Water Resources Development Public Corp., the Deficit Percent Day (DPD) Index is a commonly used indicator to evaluate the accumulation of water shortage [19]. The indicators that evaluate the recovery time for a malfunctioning system are considered the resilience indicators, and this study uses the Mean Time to Repair (MTTR) and Maximum Time to Repair (Max. TTR) as the resilience indicators. The average functioning performance of the system is estimated by calculating the ratio of Mean Time to Failure (MTTF) of the analyzed period, which is defined as the availability indicator in this study.

The study defines five indicators to evaluate the risk of water shortage (Table 1). The ten-day average water shortage ratio (hereafter water shortage ratio) is used to fit the practical operation of the facilities. The water shortage ratio (R) and DPD are calculated in Equations (3) and (4), respectively. Moreover, the study considers water shortage as a regular threat and uses the maximum annual DPD in a 2-year return period as an indicator (DPD_{50}). The details of other indicators are referred to [20]. The maximum values of R (Max. R) and DPD_{50} are selected as the water deficit indicators. With the defined indicators, the risk is quantified and described accordingly.

$$\mathrm{R} = \sum \frac{M}{D} / n, \tag{3}$$

$$\mathrm{DPD}(\% - \mathrm{day}) = \sum_{i=1}^{N} D_i - S_i / D_i \times 100, \tag{4}$$

where M is the ten-day amount of water shortage; D is the ten-day water demand; n is the number of water shortage events; i is the counter; N is the number of continuous deficit days; D_i is the water demand of the ith day; S_i is the water supply of the ith day.

Table 1. Definition of the indicators.

Indicators		Definition
Water deficit indicator 1	Maximum Ten-day Average Water Shortage Ratio (Max. R)	R is the summation of all ten-day deficits divided by the number of water shortage event
Water deficit indicator 2	Deficit Percent Day Index under 2 year return period (DPD_{50})	Reference of the tolerance of water shortage event based on the amount of deficit for a year
Resilience indicator 1	Mean Time to Repair (MTTR)	The average time for a malfunctioning system to get back to work normally
Resilience indicator 2	Maximum Time to Repair (Max. TTR)	The maximum value of all Time to Repair (TTR)
Availability indicator	MTTF/(MTTR + MTTF)	The average functioning percent of a system during the analyzed period

2.2. Risk Assessment

The risk information may be sliced from the regional risk assessment by the governmental agency, which includes the risk of the company as a component of the regional allocation system. If it is not available, which is the case in this study, the private company must conduct its own risk assessment. Then, the risks of the regional system and the company's on-site system are further distinguished as the basis to identify the adaptation options for the company.

2.2.1. Current Climate Risk Assessment

The current risk is assessed using an integrated risk assessment tool of water resources called TaiWAP [21] and the verified water supply system dynamics model. The result is further quantified with the defined indicators. The current risk is evaluated using the observed weather data. Then, the causes of the risk for status quo are discussed. The risk of the current climate may be different from that of historical events because of the changes of the climate, land use/land cover in the watershed, or water supply system. Therefore, the analysis of the causes that compose the current risk enables us to compare the current and historical risks. Moreover, the results also help track changes of the risks between the current and the baseline scenarios to examine the difference in using the observed data and the generated data.

2.2.2. Scenario Setting

The climate change and social-economic scenarios are setup before assessing the future risk. The data of the existing General Circulation Models (GCMs) in different Representative Concentration Pathways (RCPs) is available on the website of the IPCC Data Distribution Center. The GCMs with high validity, whose climate projections in the baseline period are similar to the observed data of the targeted weather station, have high priority to be selected. Three criteria are included in evaluating the validity: the correlation coefficient of annual precipitation, the normalized root mean square error (NRMSE) of the wet seasons, and the NRMSE of the dry seasons (Equation (5)). A high correlation coefficient or a low NRMSE indicate high validity. The GCMs are ranked for each criterion and the ranks are averaged, which is called the Weighted Average Ranking (WAR) method [22] (Equation (6)). Based on the WAR, the required number of GCMs is selected to derive climate scenarios.

$$\mathrm{NRMSE} = \sqrt{\frac{1}{N}\sum\nolimits_{i=1}^{N}\left(\frac{X_{sim,i} - X_{obs,i}}{X_{obs,i}}\right)^2}, \tag{5}$$

$$Rank_{avg} = \frac{1}{M}\sum\nolimits_{j=1}^{M} r_j, \tag{6}$$

where $X_{sim,i}$ is the simulated ith data; $X_{obs,i}$ is the observed ith data; N is the number of data; $Rank_{avg}$ is the average rank of the GCM; r_j is the rank of the GCM for criterion j; M is the number of criteria.

The categories of social-economic scenarios usually include the population and human development, economic conditions, and land cover/land use [6]. This study considers only the effects of the social-economic scenarios on the water demands of the agricultural, domestic, and industrial uses. The irrigation water demand is affected by the crop species, planting practices and schedules, soil types, crop areas, growing period, and potential evapotranspiration, whereas the domestic water demand ($D_{domestic}$) is affected by the population and individual water demand (Liters per Capita per Day, LPCD), rate of population served, and leakage rate (Equation (7)). The industrial water demand is commonly related to industrial development, which can be estimated by the area of factories, floor area, number of employees, and Gross Domestic Product (GDP) per capita. These scenarios of water demands can be set according to either simulation or official reports of future development.

$$\mathrm{D}_{domestic} = N \times LPCD \times R_{population\ served} \times (1 - R_{leakage}), \tag{7}$$

where N is the population; $R_{population\ served}$ and $R_{leakage}$ are the rate of population served and leakage rate of the water supply, respectively.

2.2.3. Baseline Climate Risk Assessment

The baseline risk assessment includes generating baseline weather data and analyzing the risks in baseline climate scenarios. The purpose of baseline risk assessment is to ensure the reliability of using the generated weather data and estimated water demands in the risk assessment by comparing the current and baseline risks. The GCMs with high validity were selected. Moreover, the weather data is generated based on a Richardson-type weather generator [23] using TaiWAP [21], in which the data was downscaled by bias correction [24] and the climate scenarios are setup using the delta method [25]. Then, the risk assessment of the baseline is similarly conducted as the current risk assessment. The main difference is that the climate and social-economic scenarios in the baseline are used instead of the observed weather data and water demands. More specifically, the weather data of the baseline is generated using a weather generator instead of the observed data, whereas the water demands of different uses in the climate and social-economic scenarios are estimated. With the aforementioned data, the risk is quantified using the defined indicators.

2.2.4. Future Climate Risk Assessment

First, the future risk assessment generates future weather data based on future climate scenarios. Then, the future climate risks are simulated using the generated weather data and estimated water demands of different water uses, which were modified according to the future climate and social-economic scenarios. The weather data in the baseline and future scenarios, which were generated on the same modeling basis, can be compared to examine the changes because of climate change. Moreover, by comparing the derived climate risks of the company in the baseline and future scenarios, the changes because of the climate and social-economic scenarios can be clarified. The causes of the risks are identified and related to the climate and social-economic scenarios. Hazard is mainly affected by climate scenarios, such as the stream flows in both wet and dry seasons. Exposure, such as the water supplies and demands of other water uses, and vulnerability mainly vary with the social-economic scenarios. The analysis of the causes of the risk helps to identify the origin of the risk and propose suitable adaptation measures.

2.3. Identifying and Assessing the Adaptation Options

The risk assessment method is generalized to ensure its applicability to other places, so as the adaptation option identification and evaluation. With the risk information, the feasible adaptation options are first identified, and the effectiveness of the options is quantified. Then, a company can determine to implement the regional adaptation options or propose its own on-site measures.

