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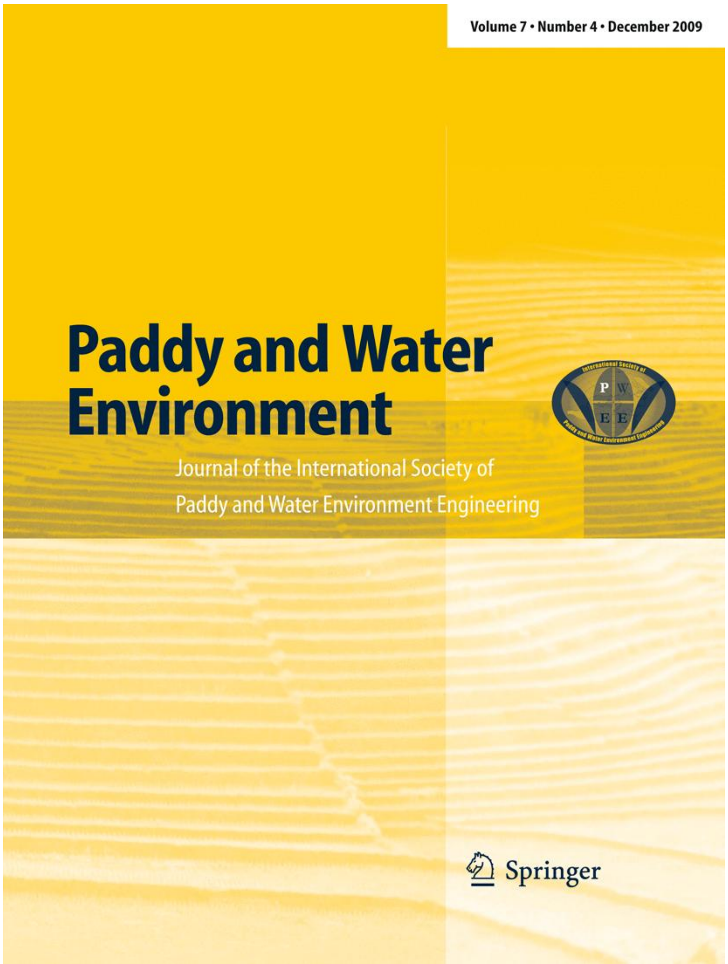

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ARTICLE

Assessing the impact of climate change on annual typhoon rainfall—a stochastic simulation approach

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Abstract Rainfall amount drawn by typhoon events accounts for a significant portion of annual rainfall in Taiwan. Changes in typhoon rainfall due to climate change may have severe consequences for water resources management. A stochastic simulation approach is proposed for evaluation of changes in typhoon rainfall under certain climate change scenarios. The number of typhoon events and total rainfall of individual typhoon events are, respectively, considered as random variables of the Poisson and Gamma distributions. Climate change scenarios were set by varying various degrees of changes in average number of typhoon events annually and the mean of event-total rainfall. Using stochastic simulation, basin-wide annual typhoon rainfalls were simulated for the Shihmen Reservoir watershed in northern Taiwan. It is found that 10% increases in average annual number of typhoon events and mean event-total rainfall will result in 18% increase in the annual typhoon rainfall of 5-year return period, whereas the annual typhoon rainfall of 10-year return period will increase by 15% under the same climate change scenario. Such increases may cause significant increase in reservoir sediment and pose challenges to reservoir management.

Keywords Typhoon rainfall · Stochastic simulation · Climate change

Introduction

In Taiwan and most of the Eastern Asia countries, typhoon rainfalls account for a significant portion of the total annual rainfall. Typhoons are major source of water resources in the region, while at the same time they also trigger devastating disasters such as floods, debris flows, landslides, etc. In addition, high concentration sediments carried in streamflow during and after typhoon events may cause serious water supply problems. For example, a moderate typhoon Aere brought torrential rain (967 mm) to Shihmen Reservoir watershed (see Fig. 1) in northern Taiwan from August 23 through 26, 2004. An estimated 2.788×10^7 m^3 of sediments were delivered into the reservoir pool causing extremely high turbidity in reservoir water. Tap water supply discontinued for more than 2 weeks due to extremely deteriorated source water quality.

