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Applying the HSPF model to predict watershed responses under the impact of climate change

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Abstract: - The objective of this study is to identify the changes in rainfall characteristics and to predict the possible environmental responses in the Shihmen Reservoir watershed in Taiwan under the climate change scenario. These objectives are made possible by looking at officially released rainfall projection data in Taiwan, and by applying the Hydrological Simulation Program-Fortran (HSPF) model, which is used to simulate hydrologic responses and diffuse pollution projections. The results show that while the change of annual precipitation is not obvious, seasonal variation and intensity of rainfall increase under the climate change scenario. Furthermore, the increase of rainfall intensity during certain seasons enlarges landslide areas and increases environmental vulnerability. Compared to diffuse pollution, the impact of climate change on hydrologic responses is difficult to control. Therefore, disaster management continues to have critical importance in achieving sustainable environmental management.

Key-Words: - climate change; diffuse pollution; HSPF; landslide.

1 Introduction

Water resources in a country are influenced by the spatial and seasonal variation of rainfall, as well as the country's unique topography. These rainfall and topography factors have a crucial impact on available water resources, which contribute to environmental vulnerability [1]. In addition to these factors, the impact of climate change is also an important concern. Various studies have reported that climate change increases the likelihood of natural disasters, such as landslides, floods, and droughts [2, 3], and even impacts water quality and river ecosystems [4, 5, 6].

These factors impact our living environment and therefore offer potentially severe problems for Taiwan. Many studies have demonstrated that extreme rainfall events frequently occur in Taiwan, and spatial and seasonal variation becomes increasingly serious [7, 8, 9, 10, 11, 12]. For example, Chen *et al.* (2009) and Chen *et al.* (2013) indicated that the meteorological drought has increased in southern Taiwan since 1960. Yu *et al.* (2015) investigated the projected streamflow drought in southern Taiwan under climate change and reported that streamflow under future scenarios during the dry period tends to decrease in January and February, yet increase in March and April. Hsu and Chen (2002) and Yu *et al.* (2006) concluded that the amount of precipitation has been increasing in northern Taiwan over the last century. Chen *et al.* (2010) proposed a statistical downscaling method for projection of daily precipitation, and claimed an increase in extreme precipitation events in northern Taiwan. These studies reveal the observed and projected hydrologic changes in Taiwan. Still, the impact of climate change on environmental factors, such as landslide and water quality, is also an important issue for our living environment.

Changing rainfall characteristics influence environmental responses in a watershed [13]. The objective of this study is to identify these changes and to investigate the variation of landslides, hydrologic responses, and the amounts of diffuse pollution in a watershed in response to rainfall changes under a climate change scenario. This study applies the Hydrological Simulation Program-Fortran (HSPF) model to predict the variation of hydrologic responses and the amounts of diffuse pollution when rainfall characteristics and landslides change. Predicting the variation of watershed responses under the impact of climate change is crucial for sustainable watershed management.

2 Methods

2.1 Watershed description and hydrologic data

The Shihmen Reservoir watershed, which is located in northern Taiwan and covers an area of about 760 km^2, provides the setting for this case study. Most of the land-use in this watershed is forest (about 720 km^2). Although the total area of landslides in this watershed is less than 5 km^2, landslides are still a major source of soil erosion and diffuse pollution. When the diffuse pollution flows into the reservoir, it may influence the reservoir water quality and impact the normal functions of the reservoir, particularly for the public water supply.

Fig. 1 shows three rainfall stations, Paishih, Kalaho, and Kaoyi, in the Shihmen Reservoir watershed. This study collects daily rainfall data, daily streamflow data, and daily reservoir inflow data from the reservoir authorities. By using the Thiessen polygon method, the weights of the Paishih, Kalaho, and Kaoyi stations are calculated as 0.33, 0.27, and 0.40, respectively. The average precipitation of the Shihmen Reservoir watershed can be estimated according to the rainfall records and the weights of these stations.