2.3.1. Identifying the Adaptation Options

Understanding the causes of risks, i.e., the hazard, exposure, and vulnerability, helps one determine the effective adaptation options. The existing regional adaptation measures and options and the division of responsibilities can first be collected from the literatures. The adaptation measures and options implemented by the regional authorities or those requiring on-site investments of companies are identified. In addition, the companies can invest in regional adaptation measures that cannot be realized in time, or additional on-site measures considering the location, technology, financial resources, and operating objectives of the company. Finally, the feasible adaptation options are determined based on the integral assessment.

2.3.2. Evaluating the Adaptation Options

First, the criteria to rate the adaptation options are established. The most commonly used criterion is their effectiveness in reducing the water shortage risk. Then, the identified adaptation options are evaluated based on the selected criteria. There are other criteria such as the feasibility, uncertainty, and side effects of the options. Notice that the study focuses only on the field of water resources, and the analysis of the competition between adaptation options of different fields is recommended for cross-sectoral problems. Moreover, various approaches to sort or rank a set of options have been applied to evaluate the suitability of each adaptation option, such as the multi-criteria analysis and analytic hierarchy process. The main concept of these approaches is to determine the priorities of the alternatives based on the scores of the alternatives in the selected criteria and the corresponding weights of the criteria. The results support the decision-making of the company on either investing in the existing options or implementing additional on-site measures. The former helps to reduce the regional risk of water shortage and is beneficial to the company.

3. Study Case

This study focuses on developing climate adaptation plan for a company considering the climate risks and adaptation measures of both regional system and the company's on-site system. The Sixth Naphtha Cracker Complex Park of Formosa Plastics Corporation (FPC) was selected as the study case. FPC is a self-motivated company that invests in reducing risk and increasing the resilience of the water supply in future climate and social-economic scenarios. The water used by FPC comes from the special pipelines connected to Jiji Weir. Therefore, the scope of the study includes the Chuoshui River watershed. Because this study focuses on the water supply of FPC, other industrial water uses and the domestic use are called public water use. The FPC requires 280 thousand cubic meters of water every day. The FPC has the water right during the wet seasons (May through October), but it must buy water from farmers during the dry seasons (November through April of the following year).

Chuoshui River is the longest river in Taiwan with a 186.6-km-long main stream. The major water demand in the watershed is from agriculture, with 1.8 and 1.5 billion cubic meters per year in average for Changhua and Yunlin, respectively. The temporal and spatial distribution of the precipitation are uneven in the watershed. Therefore, three weather stations and three gauge stations are selected based on the official report [26], as shown in Figure 3. The maximal difference in annual precipitation for the weather stations is 1055 mm, and the precipitation during wet seasons accounts for 76.7~85.4% of the precipitation in the entire year. The differences of monthly-average temperature within a year for all weather stations are approximately eight Celsius, and the maximum monthly temperatures are 16–22 Celsius [27].

The main water supply facilities in the watershed are Wushe Reservoir, Sun-Moon-Lake Reservoir, Jiji Weir, and Linnei Water Treatment Plant (Figure 4). The two reservoirs are also used for power generation because of the large difference in upstream elevation, and the amounts of water used for power generation are based on the operation rules of the reservoirs. Details of the facilities are described as follows.

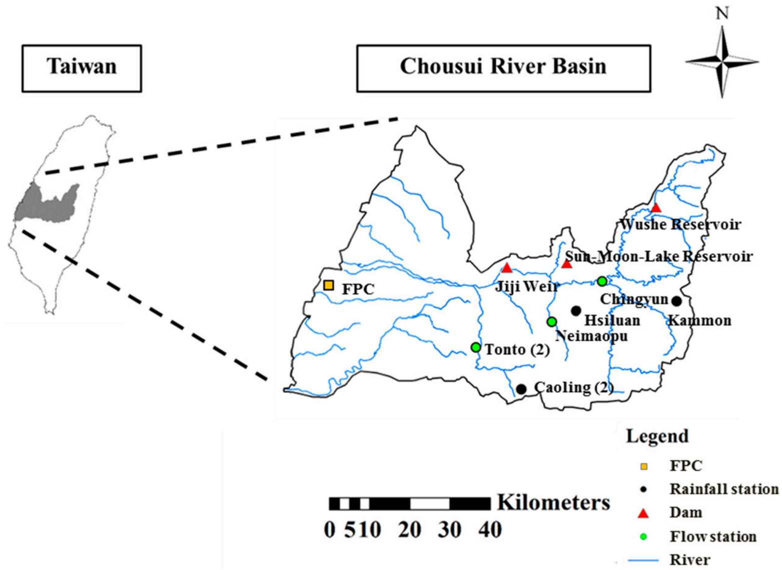

Figure 3. Location of study area, weather stations, and gauge stations.

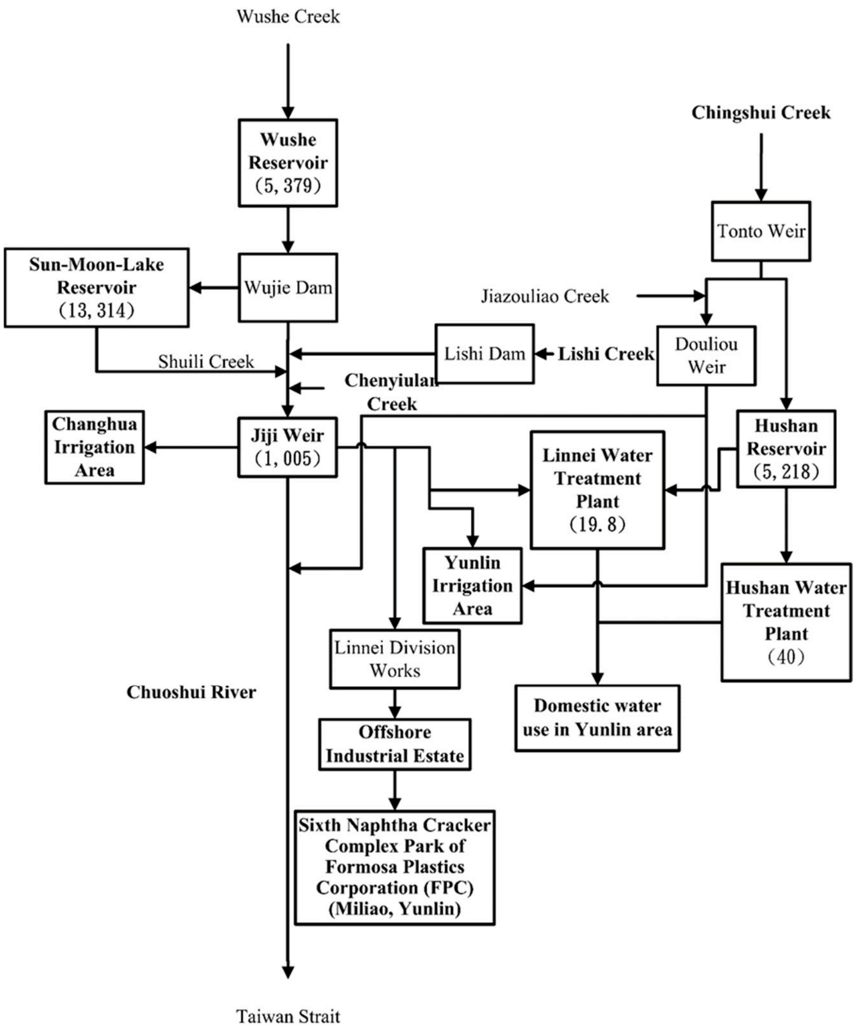

Figure 4. System of water resources allocation in Chuoshui River watershed. Numbers in reservoirs are storage capacity (10^4 cubic meters) and that in Water Purification Stations are the treatment capacity (10^4 cubic meters per day).