On average, typhoon rainfall accounts for approximately 22% of annual rainfall in Shihmen Reservoir watershed. High dependence on typhoon rainfalls for water supply and heavy damages brought about by typhoons make Taiwan particularly vulnerable to impact of climate change on annual typhoon rainfall. Therefore, evaluating the impact of climate changes on annual typhoon rainfall is crucial for water resources management and planning.

Most of climate change studies aiming to assess impact on regional- or local-scale hydrological processes involve usage of general circulation models (GCMs) and some sorts of downscaling techniques (Li and Sailor 2000; Hanson and Dettinger 2005; Ghosh and Mujumdar 2006; Xu et al. 2007). However, the scenarios set for GCMs are not directly linked to basin-scale hydrological processes, even though most practices of water resources management and measures that should be taken to cope with potential climate changes are essentially in basin-scale. Furthermore,

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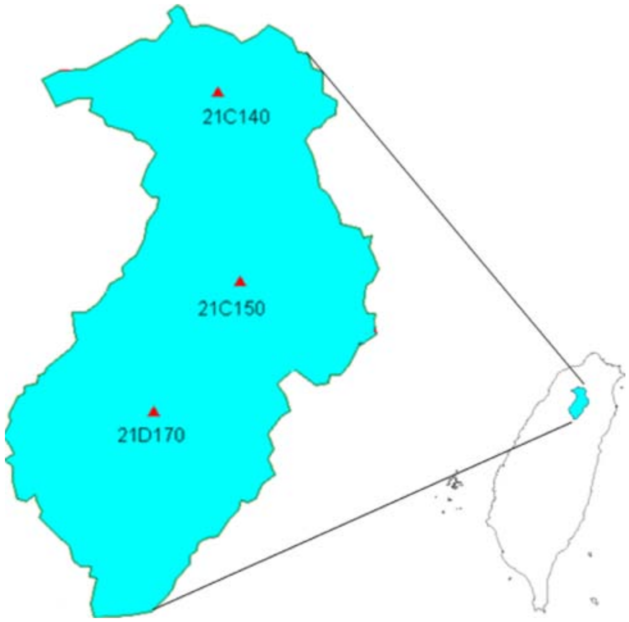

Fig. 1 Locations of Shihmen Reservoir watershed and three rain stations selected for this study

downscaling techniques (either dynamic or statistical) inevitably introduce uncertainties to projected changes, and such uncertainties often are not quantitatively addressed or are ignored in reports of climate change assessment. Stochastic simulation of typhoon occurrences and total rainfall of individual typhoon events are thus necessary to assess the uncertainties of climate change impact on annual typhoon rainfall. In light of the importance of typhoon rainfall for Taiwan's water management, this study aims to assess the impact of climate changes on annual typhoon rainfall from a stochastic point of view.

Study area and rainfall data analysis

The Shihmen Reservoir watershed in northern Taiwan was selected for this study. It encompasses a total area of 763 km^2, and the reservoir is a major source of water supply for northern Taiwan. Fifty-one years (1957–2007) of hourly rainfall data at three raingauge stations (21C140, 21C150, and 21D170) were collected.

Partitioning storm events for typhoon rainfall extraction

Typhoons typically occur in between mid June and mid November in Taiwan. During that time period, there are also summer convective storms which are characterized by short durations (usually less than a few hours) as compared to typhoon events. In order to differentiate typhoons and convective storms and to extract rainfall data of typhoon events, two criteria—the minimum interevent time and minimum storm duration—are need. The interevent time is defined as the time span from the end of a storm event to the beginning of the next event. Typhoons are tropical cyclones and they generally consist of a few spiral rain bands and thus may bring high intensity and intermittent rainfalls. Because of its intermittent and long duration raining characteristic, a minimum interevent time of 8 h and a minimum duration of 12 h were adopted in this study to extract typhoon rainfall for subsequent analyses. Using these criteria, typhoon events and their corresponding hourly rainfalls at three raingauge stations were extracted. Table 1 lists statistical properties of typhoon rainfall data at these stations.

Modeling storm duration and total rainfall depth

Stochastic simulation is the work of generating random samples of a given probability distribution. Key properties characterizing a random process of storm rainfall include: interarrival time, interevent time, storm duration, total rainfall depth, and time distribution of the total rainfall. Figure 2 depicts these properties of storm rainfall time series.