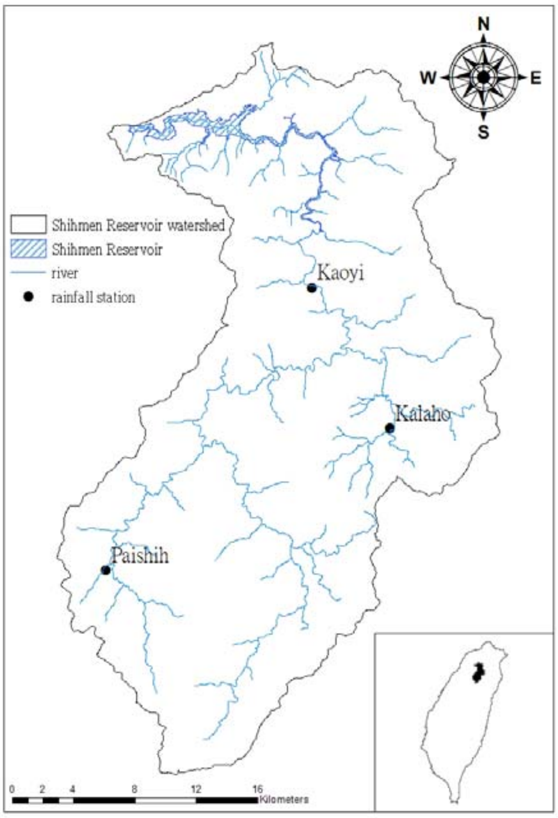


Fig. 1 Case area: the Shihmen Reservoir watershed

2.2 Scenario data under climate change

The climate change projection data in the case area are available from the Taiwan Climate Change Projection and Information Platform Project (TCCIP), provided by the National Science and Technology Center for Disaster Reduction in Taiwan. The TCCIP dataset is officially released climate projection data that is used to investigate climate change impacts in Taiwan. The TCCIP provides downscaled monthly rainfall changes according to the climate projections from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. The climate projections are based on the IPCC's Special Report on Emissions Scenarios (IPCC SRES, 2000) that describes four emission scenarios: A1, A2, B1, and B2. These scenarios contain various driving forces of climate change, including population growth and socio-economic development. Scenario A1 is divided into three subsets—A1FI, A1T, and A1B—which represent different directions of technological change in climatology. This study considers the climate change scenario A1B to be the most favorable when concerning a balanced approach to understand energy consumption, and so forms the best research backdrop to find the most appropriate sustainable environmental system.

The TCCIP database provides downscaled monthly rainfall changes from different climate models under various scenarios. The water authorities in Taiwan suggest the use of average model outputs under scenario A1B to have a common basis in assessing the climate change impacts on different fields. The monthly rainfall changes provided by the TCCIP database are defined based on the baseline from 1980 to 1999 and the projection period from 2020 to 2039. The TCCIP database does not have downscaled daily rainfall information. Thus, this study utilizes the rate of monthly rainfall change to obtain the projected daily rainfall within a watershed. That is, the observed daily rainfall data within a certain month in the baseline are multiplied by the rate of monthly rainfall change to acquire the projected daily rainfall data within that month in the projection period.

2.3 Watershed model—the HSPF model

The Better Assessment Science Integrating point & Non-point Sources (BASINS) model—developed by the United States Environmental Protection Agency—is an integrated decision-making system and a geographically-based watershed assessment tool that can connect with and grab information from the geographic information system. The HSPF model, which is one module of the BASINS model, has been popularly applied in the prediction of hydrologic responses, pollution transportation, and water quality responses in watershed environments [14, 15]. This study applies the HSPF model to predict the variation of hydrologic responses and the amounts of diffuse pollution under the impact of climate change. Because there is no water quality monitoring station in the case area, this study collects the parameters of watersheds surrounding the case area from previous studies to obtain the required parameters of the HSPF model.