There are two reservoirs in the Chuoshui River watershed. Wushe Reservoir is located in Wushe Creek, which is the upstream of Chuoshui River, with a drainage area of 216 km^2. Sun-Moon-Lake Reservoir is an off-site reservoir with a drainage area of 520 km^2. Wushe Reservoir is mainly used for power generation, whereas Sun-Moon-Lake Reservoir provides domestic and agricultural uses in addition to power generation. The discharging principles of the two reservoirs are based on the water level and operation rules of the reservoirs. Moreover, Linnei Water Treatment Plant provides most of the public use in Yunlin with the capacity of 198 thousand cubic meters per day. Based on the operation manual of Jiji Weir, the public and agricultural water uses are first supplied according to the ratio of water-right registrations, and the remainder is allocated to industrial use.

Since the water shortage of the company is highly related to the regional agricultural, domestic, and industrial water uses, the concerned issues in the regional water supply system are defined at the very beginning of the adaptation planning. A study reviewed the historical extreme weather events is used to clarify the concerned key issues of the watershed where FPC is located [28]. Drought events directly affect the water supply system because they may cause low water level in the rivers and reservoirs and consequently different extents of water rationing in Yunlin and Changhua. It is mainly because the water supply facilities could not save water in the wet seasons for the use in the dry seasons. In addition, the typhoon events, landslides, and other types of disasters are likely to pose risks to the water supply system, such as causing reservoir siltation or other damages to the water supply infrastructures.

The causes of risks are clarified for the regional system and FPC's on-site system to assist the risk assessment and adaptation option evaluation. The separation of the two systems helps identify the interaction of water resources between the company and the regional system. For the regional system, hazards mainly originate from the climate-watershed system, which includes the unevenly distributed precipitation and great discharge disparity between wet and dry seasons. Moreover, the exacerbation of the difference between wet and dry seasons may be more extreme in the future climate scenarios [20]. The expansion of the science-based industrial park in mid-Taiwan, increase in domestic water demand because of population growth, and pressure of the large irrigation water demand make the regional system expose to drought events. High sensitivity is caused by the water use characteristics of the system, whereas the low adaptive capacity is mainly from insufficient water supply facilities or poor management. Agriculture is particularly sensitive to drought because of the inherent characteristics of paddy fields. Furthermore, an insufficient water supply includes lack of facilities, large water leakage, and poor management of governmental or private sectors. Combined with the difficulties in expanding the water supply capacity such as building facilities like reservoirs, dams, or weirs or using groundwater, the insufficient water supply increases the vulnerability of the regional system. Notice that the system of adaptation planning for the regional system includes the agricultural, domestic, and industrial uses.

The system that the adaptation planning in this study aims to protect is FPC. For the company's on-site system, because almost all water used by FPC is from Jiji Weir, the hazards of the regional system pose a great risk to the FPC's on-site system. Moreover, the growing water use for increasing production may further exposes FPC to drought risk. The exposure and adaptive capacity of FPC are partly inherited from the regional system. Although the hazard and exposure of the company are further affected by its location, the sensitivity of the company is affected by the water-use characteristics of the production. FPC has a relatively low sensitivity because it require less cooling water than other industries such as the chemical industry, food manufacturing, and textile industry. Moreover, the high vulnerability of FPC is caused by the lack of facilities and insufficient water supply because of poor management, e.g., the failure of ordering tank cars to deliver water in time.

The existing water resource management measures are analyzed based on the official report [29]. The measures aim to reduce the water demand, increase the water supply, and enhance the water management, as described below. By providing financial incentives to fallow groundwater-supported rain-fed farming, afforestation, and water-saving facilities, the irrigation water demand can be reduced.

Moreover, the water supply facilities under construction are expected to provide additional water resources. For example, the capacity of Hushan Reservoir is 312 thousand cubic meters which is expected to support the public water use. It is beneficial to FPC because the demands from Jiji Weir, where FPC uptakes water, is reduced. The actions to enhance the overall water management are: improving the cooperation of the Farm Irrigation Association Unions in Changhua and Yunlin, systematically allocating water, increasing the water usage efficiency, increasing the available water by setting up ponds, and using the return flows. Among these actions, most actions that increase the water usage efficiency of different uses are beneficial to FPC because the water right of industries is posterior to public and agricultural uses.

Then, the cause-oriented adaptation options are analyzed. The study collects the related adaptation measures and options from the Water Resources Agency (WRA) [24,30]. The adaptation measures and options of the Chuoshui River watershed in response to the causes of the risk are identified. Because hazard is usually controlled by reducing the emission of greenhouse gases, which is a global-scale issue, the study focuses on the adaptation options that affect the exposure and vulnerability. Options such as building reservoirs, building a regional desalination plant, or reducing the domestic water demands are beyond the reach of FPC. Notice that the water conservation of industrial use implies that the government helps the industries to save water. Moreover, some adaptation options have been proposed and evaluated by FPC, such as rainwater harvesting, which should be performed by FPC.

4. Development of Adaptation Plan for the Study Case

The study aims at developing methods for climate adaption planning for a company in future climate and social-economic scenarios; it focuses on evaluating the climate risk and assessing the adaptation options. The adaptation plan is developed based on the perspective of FPC, and the regional water supply system of the Chuoshui River watershed is used as an example.

4.1. Model Verification and Indicator Definition

Verification of Assessment Models

Before applying simulation models to assess the climate risks, the hydrological model and water supply system dynamics model must be verified. The downscaled weather data is verified before it is used to project future flows. The coefficient of determination (R^2) and coefficient of efficiency (CE) between the generated and observed daily precipitation are used as indicators [31,32], which are higher than 0.98 for all rainfall stations in Table 2. Then, the study uses the data from the main streams of the Chuoshui River watershed, i.e., Chingshui Creek, Lishi Creek, and Chenyiulan Creek, to verify the GWLF. The calibrated parameters required for model verification are collected and listed in Table 2 [26]. The daily weather data of the nearby weather station and gauge station of each stream is used in model verification. All results are higher than 0.87, except the value of CE of Lishi Creek is 0.55. Then, the system dynamics model is used to simulate the allocation of water resources. The observed and simulated flows of Jiji Weir have two indicators: R^2 is 0.93, and CE is 0.83. The simulation is consistent with the observation, which ensures the rationality of the calibrated parameters.

Table 2. Parameters and results for GWLF verification.

Watershed	Chingshui Creek	Lishi Creek	Chenyiulan Creek
Periods	1986–2005	1986–2000	1986–2005
Rainfall station	Caoling (2)	Kammon	Hsiluan
Weather station	Sun Moon Lake	Sun Moon Lake	Sun Moon Lake
Gauge Station	Tonto (2)	Chingyun	Neimaopu
Area (10^3 Ha)	25.4	4.7	167.6
Average elevation (10^3 m)	1.2	1.9	1.6
CN2	81	45	60
Cover Coefficient	0.5	0.8	0.5
Recession Coefficient	0.04	0.04	0.02
Coefficient of determination (R^2)	0.99	0.87	0.94
Coefficient of efficiency (CE)	0.89	0.55	0.89

4.2. Risk Assessment

4.2.1. Current Climate Risk Assessment

To estimate the current climate risks, the study uses the weather data from 2005 to 2009 because of data availability [27]. The daily public water demand is 251 thousand cubic meters, as determined by the WRA [33]. The daily water demand of FPC is 283 thousand cubic meters. The agricultural water demand is estimated by averaging the collected data of the planned irrigation water demand, with the average of 50.6 and 42.0 million cubic meters per ten-day period for Changhua and Yunlin, respectively [28]. The tolerable risk of water shortage in this study is defined assuming that SI is 1. The supplies of different water uses are simulated. The water supply for public use is 260 thousand cubic meters, as estimated in WRA report [33]. The risk of public water use in the study area is acceptable because the carrying capacity of the water supply system is larger than the demand when SI is 1. However, there is a water shortage of agricultural use from 2 to 17% of the planned irrigation water demand during 2005–2009 because the irrigation water demand is much larger than the current available water supply, which increases the exposure of FPC to water shortage. The risk of the study case probably originates from the low adaptive capacity of water supply facilities.

