

Estimating impact of rainfall change on hydrological processes in Jianfengling rainforest watershed, China using BASINS-HSPF-CAT modeling system



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ABSTRACT

Climate change over the past several decades has resulted in shifting rainfall pattern and modifying rainfall intensity, which has exacerbated hydrological processes and added the uncertainty and instability to these processes. This study ascertained impacts of potential future rainfall change on hydrological processes at the Jianfengling (JFL) tropical mountain rainforest watershed in Hainan Island, China using the BASINS (Better Assessment Science Integrating Point and Nonpoint Sources)-HSPF (Hydrological Simulation Program-FORTRAN)-CAT (Climate Assessment Tool) modeling system. The HSPF model was calibrated and validated with available measured data prior to its applications. Three simulation scenarios were then performed to gain a better understanding of the impacts of different rainfall rates and storm intensities on stream discharge, surface water runoff from forest land, and water outflow from the JFL watershed outlet. Results showed that a 10% increase in rainfall rate could result in 1.3 times increase in stream discharge, surface runoff, and water outflow. A potential future wet climate could have profound impacts on hydrological processes at the JFL watershed, whereas a potential future dry climate could result less impacts on stream discharge, surface runoff, and water outflow at the same watershed. Our simulation further revealed that climate change driven by extreme rain storms had greater impacts on annual surface runoff than on annual stream discharge. The coupled CAT-HSPF model is a useful tool to modify historical rainfall data for projecting future rainfall variation impacts on forest hydrological processes due to climate change. This approach would be able to extend to other regions around the world.

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1. Introduction

Climate change over the last several decades has resulted in modifying precipitation pattern and intensity (Bates et al., 2008). Precipitation change has resulted wetting in the Northern Hemisphere mid-latitudes, drying in the Northern Hemisphere subtropics and tropics, and moistening in the Southern Hemisphere subtropics and deep tropics in recent decades as detailed by Zhang et al. (2007) and Bates et al. (2008). Bates et al. (2008) reported that heavy rainfall has increased over most areas, whereas the very dry land area has increased more than doubled globally since 1970s. Tank et al. (2009) stated that air temperature in 2100 is expected to be 1.1–6.4 °C higher than that in 1900, accompanied by changes in rainfall intensity and amount. Each of the past three decades

has been successively warmer than any previous decades based on instrumental records and the decade of the 2000s has been the warmest (Tank et al., 2009).

Forest and water are inextricably connected and the movement, distribution, quality, and quantity of water in forest lands are regulated by forests (NRC, 2008). Forests process water that not only sustains ecological functions, but also is used for agriculture, industrial, and human consumption. Climate change exacerbates hydrologic processes and adds the uncertainty and instability to these processes. Therefore, assessment of hydrologic processes affected by climate change is essential to water resource management, water supply planning, environmental protection, and ecological restoration. In recent years, numerous studies have been performed to investigate impacts of climate change such as air temperature and rainfall change on hydrologic processes, including stream discharge, overland flow, surface evaporation and water yield, in forested watersheds (Brooks, 2009; Huntington et al., 2009; Campbell et al., 2011; Ouyang et al., 2015a,b; Li et al., 2016;