3 Results and Discussion

3.1 Impact of climate change on rainfall characteristics

This study compares the observed rainfall characteristics in the baseline from 1980 to 1999, and the projected rainfall characteristics in the projection period from 2020 to 2039 in the Shihmen Reservoir watershed. Table 1 shows the change of average annual precipitation and the changes of precipitations during the rainy season (from May to October) and the dry season (from November to April) over these two periods. The average annual precipitation was 2,492 mm in 1980-1999 and is projected to be 2,467 mm in 2020-2039, indicating a slight decrease in annual precipitation under the current climate change scenario.

Table 1 Change of rainfall characteristics

Rainfall characteristics	Period		Increased rate
	1980-1999	2020-2039	
Average annual precipitation (mm)	2492	2467	-1.01%
Average precipitation during the rainy season (mm)	1755	1765	0.55%
Average precipitation during the dry season (mm)	737	702	-4.72%
Precipitation ratio	2.38	2.51	5.54%

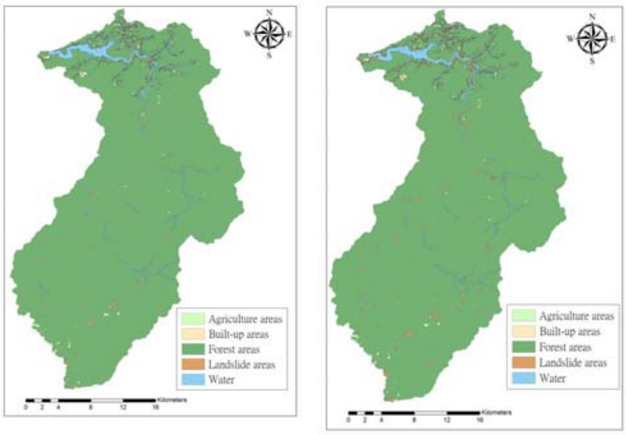
Note: Precipitation ratio is the ratio of the precipitation during the rainy season to that during the dry season.

The average precipitations during the rainy season and the dry season were 1,755 mm and 737 mm, respectively, in the period from 1980 to 1999. The projected average precipitations during the rainy season and the dry season will be 1,765 mm and 702 mm, respectively, in the period from 2020 to 2039, which indicates that the seasonal variation of rainfall will widen. The precipitation during the rainy season will have a 0.55% increase, while the dry season will have a 4.72% decrease. The ratio of the precipitation during the rainy season to that during the dry season is defined as the precipitation ratio herein. The precipitation ratio was 2.38 in the baseline and is set to increase to 2.51 in the projection period, signifying a rise of 5.54% in precipitation ratio. The projection of an intensified precipitation ratio under the climate change scenario indicates that water resources vary significantly and water environment management will become increasingly important.

3.2 Impact of climate change on landslide areas

Without watershed conservation and environmental protection, as rainfall intensity increases, landslide areas will certainly increase. However, it is difficult to predict landslide areas that are a result of changing rainfall characteristics. Chen (2011) compared rainfall intensities of Typhoons Morakot and Toraji, as well as the changes of landslide areas during these two typhoons, and developed a linear relationship between the changes in rainfall intensity and the increase in landslide area. Based on the findings in Chen (2011), our study predicts the variations of landslide area resulting from changing rainfall intensity, including the change in the precipitation ratio [16].

As rainfall intensity increases, landslide areas grow in size. The precipitation ratio increases by 5.54% under this climate change scenario, showing that the landslide areas in the Shihmen Reservoir watershed can enlarge to twice their original size. Though it is difficult to predict the exact location of increased landslide areas, we know that erosion potential and land vulnerability is higher surrounding the existing landslide areas and in areas with a slope larger than 30%. Thus, this study applies buffer analysis and overlap analysis to figure the increased landslide areas, as shown in Fig. 2.