4.2.2. Scenario Setting

The settings of the climate change and social-economic scenarios are described below. Future climate scenarios are derived based on the climate projections of GCMs. Five GCMs with most representative data to the observed data of the study area are selected based on the WAR method: MIROC5, CCSM4, HadGEM2-AO, CESM1-CAM5, and MRI-CGCM3. Details of the GCM selection can be referred to [34]. RCP 4.5 and 8.5 are selected to represent the medium-low and high-end scenarios. This study uses TaiWAP to generate the precipitation and temperature in the baseline and future scenarios.

Then, the water demands of different water uses are estimated. In this study, the agricultural water demand changes with the length of the growing period and the potential evapotranspiration, whereas the planting area and type of plant are assumed constant in future social-economic scenarios. The generated weather data and irrigation water demand are simulated using TaiWAP, with the data of the historical planned irrigation water demand. The future domestic water demand is calculated based on Equation (7) with the estimated population, LPCD, rate of the population served, and leakage rate (Table 3). The effect of the climate on the industrial water demand mainly comes from the cooling water demand. Concerning the types of company in the study case, the industrial water demand only changes with the social-economic scenarios. The demand of industrial use is highly correlated with the GDP per capita in the study case. This study uses the medium-level growth as the social-economic scenario and estimates the water demands of public use according to the simple linear regression between industrial water use and GDP [26].

Table 3. Parameters used for projecting domestic water demand under baseline and future scenarios.

Period	Population (10^3)	LPCD (Liters)	Rate of Population Served (%)	Leakage Rate (%)	Domestic Water Demand (m^3/Day)
1986–2005 (Baseline)	715.1	236	93.93	71.12	228,441
2021–2040	705.6	236	96.03	71.95	226,078

4.2.3. Baseline Climate Risk Assessment

The baseline climate risk assessment uses the generated weather data and model parameters based on the baseline climate and social-economic scenarios. The generated weather data in the baseline climate scenario is the input of the GWLF for the upstream flow simulation. The generated precipitation of the Chuoshui River watershed in the baseline scenario shows an unevenly seasonal distribution. Specifically, the flow accounts for 80–90% in the wet seasons and 10–20% in the dry seasons.

In addition to the inflows of the creeks, the demands of different water uses are determined based on the climate and social-economic scenarios as the input parameters of the water supply system dynamics model. The public and FPC water demand are 247 and 283 thousand cubic meters per ten-day period in the baseline scenario, respectively. The planned irrigation water demands of Changhua and Yunlin area are 1.8 and 1.5 billion cubic meters per year, respectively.

The water supply to satisfy the domestic water demand in Yunlin is 251 thousand cubic meters per day, and the simulated water supply capacity is 259.7 thousand cubic meters per day. Therefore, the supply can satisfy the demand when SI is 1. Jiji Weir provides water for the agricultural uses of Yunlin and Changhua. The simulated water supplies from Jiji Weir for Yunlin and Changhua are 1.5 and 1.4 billion cubic meters per year, respectively. The water supply is less than the average planned irrigation water demand; therefore, there is water shortage in the entire year as shown in Figure 5. The simulated annual water demand of FPC is 103 million cubic meters, which is similar to 108 million cubic meters per year that Jiji weir provides through the industrial special pipelines. To summarize, the water supply for public water use of Yunlin is sufficient under acceptable risks, which is highly attributed to the ground water treatment plant. However, water shortage may occur for agricultural use and FPC.

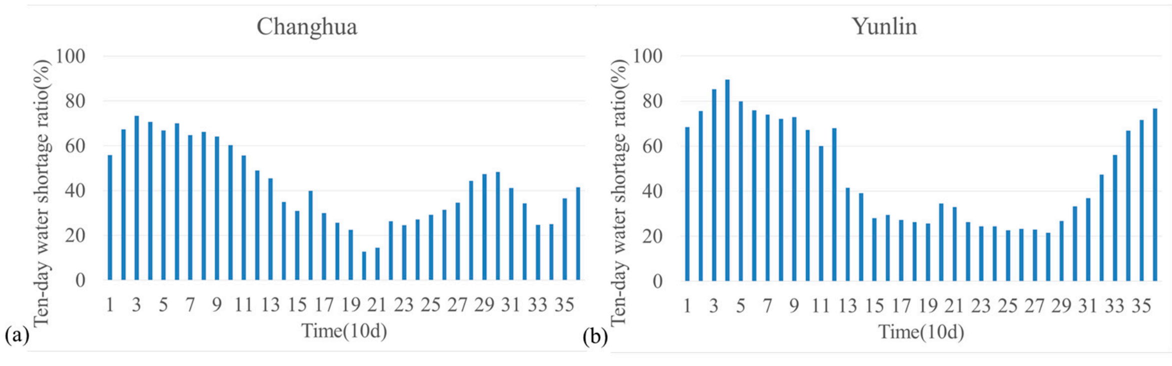

Figure 5. Water shortage ratio (R) in Changhua (**a**) and Yunlin (**b**) for agricultural water use.

The water shortage of FPC for the baseline are listed in Table 4. The maximum shortage is mainly in the dry seasons because the water rights of public and agricultural uses are prioritized over FPC. Therefore, alternative water sources in the dry seasons is recommended to reduce the water shortage amount, increase resilience, and increase the availability. Figure 6 shows the amounts of annual maximum water shortage, 17.7, 126.7, and 169.1 thousand cubic meters per day in the return periods of 2, 5, and 10 years, on a logarithmic axis. These values are calculated based on the sorted annual maximum water shortage from the simulated 200-year water supply and demand data.

Table 4. Analysis of water shortage of Formosa Plastics Corporation (FPC) under baseline.

Max. R (%)	DPD_{50} (%-Day)	MTTR (Ten-Day)	Max. TTR (Ten-Day)	Availability (%)
80.82	62.53	1.53	7	0.94

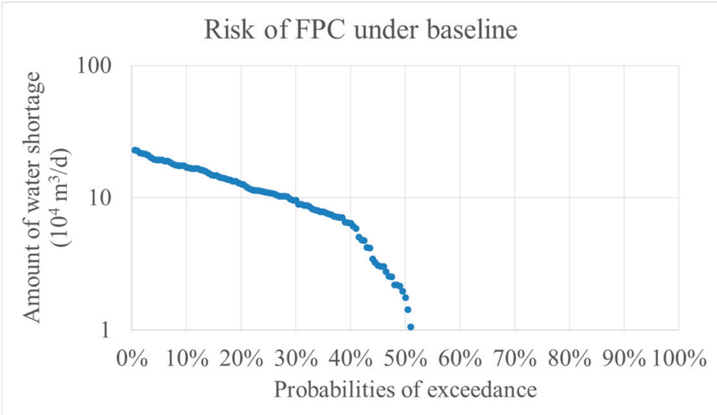

Figure 6. Probabilities of exceedance of the annual maximum water shortage amounts on a logarithmic axis.