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Luce et al., 2016; Mouri et al., 2016; Trisurat et al., 2016; Zhou et al., 2016). Brooks (2009) estimated potential impacts of global climate change on hydrology and ecology of ephemeral freshwater systems in forests of the northeastern United States. These authors found that watershed hydrology is strongly affected by weather patterns (short-term) or climate trends (long-term). Huntington et al. (2009) overviewed the climatic change impacts on hydrologic conditions in the northeastern United States and their implications in forest ecosystems. They argued that climate-induced hydrologic changes could have profound effects on forest structure, composition, and ecological functioning. Campbell et al. (2011) evaluate the impact of climate change on the timing and quantity of streamflow at small watersheds at the Hubbard Brook Experimental Forest in New Hampshire, USA. Their results indicate that earlier snowmelt and the diminishing snowpack are advancing the timing and reducing the magnitude of peak discharge. They further deduced that the past increases in precipitation have caused annual elevated water yield significantly, which is a trend expected to continue under future climate change. Ouyang et al. (2015a,b) investigated the impacts of future rainfall and air temperature variations upon water discharge, water yield, and evaporative loss in the Lower Yazoo River Watershed (LYRW) that consists of 61% forest land and 31% agriculture land in the bottomland of Mississippi, USA using the HSPF (Hydrological Simulation Program-Fortran) model. These authors found that a 6.4% decrease in rainfall amount results in, respectively, 11.8% and 10.3% decreases in water yield and evaporative loss. Li et al. (2016) assessed the impacts of future climate change on river discharge of Grand River Watershed in Ontario, Canada. Their results show that water availability is expected to increase in winter while it is very likely to decrease in summer. Combalicer et al. (2010) assessed climate change impacts on water balance in the Mount Makiling forest, Philippines using the lumped hydrologic BROOK90 model. They found that the impacts of climate change on water balance reflected dramatic fluctuations in hydrologic events leading to high evaporation losses, and decrease in streamflow, while groundwater flow appeared unaffected. These studies with mixed results from different regions have provided invaluable insights into impacts of climate change on hydrological processes in forest watershed ecosystems around the world.

More specifically, Zhou et al. (2011) quantified the hydrologic responses to historic climate conditions (1950–2009) in an intact small forested watershed from the Dinghushan Biosphere Reserve in Guangdong Province, a sub-tropical region in South China, using the SWAT (Soil and Water Assessment Tool) model. These authors found that the historic climate conditions have induced more extreme hydrological events in the watershed. However, no effort has been devoted to investigating the impacts of potential future climate change, especially rainfall variations, upon daily and annual stream discharge, surface water runoff from forest land, and water outflow from watershed associated with potential droughts and intensive storm events in tropical rainforest watersheds. Knowledge of these phenomena is crucial to mitigating the likelihood of future climate impact on potential risks of water resources and implementing good forest practices for adapting to future climatic conditions in the tropical region.

The goal of this study was to assess the impacts of future rainfall variations due to climate change upon hydrological processes from the Jianfengling (JFL) tropical rainforest watershed in Hainan Island, China using US-EPA (Environmental Protection Agency)'s BASINS (Better Assessment Science Integrating Point and Nonpoint Sources)-HSPF (Hydrological Simulation Program-FORTTRAN)-CAT (Climate Assessment Tool) model. Although numerous studies have been made to apply the BASINS-HSPF model for watershed hydrology and water quality analysis (Ouyang et al., 2013, 2015), a thorough literature search revealed that very few effort has been devoted to utilizing the CAT model for climate change sce-

nario assessment. The specific objectives of this study were to: (1) develop a BASINS-HSPF-CAT model to estimate hydrological processes at the JFL watershed; (2) calibrate and validate the model using field measured data; and (3) apply the resulted model to investigate daily and annual stream discharge, surface runoff from forest land, and water outflow from the JFL watershed outlet, as affected by potential rainfall variations due to climate change.

2. Materials and methods

2.1. Study site

The JFL mountain watershed with an area of 636.84 km² is located in southwest of Hainan Island, China between 18°20' and 18°57' N and between 108°41' and 109°12' E (Fig. 1). This watershed is covered with 93.18% of tropical rainforest (Li et al., 2002; Zhou et al., 2016). There are three catchments based on rainforest ages at this location, namely the primary forest catchment, the secondary forest catchment, and the plantation catchment. The primitive forest catchment includes tree species such as *Castanopsis patelliformis*, *Lithocarpus fenzelianus*, *Livistona saribus*; the secondary forest catchment consists of naturally regenerated tree species such as *Castanopsis fissa*, *Sapium discolor*, *C. tonkinensis*, *Syzygium tephrodes* and *Schefflera octophylla* (Huang et al., 1988; Zeng et al., 1997; Xu et al., 2009); and the plantation catchment comprises of *Cunninghamia lanceolata*, *Pinus caribaea* Morelet, *Dacrycarpus imbricatus*. The watershed is about 800 to 1000 m above sea level with an average annual precipitation of 2449 cm, a mean annual temperature of 19.8 °C, an average slope of 20%, and a dominated lateritic yellow soil (Zhou et al., 2009). Several gage stations have been initiated to monitor stream discharge and water quality at the watershed since 1990s although the monitoring activities for most of them are discontinued, intermittent, or in short-duration due to the budget constraints. In this study, hydrologic data from the gage station located at the watershed outlet (Fig. 1) was used for model calibration and validation. Other data for developing the JFL HSPF model such as land use, soil type, topography, rainfall, air temperature, and stream discharge are obtained from our JFL Forest Research Lab.