This study aims to assess the impact of climate change on annual typhoon rainfall. Thus, only the total depth and interarrival time will be considered in subsequent simulation, while the time distribution of total depth and storm duration are not our major concern. Since typhoon season in Taiwan spans from mid June to mid November, the interarrival time and number of typhoon events that may occur in one year are directly related. The number of

Table 1 Properties of typhoon rainfall at three selected raingauge sites

Rainfall properties	Raingauge Station		
	21C140 (0.27)[a]	21C150 (0.31)[a]	21D170 (0.42)[a]
Average number of typhoons per year	3.98	3.78	4.59
Average of event-total rainfall (mm)	149.38	145.39	125.57
Standard deviation of event-total rainfall (mm)	177.79	178.80	165.99

[a] Thiessen's polygon weight

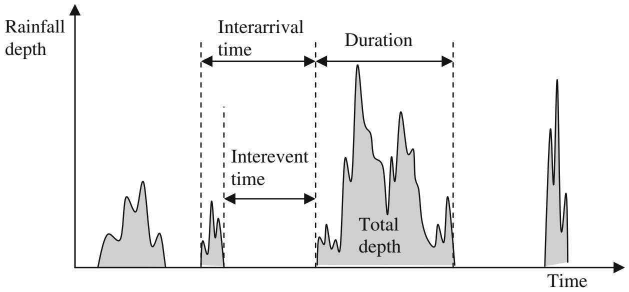

Fig. 2 Parameters of a storm rainfall time series

typhoon events varies from one year to the other, and can be considered as a Poisson random variable of the following probability mass function:

$$p(x;\lambda) = \frac{e^{-\lambda}\lambda^{x}}{x!}, \quad x = 0, 1, 2, \ldots \tag{1}$$

where x represents the number of occurrences in a specified time period (1 year in our study) and λ is the mean number of occurrences, i.e., $\lambda = E(X)$. From Table 1, parameter λ of the three raingauge sites were estimated as 3.98, 3.78, and 4.59 events per year for Station 21C140, 21C150, and 21D170, respectively.

Many studies have shown that flood volume, storm duration, and rainfall intensity of storm events can be characterized by gamma random variables (Yue 2001; De Michele and Salvadori 2003). Chi-square goodness-of-fit test was applied to total depth of typhoon events at the three raingauge stations for hypothesis test of gamma distribution. It was concluded that total depth of typhoon events has a gamma density since the null hypothesis was not rejected at 5% level of significance. The gamma density has two parameters and can be expressed by

$$f(x;\alpha,\beta) = \frac{x^{\alpha-1}e^{-x/\beta}}{\Gamma(\alpha)\beta^{\alpha}}, \quad x \geq 0, \ \alpha > 0, \ \beta > 0, \tag{2}$$

where the shape factor α and scale factor β are related to the mean and variance of random variable X through the following equations:

$$E(X) = \alpha\beta \tag{3}$$

$$\mathrm{Var}(X) = \alpha\beta^{2}. \tag{4}$$

Thus, distribution parameters (α and β) of event-total rainfall at three raingauge stations were estimated using the mean and standard deviation of event-total rainfall of individual stations listed in Table 1.

Setting climate change scenarios

It is generally known that climate change impacts will affect almost all sectors in our life—from agricultural production, water supply, sea-level rise, flooding, drought, forestry, wildfire risk, to public health, and electricity supply. It is now apparent that the more greenhouse gases (GHGs) accumulate in the Earth's atmosphere, the greater the warming and the more severe and costly the impacts will be. Many research works about climate change consider scenarios of future GHG emissions—low, medium high, and high emissions—and explore associated climate changes through modern climate models of differing sensitivity to GHG concentrations.

An assessment report prepared for California Environmental Protection Agency concluded that climate models yield more conclusive projection on increases in temperature, whereas climate model results are inconclusive on projection of changes in precipitation (California Climate Change Center 2006). Another assessment report for the US Global Change Research Program (US-GCRP) also found that GCMs poorly reproduce detailed precipitation patterns (Gleick and Adams 2000). Precipitation relies on meteorological conditions that often occur at scales smaller than GCMs currently resolve. As a result, accurate regional precipitation projections require GCMs with higher resolution and accuracy than the current models provide (Gleick and Adams 2000). Because of the differences between these GCM results, researchers have little confidence in specific regional projections of precipitation. In light of inconclusive projections on regional precipitation by GCMs, we argue that alternative approaches to the assessment of climate change impact on rainfall at regional to local scales are worth pursuing.