4.2.4. Future Climate Risk Assessment

The future risk assessment includes generating future weather data and analyzing risks in future climate and social-economic scenarios. In the wet seasons, most climate projections show higher precipitation in the future than in the baseline at RCP 8.5, whereas slightly less precipitation is found at RCP 4.5. In the dry seasons, all climate projections show less precipitation in the future climate scenarios. Because of the low precipitation in the dry seasons, small disruptions to the models may significantly change the modeling results. This behavior is exemplified by climate projections that show less precipitation at RCP 4.5 than RCP 8.5, such as CESM1-CAM5 and HadGEM2-AO. Then, the generated weather data based on different climate scenarios is used in the GWLF model. In the climate and social-economic scenarios, the daily public and FPC water demands estimated from the official report are 282 and 365 thousand cubic meters, respectively [33]. The changes in irrigation water demands are 3.2–20.2%.

The changes of flows in the wet and dry seasons in the baseline and future scenarios are shown in Figure 7, which include Lishi Creek, Chingshui Creek, and Chenyiulan Creek. In the wet seasons, the flows increase at RCP 8.5 but decrease at RCP 4.5 for almost all climate projections of the GCMs. In the dry seasons, the flows decrease at both RCP 8.5 and RCP 4.5 for almost all climate projections. Affected by the climate projections of the precipitation, CESM1-CAM5 and HadGEM2-AO show less flows at RCP 4.5 than at RCP 8.5. To summarize, it is notably likely that the upstream flows decrease in the dry seasons in future climate scenarios, which magnifies the risk of water shortage. Moreover, the climate projections vary in the wet seasons for two RCP scenarios. It is recommended to consider both climate projections as possible scenarios and evaluate the risk of the worst case for adaptation planning.

According to the simulations of river flows and water allocations, the public water demand of Yunlin in the period of 2021–2040 is 286 thousand cubic meters per day. The water resources is from the conjunctive use of surface water from Jiji Weir and Hushan Reservoir. The water supplies within the tolerance of water shortage (e.g., SI = 1) can satisfy the requirements of public use in the future climate and social-economic scenarios, except the climate projection of CESM1-CAM5 at RCP 4.5 with daily deficits of 18.8 thousand cubic meters. The water shortage ratios of agricultural use are shown in Figure 8. The water shortage ratios and interquartile range increase in the dry seasons, the latter of which indicates high model uncertainties. The model uncertainties of GCMs are higher at RCP 4.5 than at RCP 8.5. The increases in water shortage ratios of Changhua at RCP 4.5, shown in percentages in the figures, are 6.2% and 10.0% in the wet and dry seasons, respectively. For Yunlin, 3.1% and 5.2% are found at RCP 8.5, and 6.5% and 6.1% are found at RCP 4.5. In summary, the water shortage of irrigation increases from 5.2% to 10.0% in the dry seasons for different climate projections, which is consistent with previous studies that find the exacerbation of drought in the dry seasons in Taiwan [20]. Moreover, the relatively less water shortage of the 32th to 36th ten-day period in Changhua enlightens FPC in identifying the adaptation options. More specifically, investing in reducing the water shortage of Changhua in these periods may benefit the water use of FPC in the dry seasons.

The simulated water shortage ratios of FPC in the period of 2021–2040 are shown in Figure 9. The no-climate-change scenario implies using the generated weather data of the baseline with the estimated future water demands. In the no-climate-change scenario, the ratios in the dry seasons still increase compared to the baseline because of the increased water demand of FPC. The increasing water shortage ratios are found for most climate projections compared to the baseline with 42.2% and 48.6% on average for RCP 8.5 and 4.5, respectively. The increase in water shortage ratio for FPC is more than four times of that for the agricultural use, which provides sufficient motivation to FPC to invest in adaptation planning. The indicators of water shortage are analyzed and shown in Figure 10. The results show that Max. R, DPD_{50}, and the average and maximum time for a malfunctioned system to work are most likely to increase, and the percent of average function states of the system decreases. Thus, the water shortage becomes more severe, whereas the resilience and availability of that decrease in the future climate and social-economic scenarios.

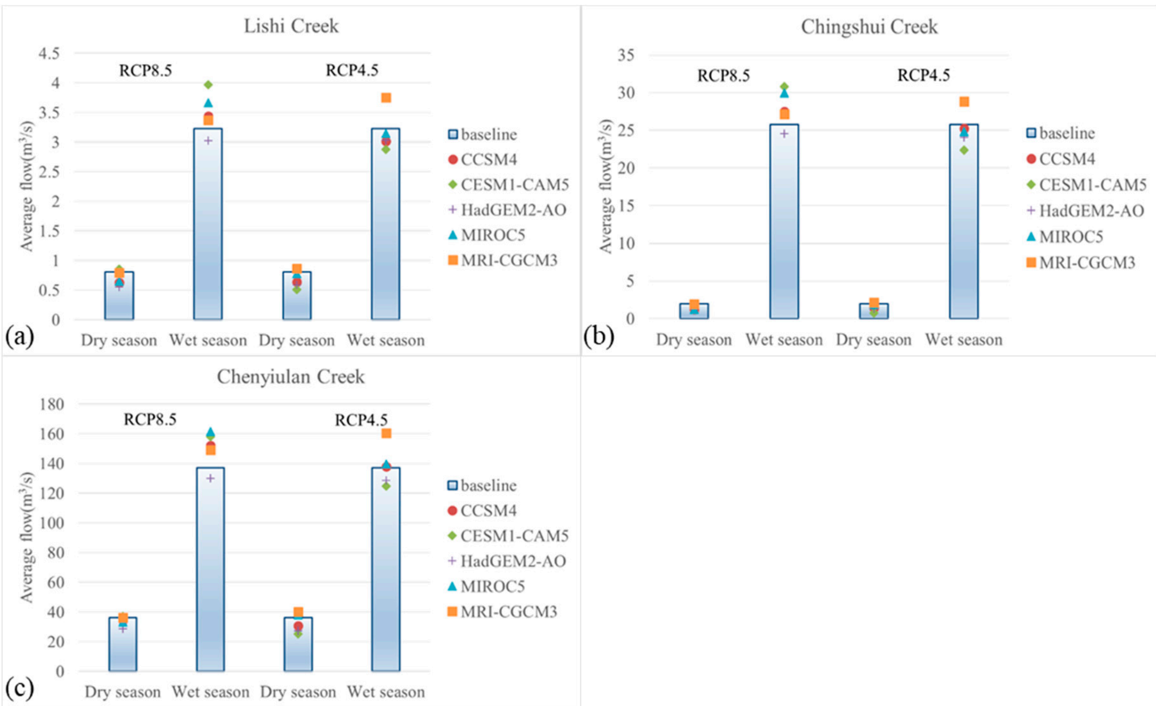

Figure 7. Changes of flows of Lishi Creek (**a**), Chingshui Creek (**b**), and Chenyiulan Creek (**c**) in the wet and dry seasons under baseline and future scenarios.