2.2. Model description

The US-EPA watershed modeling system, BASINS-HSPF-CAT, was selected for this study. BASINS is a multipurpose environmental analysis system for use by regional, state, and local agencies, research institutes and universities to perform watershed hydrology and water quality studies. The BASINS system integrates an open source geographic information system (GIS) program (MapWindow), watershed and meteorological data, and state-of-the-art environmental assessment and modeling tools (e.g., HSPF, SWAT, and SWMM) into one convenient package (US-EPA, 2009).

HSPF is a comprehensive model developed by Aqua Terra Inc. through US-EPA for simulating water quantity and quality in watersheds of almost any size and complexity (Bicknell et al., 2001). HSPF can simulate both the land area of watersheds and the water bodies like streams or lakes. This model uses information such as daily historic rainfall, temperature and solar radiation data; land surface characteristics such as land use patterns; and land management practices to simulate hydrological processes and water quality (e.g., nutrients, pesticides, and sediments) at a watershed outlet. An elaborate description of the HSPF model can be found in Bicknell et al. (2001).

The CAT model was first incorporated into US-EPA's BASINS modeling system in 2007 with the goal of increasing the capacity of BASINS users to conduct watershed based studies due to

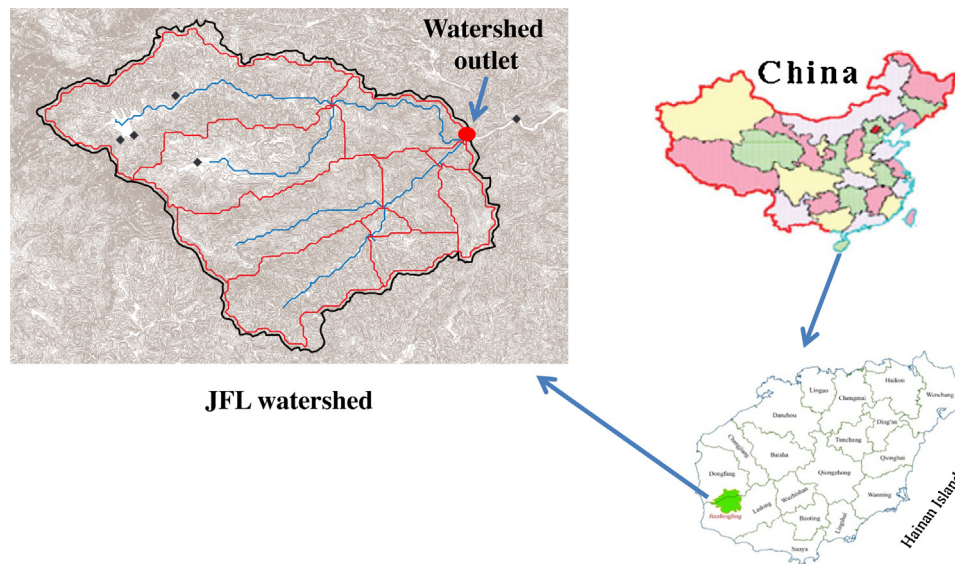


Fig. 1. Location of Jiangfengling (JFL) watershed in Hainan Island, China.

potential climate variability and change on water resources (USEPA, 2009). CAT provides flexible capabilities for creating climate change scenarios, allowing users to quickly assess a wide range of “what if” questions about how weather and climate could affect watershed systems using the HSPF, SWAT, and SWMM models. A post-processing capability is also provided for calculating management targets to water resource managers. Climate change scenarios can be created with CAT by selecting and modifying an arbitrary base period of historical temperature and precipitation data to reflect any desired future changes.