Water resources management and hydrological planning and design consider rainfall or flow data at basin-scale in space and hourly, daily, monthly to annual scale in time. Projections of meteorological or hydrological variables in such spatial and temporal scales have not been included in GCMs. Scaling techniques, either dynamic or statistical scaling, are used to extend or extrapolate GCM output to finer scales. However, downscaling from the inconclusive projection of regional precipitation may lead to disastrous decision on future water resources planning and management strategies. In addition, scenarios of future GHG emissions are not directly linked to hydrological variables of major concern in water resources planning. In order to circumvent these difficulties, we adopt an alternative approach of setting climate change scenarios particularly tailored for impact assessment of basin-scale typhoon rainfalls. Our major concerns of climate change scenarios are the annual number of typhoons and amount of rainfall a typhoon event may bring. The rationale of basing our climate change scenarios on these typhoon properties is twofold: (1) typhoons are events of synoptic scale and their occurrences and tracks can be better modeled or predicted by GCMs and (2) properties of typhoon events (for examples, duration, interarrival time, and total rainfall) are key variables in regional and local-scale hydrological modeling and water resources engineering design. In other words, we consider typhoons as a key linkage variable between global scale GCMs and basin-scale hydrological models.

There have been enormous studies on climate change impact on occurrences and tracks of typhoon events (Chu and Zhao 2004; Wu et al. 2005; Zhao and Chu, 2006; Guan and Chan, 2006; Chan and Xu 2008; Tsou and Lee 2008; Wada and Chan 2008; Goh and Chan 2009; Tu et al. 2009). However, these studies yield conflicting results over tracks and annual counts of typhoon events. Chu and Zhao (2004) applied a Bayesian change detection analysis to time series (1966–2002) of annual tropical cyclone counts over the central North Pacific and predicted a higher number of tropical cyclones in the following decade. Chan and Xu (2008) conducted a comprehensive study of the variations in the annual number of landfalling tropical cyclones (ATCs) in various parts of East Asia during the period 1945–2004. They found that none of the ATC time series shows a significant linear trend, which suggests that global warming has not led to a higher frequency of landfalling tropical cyclones or typhoons in any of the regions in Asia. Instead, each time series shows large inter-annual (2–8 years) and multi-decadal (16–32 years) variations. Wu et al. (2005) showed that during the period of 1965–2003, the subtropical East Asia has experienced increasing typhoon influence; but the typhoon influence over the South China Sea has considerably decreased due to the westward shift of two prevailing typhoon tracks in the western North Pacific. Webster et al. (2005) observed a substantial increase in the intensity of tropical cyclones in the western Pacific over the past 30 years.

The lack of clear, consistent, and convincing evidence of climate changes effect on annual counts of typhoons has led us to set our climate change scenarios (considering mean values of annual counts of typhoon events and event-total rainfall) as listed in Table 2. For the sake of conservative design or planning, as can be seen in Table 2, most scenarios assume increases in means of annual counts of typhoons and event-total rainfall.

Stochastic simulation of basin-average annual typhoon rainfall

Historical and simulated typhoon rainfall data at three raingauge stations were used for this study. Basin-average annual typhoon rainfall (BATR) was calculated by considering Thiessen's polygon weights of individual stations (see Table 1). In order to assess the statistical properties of annual typhoon rainfalls with respect to different climate change scenarios, 100,000 years of typhoon rainfalls were generated at each station. Stochastic simulation of annual typhoon rainfall at any of the three raingauge stations under certain climate change scenario was achieved in three steps: (1) generating annual number of typhoon events by simulation of Poisson random variable, (2) generating event-total rainfall for each typhoon event determined by the first step by simulation of gamma random variable, and (3) calculating annual typhoon rainfall for each of the 100,000 years of simulation. Finally, 100,000 years of basin-average annual typhoon rainfalls were calculated by Thiessen's method. Parameter setting for stochastic simulation at three stations is listed in Table 3.