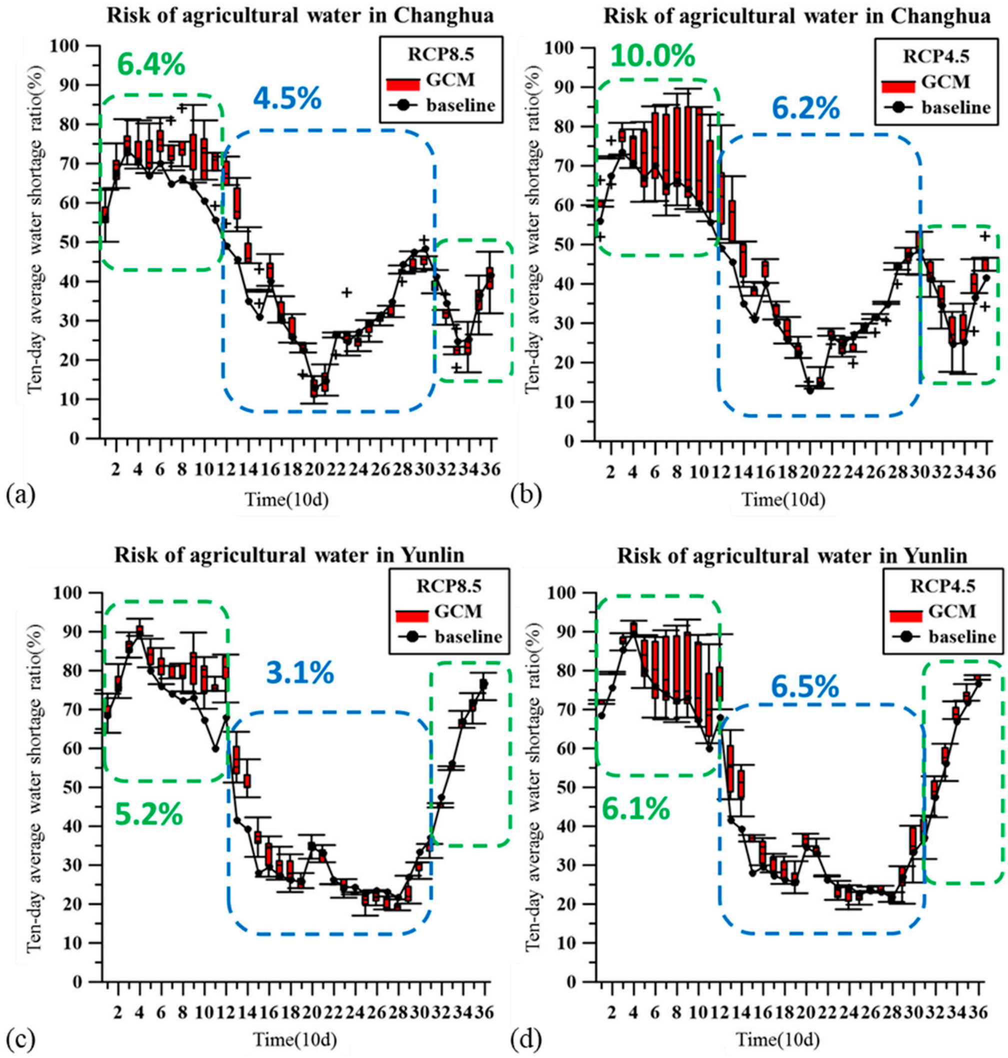

Figure 8. Water shortage ratio (R) of the irrigation water in Changhua under RCP 8.5 (**a**) and RCP4.5 (**b**) and in Yunlin under RCP 8.5 (**c**) and RCP4.5 (**d**).

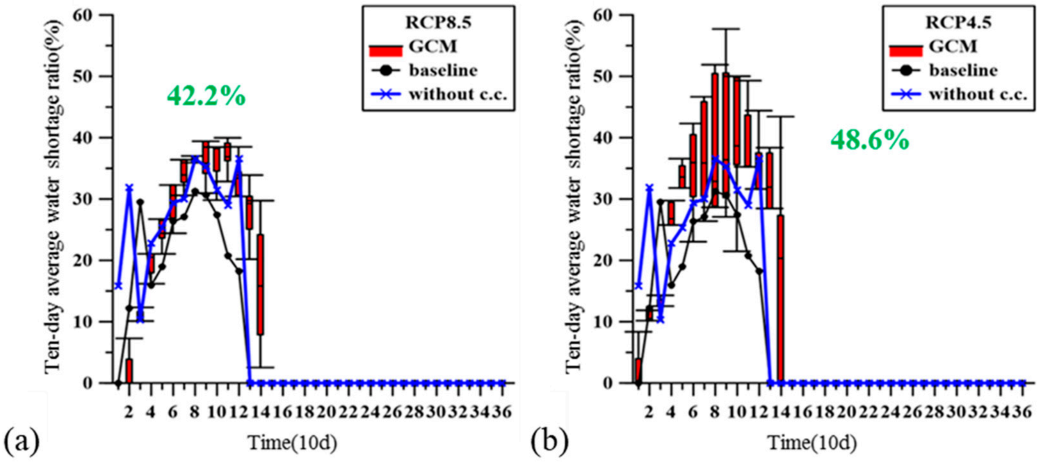

Figure 9. Water shortage ratio (R) of Formosa Plastics Corporation (FPC) under RCP 8.5 (**a**) and 4.5 (**b**) (The abbreviation without c.c. means the baseline weather data and future water demand are used in simulation).

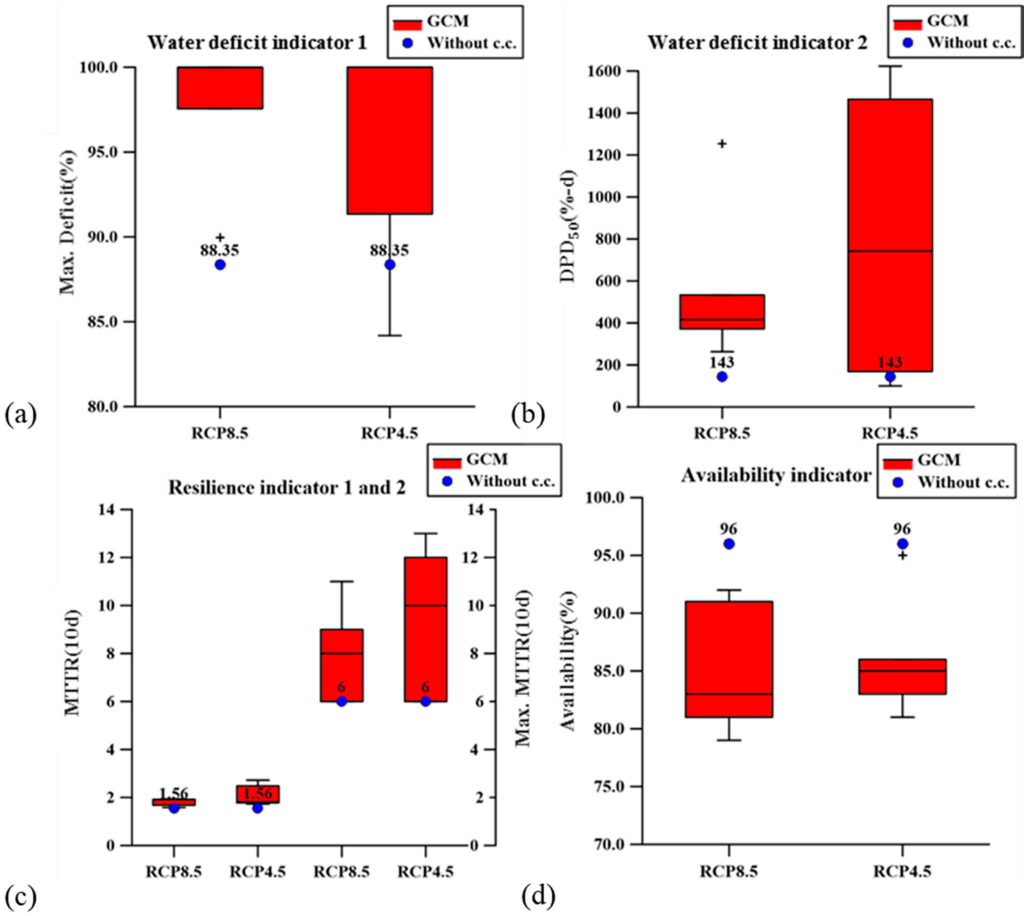

Figure 10. Values of Max. R (**a**), DPD_{50} (**b**), MTTR and Max. TTR (**c**), and Availability (**d**) for water shortage of Formosa Plastics Corporation (FPC) in 2021–2040.