2.3. Model development

Development of a HSPF model in BASINS starts with watershed delineation. The processes include to setup a digital elevation model, create the stream networks, and select watershed inlets or outlets. The HSPF model also requires land use and soil data to determine the area and the hydrologic parameters of each land use pattern. This was accomplished by using the land use and soil classification tool in BASINS (version 4.2).

The HSPF model is a lumped parameter model with a modular structure. Pervious land segments over which an appreciable amount of water infiltrates into the ground are modeled with the PERLND module. Impervious land segments over which infiltration are negligible, such as paved urban surfaces, are simulated with the IMPLND module. Processes occurring in water bodies like streams and lakes are treated with the RCHRES module. These modules have several components dealing with the hydrological processes and processes related to water quality. In this study, the PERLND, IMPLND, and RCHRES modules of the HSPF model were used. The PWATER section of PERLND is a major component of the model that simulates the water budget, including surface flow, inter-flow and ground water behavior. The HYDR section of the RCHRES is utilized to simulate the hydraulic behavior of the streams and lakes. Elaborated information about the structure and functioning of these modules can be found in the elsewhere (Bicknell et al., 2001).

The major steps in watershed modeling with HSPF are the mathematical description of the watershed, the preparation of input meteorological and hydrological time series, and the estimation of input parameter values through model calibration and validation. The time series are fed to the model by utilizing a standalone

Table 1
Input parameters used for model calibration.

Parameter	Value
LZSN (lower zone nominal storage, m)	6.5
UZSN (upper zone nominal storage, m)	2
INFILT (index to the infiltration capacity of the soil)	0.5
LZETP (lower zone ET parameter)	0.9
IRC (interflow recession parameter)	0.5

program called the Watershed Data Management program (WDM) provided in BASINS. Fig. 2 shows the HSPF model for the JFL watershed with a total of 11 major streams (or reaches) selected for this study. Table 1 lists the input parameter values used for model calibration.

2.4. Simulation scenarios

To gain a better understanding of potential future rainfall impacts on stream discharge in the watershed, surface runoff from forest land, and water outflow from watershed outlet, three simulation scenarios were performed in this study. The first scenario (base scenario) was chosen to predict daily and annual hydrological processes with historical rainfalls. In this scenario, all of the simulation conditions and input parameter values were the same as those used in model validation. The second scenario was selected to project the potential impacts of rainfall variations (i.e., wetting and drying), namely increased and decreased 20% of the historical daily rainfall records with a 10% interval each, upon daily and annual hydrological processes. In this second scenario, all of the simulation conditions and input parameter values were the same as those used in the first scenario except for rainfall data. The third scenario was designed to project how the potential storm intensifications affect the daily and annual hydrological processes. In this third scenario, only the highest 20% of the rainfall rates that are greater than 7 cm/d were selected to adjust. The adjustments were accomplished by multiplying the highest 20% rainfall rates by 10%, and the intensified storms are those with the volume of rainwater from the adjustments are equal to or greater than 10% of the total volume of rainwater during the entire 12-year simulation period. The selection of these three simulation scenarios reflects the major potential future rainfall trends in this watershed based on our his-