Discussions

Assessment of climate change impact on annual typhoon rainfall is based on two criteria—(1) changes in the expected value of annual typhoon rainfall and (2) changes in the $100 \times p$ % quantile of annual typhoon rainfall. The first criterion considers the average effect of climate change, while the second criterion addresses effect of climate change on annual typhoon rainfall of specific return periods. In this study, p values of 0.8, 0.9, and 0.95 are

Table 2 Scenarios of climate change considered in this study

Scenario	Description	Parameter setting
0	Current situation	$(\mu(N), \mu(R))$
1	Mean of annual counts of typhoons reduced by 10%, mean of event-total rainfall remains the same.	$(0.9\mu(N), \mu(R))$
2	Mean of annual counts of typhoons increased by 10%, mean of event-total rainfall remains the same.	$(1.1\mu(N), \mu(R))$
3	Mean of annual counts of typhoons increased by 20%, mean of event-total rainfall remains the same.	$(1.2\mu(N), \mu(R))$
4	Mean of annual counts of typhoons increased by 10%, mean of event-total rainfall increased by 10%.	$(1.1\mu(N), 1.1\mu(R))$
5	Mean of annual counts of typhoons increased by 10%, mean of event-total rainfall increased by 20%.	$(1.1\mu(N), 1.2\mu(R))$
6	Mean of annual counts of typhoons increased by 20%, mean of event-total rainfall increased by 10%.	$(1.2\mu(N), 1.1\mu(R))$
7	Mean of annual counts of typhoons increased by 20%, mean of event-total rainfall increased by 20%.	$(1.2\mu(N), 1.2\mu(R))$

Note: $\mu(N)$ and $\mu(R)$ represent expected values of annual typhoon counts and event-total rainfall, respectively

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Table 3 Parameter setting for stochastic simulation of typhoon rainfall

Scenario	21C140			21C150			21D170		
	$\mu(R)$	$\mu(N)$	$\sigma(R)$	$\mu(R)$	$\mu(N)$	$\sigma(R)$	$\mu(R)$	$\mu(N)$	$\sigma(R)$
0	149.38	3.98	177.8	145.39	3.78	178.8	125.57	4.59	166.0
1	149.38	3.58	177.8	145.39	3.41	178.8	125.57	4.13	166.0
2	149.38	4.38	177.8	145.39	4.16	178.8	125.57	5.05	166.0
3	149.38	4.78	177.8	145.39	4.54	178.8	125.57	5.51	166.0
4	164.32	4.38	177.8	159.93	4.16	178.8	138.13	5.05	166.0
5	164.32	4.78	177.8	159.93	4.54	178.8	138.13	5.51	166.0
6	179.26	4.38	177.8	174.47	4.16	178.8	150.69	5.05	166.0
7	179.26	4.78	177.8	174.47	4.54	178.8	150.69	5.51	166.0

Note: $\sigma(R)$ represents standard deviation of event-total rainfall in mm

considered. For $p = 0.8$, 0.9, and 0.95, $100\times p$ % quantiles, respectively, represent the amount of annual typhoon rainfall corresponding to 5-, 10-, and 20-year return periods.

Based on the results of stochastic simulation of typhoon rainfalls at three raingauge sites, cumulative distribution function (CDF) of BATR with respect to specific climate change scenarios can be established. These CDFs are demonstrated in Fig. 3. Apparent changes in CDF can be observed, particularly for scenarios 4–7. Empirical probability density functions of BATR associated to scenarios 0, 4, and 7 are also shown in Fig. 4.

Assuming an increasing trend in frequency and intensity of typhoon events, potential impacts of climate change based on scenarios 4 through 7 should be assessed for planning of future water management strategies.

Assessing changes in expected value of basin-average annual typhoon rainfall

For the current situation (scenario 0), expected value of BATR is 572.79 mm. Expected BATR under various climate change scenarios are summarized in Table 4. Considering expected value of BATR of the current situation (scenario 0) as reference basis, changes in expected value of BATR of other scenarios vary from −9.76% for scenario 1 to 44.09% for scenario 7. The mean BATR of scenario 0 (572.79 mm) corresponds to a return period of 2.42 years. The same amount of BATR corresponds to a return period of 2.76 years if the expected value of annual typhoon counts is reduced by 10% (i.e., scenario 1).