(Baseline:1980-1999) (Future period:2020-2039)

Fig. 2 Change of landslide areas

3.3 Impact of climate change on hydrologic responses

The change of rainfall characteristics and landslide areas influence hydrologic responses in the Shihmen Reservoir watershed. Table 2 shows the variation of hydrologic responses, such as peak flow, average annual flow, and average flows during the rainy season and the dry season, as simulated by the HSPF model. The peak flow was 1,590 cm in the period from 1980 to 1999. Under the climate change scenario, the peak flow will increase by 17%, while the peak flow will be 1,859 cm in the projection period from 2020 to 2039. In the baseline, the average flows during the rainy and dry seasons were 37.31 cm and 19.07 cm, respectively, while the projected average flows during the rainy and dry seasons will be 37.27 cm and 18.39 cm, respectively. The results indicate that the change of average flow is not as obvious as the variation of peak flow under the climate change scenario.

Table 2 Change of hydrologic responses

Hydrologic responses	Period		Increased rate
	1980-1999	2020-2039	
Peak flow (cm)	1590	1859	16.92%
Average annual flow (cm)	28.26	27.91	-1.25%
Average flow during the rainy season (cm)	37.31	37.27	-0.10%
Average flow during the dry season (cm)	19.07	18.39	-3.54%

Furthermore, as watershed conservation strategies are implemented in the case area to avoid any increased landslide areas (to maintain the present condition of land use), the variation of hydrologic responses—peak flow in particular—is still large. The projected peak flow will be 1,848 cm under the present land use scenario (with only a little less than 1,859 cm under the enlarged landslide scenario), because of the variation in projected rainfall. Thus, disaster management is important when facing the impact of climate change.

3.4 Impact of climate change on the amounts of diffuse pollution

As rainfall characteristics, landslide areas, and hydrologic responses vary under the climate change scenario, the amounts of diffuse pollution from the watershed are consequentially influenced by these variations. Table 3 shows the variation of diffuse pollution responses, such as annual loads of suspended solids (SS) and total phosphorus (TP). The amounts of diffuse pollution under different scenarios are simulated by the HSPF model. The annual loads of SS and TP were 3,988,447 kg/yr and 16,873 kg/yr in the baseline from 1980 to 1999. The projected annual loads of SS and TP will be 4,367,176 kg/yr and 18,865 kg/yr, respectively, in the projection period from 2020 to 2039. The results indicate that the variation of rainfall, landslide areas, and hydrologic responses will result in a 10% increase of SS and a 12% increase of TP.

Table 3 Change of diffuse pollution responses

Diffuse pollution responses	Period		Increased rate
	1980-1999	2020-2039	
SS (kg/yr)	3988447	4367176	9.50%
TP (kg/yr)	16873	18865	11.81%

4 Conclusions

This study compares the rainfall in the baseline from 1980 to 1999 and the projected rainfall in the future period from 2020 to 2039 and evaluates the variation of landslides, hydrologic responses, and the amounts of diffuse pollution under the climate change scenario A1B. The HSPF model is an important tool for this study to predict hydrologic responses and the amounts of diffuse pollution.

Comparison of the observed rainfall in the baseline and the predicted rainfall in the projection period indicates an increase in rainfall intensity under the climate change scenario. Intensified rainfall can worsen the landslide situation, increase the amount of diffuse pollution, and subsequently deteriorate the water quality. Under the climate change scenario A1B, the change of precipitation ratio is about 5.54%, and the peak flow, SS, and TP have respective increases of about 17%, 10%, and 12%.

Both rainfall intensity and landslide area are projected to increase under the climate change scenario. However, landslide areas can be controlled by implementing suitable soil conservation and watershed management to reduce the impact of climate change on landslides. When effective structural and non-structural soil conservation strategies are implemented in a watershed, the amounts of diffuse pollution, particularly SS, can greatly decrease. However, the control efficiency of hydrologic responses is not satisfied. Although the variation of environmental responses may be different in other watersheds, the findings indicate that disaster management has become increasingly important when facing the impact of climate change.

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