The corresponding probabilities of exceedance are calculated based on the sorted amounts of annual maximum water shortage, from the 200-year simulated water supply and demand data (Figure 11). The amounts of annual maximum water shortage of FPC in different climate and social-economic scenarios are listed in Table 5. Although few scenarios show the decreasing water shortage, others show more severe water shortage than the current and no-climate-change scenarios. In addition, the study calculates the amounts of ten-day water shortage based on 200-year data of irrigation water supply and demand and obtains the annual average amounts of water shortage. The results show that the amounts increase in all scenarios. The worst scenario is the climate projection of the CESM1-CAM5 model at RCP 4.5 for both Changhua and Yunlin with additional 493 and 374 million cubic meters water deficit compared to the no-climate-change scenario, respectively. Thus, the reduction in irrigation loss and increase in water-use efficiency are necessary to reduce the water shortage of agricultural use. FPC buys water from agricultural use in the dry season and may consequently inherit the increasing risks of the agricultural water use. The difference in risks of FPC between the baseline and the future scenarios is analyzed. Table 6 shows increasing Max. R, DPD_{50}, MTTR, and Max. TTR and decreasing Availability in the future.

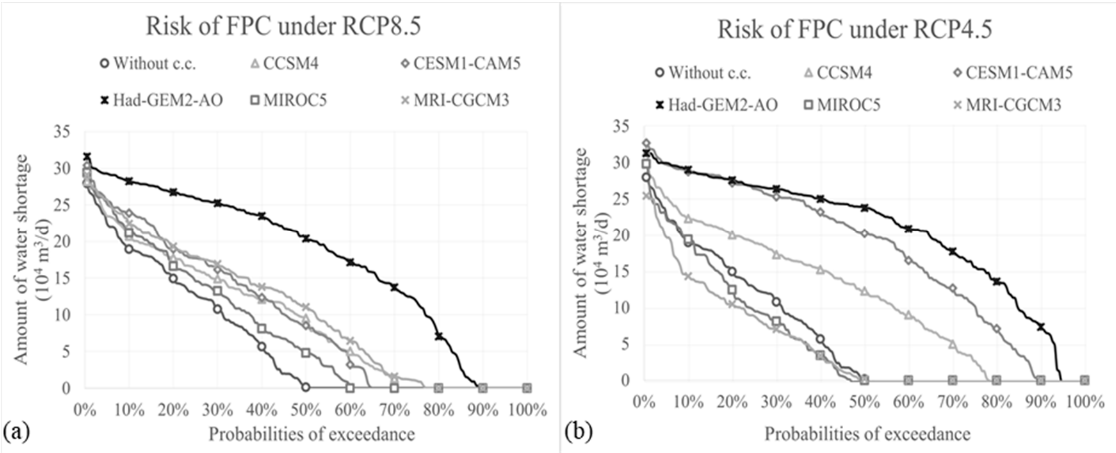

Figure 11. Probabilities of exceedance of the annual maximum water shortage amounts under RCP 8.5 (**a**) and 4.5 (**b**).

Table 5. Analysis of maximum amount of water under different return periods and scenarios.

Return Period (Year)/Scenarios		2	5	10
Current		1.77	12.67	16.91
2021–2040		0.15	14.96	18.95
RCP8.5	CCSM4	9.56	17.75	20.73
	CESM1-CAM5	8.56	18.99	23.90
	Had-GEM2-AO	20.41	26.77	28.26
	MIROC5	4.80	16.63	21.21
	MRI-CGCM3	11.07	19.31	22.45
RCP4.5	CCSM4	12.27	20.04	22.31
	CESM1-CAM5	20.23	27.22	28.73
	Had-GEM2-AO	23.77	27.57	29.02
	MIROC5	0.00	12.46	19.38
	MRI-CGCM3	0.19	10.49	14.33

Table 6. Difference of risks of FPC water use under baseline and future scenarios.

Indicators		Max. R (%)	DPD_{50} (%-d)	MTTR (Ten-Day)	Max. TTR (Ten-Day)	Availability (%)
No-climate-change scenario		7.53	84.29	0.03	−1	0.02
RCP4.5	CCSM4	19.18	676.70	0.25	6	−0.13
	MIROC5	10.53	106.16	0.29	−1	0.01
	HadGEM2-AO	19.18	1529.09	0.95	3	−0.09
	CESM1-CAM5	19.18	1437.38	1.19	5	−0.11
	MRI-CGCM3	3.36	39.53	0.20	−1	−0.08
RCP8.5	CCSM4	19.18	369.91	0.39	2	−0.02
	MIROC5	19.18	215.90	0.41	−1	−0.11
	HadGEM2-AO	19.18	1181.13	0.38	4	−0.15
	CESM1-CAM5	16.74	323.12	0.15	1	−0.13
	MRI-CGCM3	9.14	498.40	0.05	−1	−0.03

4.3. Identifying and Assessing the Adaptation Options

4.3.1. Identifying the Adaptation Options

The adaptation options are defined from the viewpoints of FPC. However, the adaptation measures that the government proposed for the watershed where FPC is located must be considered. Most adaptation options are implemented by the regional authorities, whereas some may require local collaboration such as rainwater harvesting, waste-water recycling, and on-site desalination plant. The regional adaptation planning is likely slowly realized. Therefore, FPC also considers the smart agricultural water management as a feasible adaptation option. This study discusses with the FPC and determines three most feasible adaptation options as follows.

1. Water reuse and investment in a desalination plant.
2. Development of smart agricultural water management to save water.
3. Rainwater harvesting.

The location of FPC is beneficial to use water from its on-site desalination plant. Moreover, the nearby Yunlin industrial water treatment facility and Douliu water recycle center reduce the cost of FPC in reusing water from the public sectors. The options also include reducing the leakage rate of agricultural irrigation channels, promoting the drip irrigation technology, and using the agricultural return water. The reason is that FPC can financially invest in both research and technology development, which is notably beneficial with a relatively small investment because the agricultural use accounts for the largest water demand. Moreover, FPC is near the Changhua and Yunlin irrigation areas, which also uses water from Jiji Weir and can directly benefit from the saved water in the watershed. In addition, the implementation of rainwater harvesting for FPC is a flexible and low-cost decentralized adaptation option with relatively small effects to the ecosystem.

4.3.2. Evaluating the Adaptation Options

The study evaluates the effects of three adaptation options on reducing the risk of water shortage of FPC. The effects of the adaptation options through literature review and modeling estimation are shown in Table 7. Then, the water supply system dynamics model is used to examine the risk of FPC. The results are compared with the amounts of water shortage in 2021–2040 without adaptation to examine the relative performances of the options. The effects of the no-adaptation option are unchanged as the results in the future climate risk assessment. This study evaluates the effects of the options by calculating the water shortage of the ten-year return period as severe events affect the production, which is from the 10% water supply reduction of industries in 2015. The amounts of water shortage for no-climate-change, RCP 4.5, and RCP 8.5 scenarios are shown in Figure 12. The first option is the most effective one in reducing Max. R and DPD_{50} and increasing the resilience and availability. More specifically, the first option reduces 146.8 thousand cubic meters per day, whereas the second option reduces 36.3 thousand cubic meters per day in a no-climate-change scenario. The reason is that the waste-water reuse and sea-water desalination directly support the water use of FPC, and the smart agricultural management primarily benefits the other water users. In future climate and social-economic scenarios, the first option reduces the water shortage amounts 33–44% per day in the return period of ten years. As a result, the option of waste-water recycling and desalination is recommended for FPC.