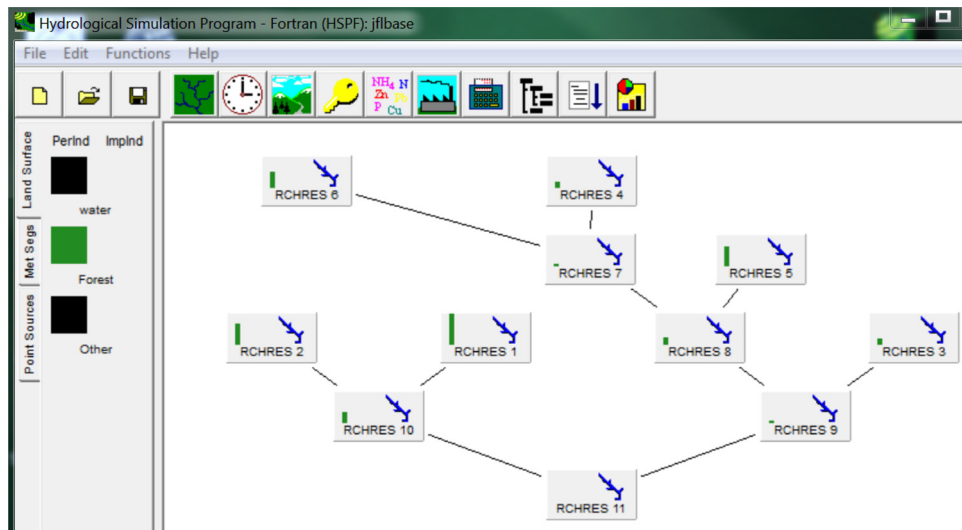


Fig. 2. The HSPF model showing 11 streams (or reaches) selected in this study.

torical rainfall data observations. This procedure was performed in CAT model. It should be noted that CAT model can calculate any percentages of rainwater volumes and storm events and this scenario is only an application example. All of other simulation conditions and input parameter values for this scenario were the same as those used in the first scenario.

Comparison of simulation results from the three scenarios allowed us to evaluate the potential impacts of rainfall variations (due to climate change) upon the daily and annual stream discharge, surface runoff, and water outflow (from the watershed outlet). The simulation period was 12 years starting at the first day of 1992 and terminating at the end of 2003 for each scenario and the simulation results from Reach 11 (or watershed outlet, see Fig. 2) were used for analysis. One of the major reasons for selecting the simulation period from 1992 to 2003 to adjust historical rainfall data for evaluating climate change impacts was that there are sufficient measured meteorological and hydrologic data from the local experimental stations for this time period. It should be noted that some predicted future precipitation data have been used to estimate climate change impacts on watershed hydrology (Ouyang et al., 2015a,b). These data are obtained from General Circulation Model (GCM) predictions (<http://cmip-pcmdi.llnl.gov/cmip5/>). Currently, we are not able to obtain such data for the JFL watershed. Additionally, future precipitation data from the GCM model may not have high resolution for relatively small JFL watershed.

3. Results and discussion

3.1. Model calibration and validation

Prior to applying the HSPF model, it must be calibrated and validated. Model calibration is accomplished by adjusting input parameters within a reasonable range to obtain a good match between field observations and model predictions, while model validation is achieved by matching the field observations and model predictions without adjusting any input parameters. The calibration period was from January 1, 1992 to December 31, 1996, whereas the validation period spanned from January 1, 1999 to December 31, 2003. To obtain fewer uncertainties, only the following most sensitive five input parameters (Donigian et al., 1984; Ouyang et al., 2013) were used for model calibration: LZSN, UZSN, INFILT, LZETP, and IRC, which are defined in Table 1.

Comparison of the observed and simulated daily stream discharges during model calibration is shown in Fig. 3. With the