In contrast, the amount of BATR equivalent to mean BATR of scenario 0 corresponds to smaller return periods under scenarios 2 through 7. For example, for scenario 7, the return period of annual typhoon rainfall of 572.79 mm is 1.59 years, a significant decrease from 2.42 years for scenario 0.

Assessing changes in quantiles of basin-average annual typhoon rainfall

Effect of climate change on extremity of annual typhoon rainfall is assessed by investigating changes in p-quantile of BATR. Table 5 summarizes 0.8, 0.9, and 0.95 quantiles of BATR under various climate change scenarios.

Comparing to changes in expected value of BATR shown in Table 4, less degree of changes in 0.8, 0.9, and 0.95 quantiles of BATR can be observed. For example,

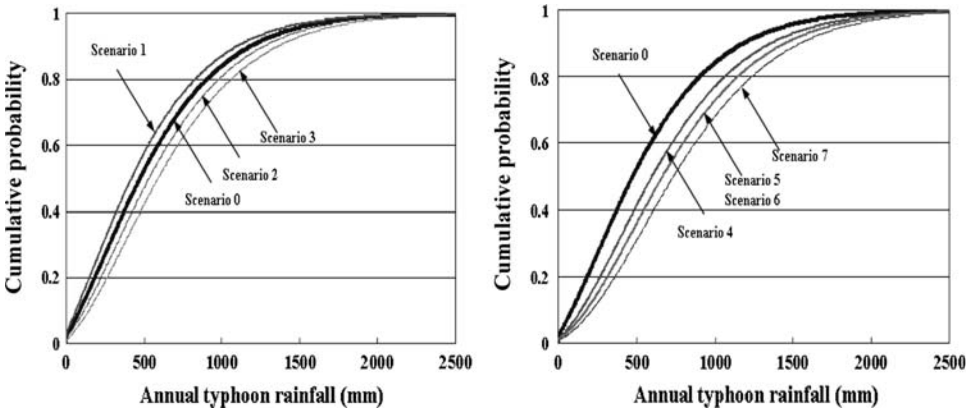

Fig. 3 Cumulative distribution functions of Shihmen Reservoir basin-average annual typhoon rainfall under different climate change scenarios

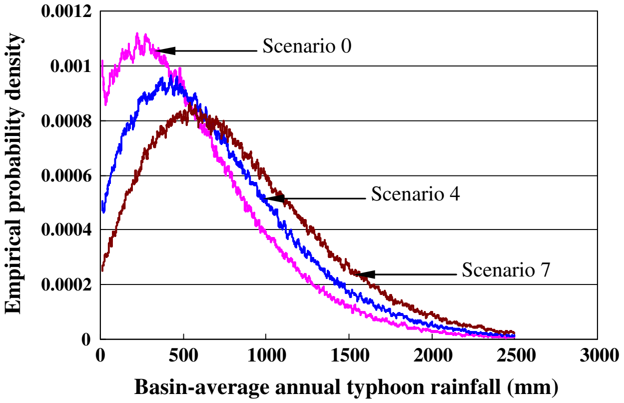

Fig. 4 Empirical probability density function of BATR of Scenarios 0, 4 and 7

10% reduction in annual counts of typhoons (scenario 1) will result in 8.4% (7.35%, 6.71%) decrease in 0.8 (0.9, 0.95) quantile of BATR, whereas under the same scenario expected value of BATR is reduced by 9.76%. Similarly, under scenario 7 (20% increase in mean of annual counts and 20% increase in mean of event-total rainfall), 0.8 (0.9, 0.95) quantile of BATR increases by 36.80% (31.08%, 26.76%) while expected value of BATR has a 44.09% increase. Such phenomenon of lesser change in more extreme events (events of higher quantile) can be observed in simulation results of all climate change scenarios.

The 0.8-, 0.9-, and 0.95-quantile BATR correspond to return periods of 5, 10, and 20 years, respectively. Thus, 10% increases in average annual number of typhoon events and mean event-total rainfall (scenario 4) will result in about 18% increase in the annual typhoon rainfall of 5-year return period, whereas the annual typhoon rainfall of 10-year return period will increase by about 15% under the same climate change scenario.