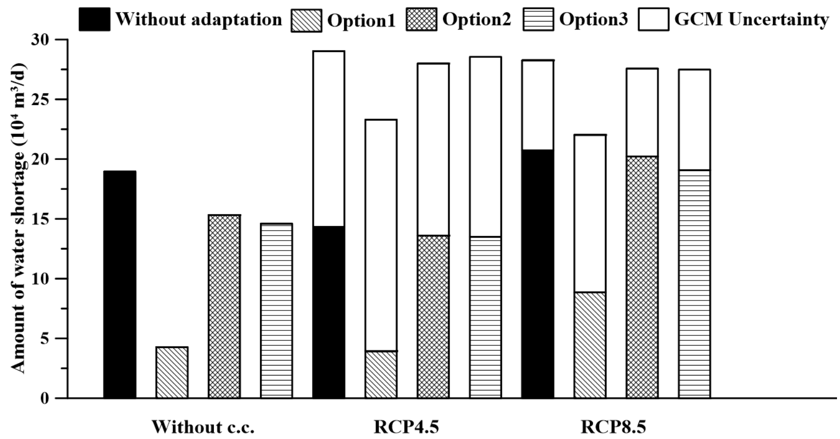

Figure 12. Amounts of water shortage of Formosa Plastics Corporation (FPC) under ten-year return period.

Table 7. Adaptation options and the expected effects.

Case	Measures	Expected Effect
Option 1	Waste-water recycling	6.3×10^6 m^3/year [1]
	Desalination	3.65×10^7 m^3/year [2]
Option 2	Reducing the leakage rate of agricultural irrigation channels	Saving 6.55×10^8 m^3/year [3]
	Promoting drip irrigation technology(Intelligent water-saving management system)	Saving 2.25×10^8 m^3/year [4]
	Using agricultural return water	4.03×10^8 m^3/year [5]
Option 3	Rainwater harvesting system	3.9×10^6 m^3/year [6]

Notes: [1] Using data of FPC in 2015 as an example, 17,308 m^3/d × 365 d/year = 6.3×10^6 m^3/year. [2] Using data of FPC in 2015 as an example, 10^5 m^3/d × 365 d/year = 3.65×10^7 m^3/year. [3] Estimated value. The Council of Agriculture (2013) [35] expected the water-saving effect to be 70 m^3/m/year; the total length of the irrigation channels of Changhua and Yunlin is 9,355,730 m. 9,355,730 m × 70 m^3/m/year = 6.55×10^8 m^3/year. [4] Estimated value. The Council of Agriculture expected the drip irrigation saving 2000 m^3/ha compared to traditional techniques such as furrow irrigation and flood irrigation [35]; the total irrigation area of Changhua and Yunlin is 112,545 ha. 112,545 ha × 2 × 10^3 m^3/ha/year = 2.25×10^6 m^3/year. [5] Estimated value. The return water of Changhua and Yunlin are 800,064 m^3/d and 304,128 m^3/d, respectively [36]. (800,064 + 304,128) m^3/d × 365 d/year = 4.03×10^8 m^3/year. [6] Using data of FPC in 2015 as an example, 10,594 m^3/d × 365 d/year = 3.9×10^6 m^3/year.

5. Discussion

Because the water rights of public and agricultural uses are prioritized over FPC, the water shortage of agriculture and FPC in the Chuoshui River watershed are identified in the current climate risk assessment. The results confirm the importance of the research goals, which is to minimize the risk of water shortage for FPC. Moreover, the results of the baseline climate risk assessment approach that of the current climate risk assessment, which indicates that the generated weather data and estimated water demands can provide reliable results of the climate risk assessment for different water uses. The future climate risk assessment shows that the public water use may still be fulfilled if the Shortage Index (SI) is equal to 1. The main reason is that the Hushan Reservoir supplements the deficit of the water supply of Jiji Weir. The more severe water shortage of agriculture and FPC in the dry seasons ensures the necessity of implementing after identifying and evaluating the adaptation options. The causes of increasing risks help identify proper adaptation options. Increasing hazard is caused by the exacerbated variation of precipitation in the wet and dry seasons. The larger exposure originates from the increasing water demand for industrial and agricultural use because of the development of industrial park and potential increasing evapotranspiration in the future, and it further affects the FPC water use. Moreover, insufficient water supply facilities and capacities cause high vulnerability when there are increasing demands, particularly in the dry seasons.

This study shows the identified adaptation options are able to reduce the risk of water shortage in the dry seasons. The study collects the related adaptation measures from official reports and determines the feasible adaptation options for FPC. The study mentions briefly the cost, location, effects on ecosystem of the adaptation options and also quantifies the effectiveness of the adaptation options. Detailed analyses on the principles to select feasible options including the location, technology, financial resources of an industrial company concerning the adaptation options are left for future studies focusing on implementing the adaptation options. The adaptation option, which consists of waste-water reuse and sea-water desalination, is the most effective one among the selected options. It implies the necessity of evaluating the effectiveness of each adaptation option using the system dynamics model of the watershed. Instead of only analyzing the expect effect of individual adaptation option, the water resources directly supply FPC should be evaluated considering the water resources in the entire watershed. Then, the results are generalized for the reference of other studies. The risk assessment and adaptation measure identification of the company require regional information. Moreover, some adaptation measures that the company implements help reduce the water shortage of the region and benefit the company itself.

6. Conclusions

The objective of the adaptation of FPC is to minimize the risk of water shortage. The risk assessments and the adaptation measures of the watershed are considered as boundary conditions because the water use of FPC is influenced by the water supply and demand of other users. FPC has to analyze the risks or adaptation measures by itself because the information is not provided by either the central or the local governmental agencies. The study uses the observed flow data to verify GWLF model and water supply system dynamics model. The simulation of the flow of Jiji Weir is consistent with the observation as a whole, which shows that the models are representative for the simulation of the water resources allocations of the study area. The water shortage of FPC is mainly in the dry seasons because the water rights of public and agricultural uses are prioritized over industrial use. Based on the regional adaptation measures proposed by the government, FPC can either invest in existing measures or implement additional on-site measures on its own. The considered adaptation options including water reuse, a desalination plant, smart agricultural water management, and rainwater harvesting. The results show that the waste-water reuse and sea-water desalination are the most effective adaptation options, which reduces the water shortage risks 33–44% per day in the return period of ten years.

A qualitative goal should be set up at the beginning of adaptation planning, and the tolerance of water shortage for a company should be set to more precisely assess the risks and evaluate the adaptation options. This study estimates the agricultural water demand in future climate and social-economic scenarios, but the planting area and type of plant in the future social-economic scenarios are assumed unchanged. Future studies that analyze the changes of these parameters in the future will more realistically estimate the future agricultural water demand. In addition to the effectiveness of each adaptation option in reducing risks, other criteria such as the feasibility and uncertainty can be considered. The results of the study show that the risk assessment and adaptation options proposed by the governments for a region help a company build the adaptation capacity. To ensure the effects of climate change adaptation, further research on planning and implementing the adaptation pathways and monitoring and modifying the adaptation plan is required. The considerations of both governmental regional adaptation options and private company's on-site measures to develop adaptation pathways are necessary in future studies, to dynamically respond to future climate and social-economical changes. By developing, monitoring, and modifying the adaptation pathways, a company is more likely to achieve its goal of adaptation and maintain the risk of water shortage within the acceptable level in future climate and social-economic scenarios.

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Conflicts of Interest: The authors declare no conflict of interest.

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