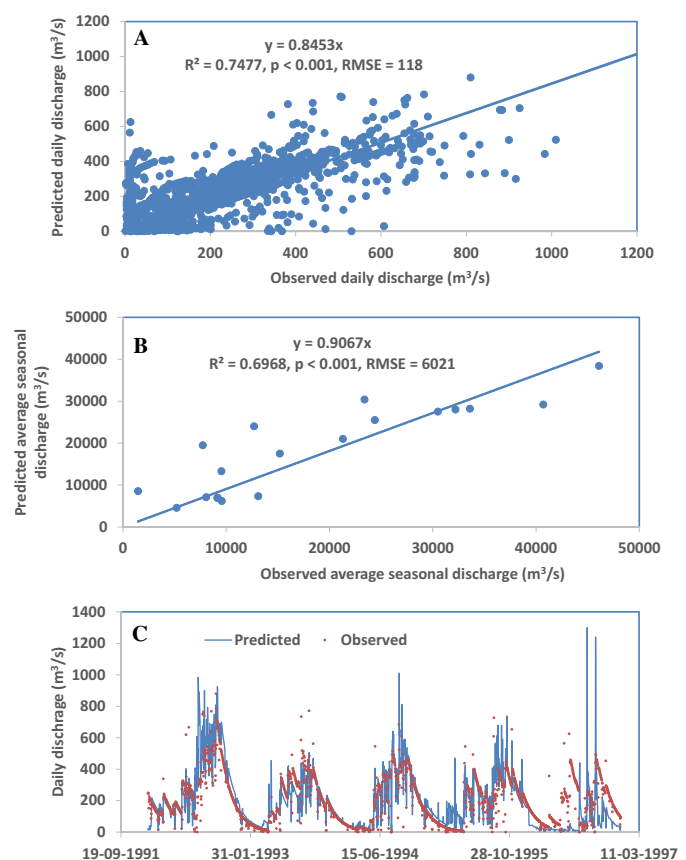


Fig. 3. Predicted and observed daily discharge (A), predicted and observed seasonal average discharge (B), and visual comparison of predicted and observed daily discharge (C) during model calibration.

values of $R^2 = 0.747$ and $p > 0.001$ for daily discharge (Fig. 3A) as well as $R^2 = 0.697$ and $p > 0.001$ for seasonal discharge (Fig. 3B), we determined that a good agreement was obtained between model predictions and field observations during model calibration. The best fit of daily discharge was further estimated graphically (Fig. 3C), showing that the peak flows from model predictions matched quite well with those from field observations.

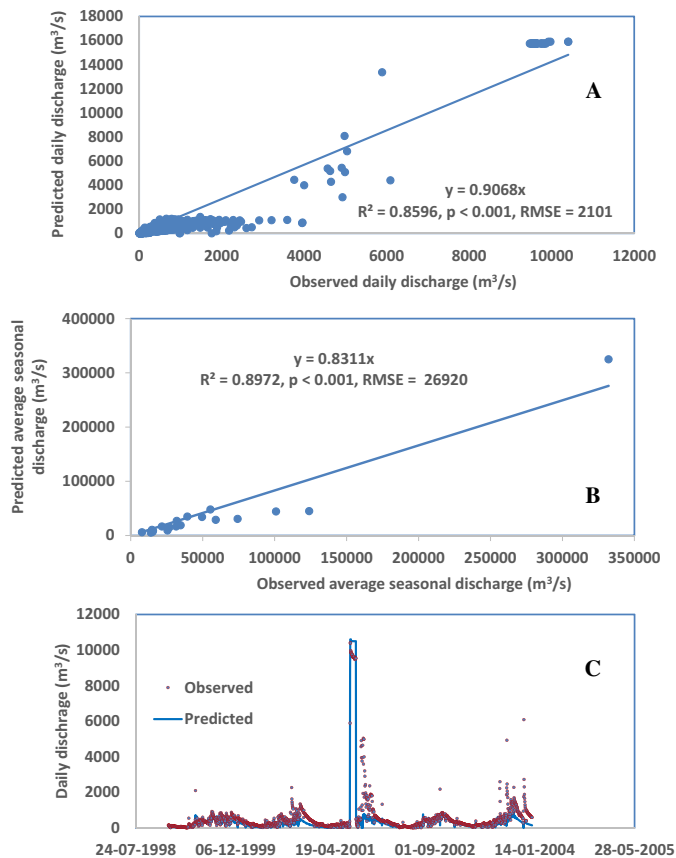


Fig. 4. Predicted and observed daily discharge (A), predicted and observed seasonal average discharge (B), and visual comparison of predicted and observed daily discharge (C) during model validation.

Validation of the calibrated model was given in Fig. 4. This figure compared stream discharges between field observations and model predictions over a time period from January 1, 1999 to December 31, 2003. Analogous to the case of model calibration and with the values of $R^2 = 0.859$ and $p > 0.001$ for daily discharge (Fig. 4A) as well as $R^2 = 0.897$ and $p > 0.001$ for averaged seasonal discharge (Fig. 4B), we concluded that a good agreement was obtained between model predictions and field observations during model validation. A visual comparison of daily peak flows between field observation and model prediction (Fig. 4C) further confirmed our conclusion.

3.2. Impacts of wet and dry climate

Daily variations of stream discharge and surface runoff from forest land for the three rainfall settings (i.e., base rainfall, increased 10%, and increased 20%) at the JFL watershed are shown in Fig. 5. The base rainfall data were obtained from the local weather station and further computed to fill the gaps for representing the average rainfall condition at the JFL watershed, whereas the other two sets of rainfall data were attained by increasing 10 and 20% of base rainfall data to account for wet climate (Fig. 5A). The daily stream discharge (Fig. 5B) and surface runoff (Fig. 5C) were predicted from the HSPF model simulations.