In addition, at the current situation, BATR of 5-year return period amounts to 905 mm. If mean of annual typhoon counts and mean of event-total rainfall increase, we can expect this amount (905 mm) to appear more frequently. Since the amount of sediment that can be delivered to reservoir is closely related to annual typhoon rainfall, it is necessary to assess how frequently should sediment flushing or dredging be conducted under different climate change scenarios. For such assessment, a cutoff BATR which necessitates sediment dredging practice is desired. For demonstration, let us assume the cutoff BATR

Table 4 Changes in expected value of annual typhoon rainfall under different climate change scenarios

Scenario	$\mu(R_B)$	Changes (%)	Cumulative probability at μ_0	Return period of annual typhoon rainfall at μ_0 (years)
0	572.79	–	0.59	2.42
1	516.87	−9.76	0.64	2.76
2	629.75	9.94	0.53	2.15
3	689.43	20.36	0.48	1.94
4	694.12	21.18	0.48	1.92
5	756.97	32.15	0.42	1.74
6	756.20	32.02	0.42	1.73
7	825.36	44.09	0.37	1.59

Note: $\mu(R_B)$ represents expected value of basin-average annual typhoon rainfall. μ_0 represents $\mu(R_B)$ of scenario 0 ($\mu_0 = 572.79$ mm)

Table 5 Changes in *p*-quantile of basin-average annual typhoon rainfall under different climate change scenarios

Scenario	$p = 0.8$		$p = 0.9$		$p = 0.95$	
	p-quantile	Changes (%)	*p*-quantile	Changes (%)	*p*-quantile	Changes (%)
0	905	–	1184	–	1446	–
1	829	−8.40	1097	−7.35	1349	−6.71
2	981	8.40	1270	7.26	1536	6.22
3	1060	17.13	1360	14.86	1633	12.93
4	1064	17.57	1360	14.86	1636	13.14
5	1148	26.85	1453	22.72	1734	19.92
6	1149	26.96	1450	22.47	1726	19.36
7	1238	36.80	1552	31.08	1833	26.76

Note: All rainfall data are in unit of mm

Table 6 Corresponding return period of cutoff BATR under different climate change scenarios

Scenario	Cumulative probability at Cutoff BATR = 905 mm	Return period (years)
0	80.00	5.00
1	83.45	6.04
2	76.32	4.22
3	72.27	3.61
4	71.83	3.55
5	67.35	3.06
6	67.10	3.04
7	62.07	2.64

equals 905 mm. At this cutoff value, sediment dredging should be conducted every 5 years on average. The corresponding return periods of 905 mm BATR under different climate change scenarios are shown in Table 6. Under climate change scenario 4, sediment dredging need to be conducted at a frequency of 3.55 years since the cutoff BATR corresponds to a return period of 3.55 years. For scenario 7, the sediment dredging frequency dramatically increases to 2.64 years, approximately half of the interval under current situation.

Conclusions

In this study, we assess the effect of climate changes on annual typhoon rainfall of the Shihmen Reservoir watershed in northern Taiwan. Stochastic simulation of two random variables of typhoon events, namely annual counts and event-total rainfall, under different climate change scenarios were conducted for three raingauge sites and statistical properties of basin-average annual typhoon rainfall were derived. Different climate change scenarios were set by considering changes in mean of annual counts of typhoons and mean of event-total rainfall. Such scenarios are different from scenarios of varying GHGs emission rate; however, they provide direct link to variables of local-scale hydrological models. A few concluding remarks are drawn as follows:

1. 10% increases in average annual number of typhoon events and mean event-total rainfall will result in 18% increase in the annual typhoon rainfall of 5-year return period, whereas the annual typhoon rainfall of 10-year return period will increase by 15% under the same climate change scenario.
2. Mean BATR of the current situation (572.79 mm) corresponds to a return period of 2.42 years. The same amount of BATR corresponds to a return period of 2.76 years if the expected value of annual typhoon counts is reduced by 10% (i.e., scenario 1).
3. For scenario 7, the return period of annual typhoon rainfall of 572.79 mm is 1.59 years, a significant decrease from 2.42 years of scenario 0 (the current situation).
4. Comparing to changes in expected value of BATR, lesser changes in more extreme events can be observed under all climate change scenarios.
5. Sediment dredging will become more frequent if mean of annual typhoon counts and mean of event-total rainfall increase.

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