It is apparent that increase in rainfall rate boosted stream discharge although the percent increase in rainfall rate was not necessary proportional to the percent increase in stream discharge (Fig. 5B). For example, an increase in rainfall rate by 10% increased the stream discharge from 634 to 15,200 m^3/s (or about 24 times) on August 29, 1995, while an increase in rainfall rate by 20% increased the stream discharge from 634 to 68,600 m^3/s (or about

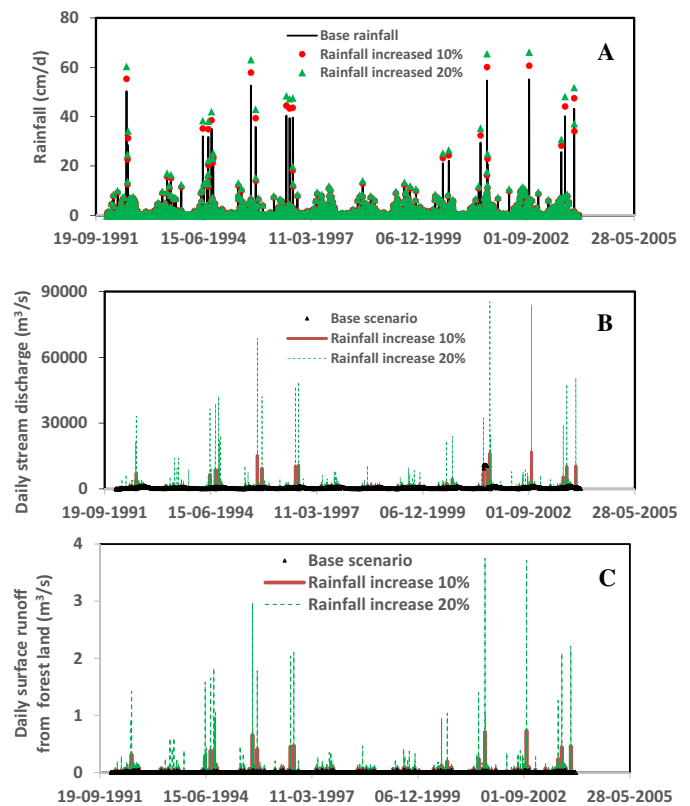


Fig. 5. Input rainfall (A) and simulated daily stream discharge (B) and surface runoff (C).

108 times) on the same date. This finding indicated that the JFL watershed was not able to conserve more excess water as the rainfall rate increased. In other words, a small (e.g., 10%) increase in future rainfall rate could result in a large stream flow. Overall, the total stream discharge for the entire 12-year simulation period were $2.0\text{E}+06$, $2.6\text{E}+06$, and $4.3\text{E}+06$ m^3/s , respectively, for the base rainfall, increased 10% rainfall, and increased 20% rainfall. The 10 and 20% increases in rainfall rate increased the total stream discharge by 1.3 and 2.1 times, respectively. Therefore, a potential future wet climate could have profound impacts on stream flows at the JFL watershed.

Taking the advantage of HSPF model, users can output surface water runoff simulations from different land uses such as crop land, forest land, and wetland. Comparison of the results in Fig. 5C shows that effects of rainfall rate on surface water runoff from forest land were significant. For instance, an increase in rainfall rate by 10% increased the surface runoff in forest land from 0.0259 to 0.662 m^3/s (or about 26 times) on August 29, 1995, whereas an increase in rainfall rate by 20% increased the surface runoff from 0.0259 to 2.97 m^3/s (or about 115 times) on the same date (Fig. 5C). This finding was similar to the case of stream discharge, i.e., a small increase in future rainfall rate could also result in high surface runoff from forest land although the surface runoff was several orders of magnitude lower than the stream discharge. Results suggested that the rainfall event is an important driving force for daily variations of stream discharge and surface runoff from forest land. These findings were in consistent with those reported by Ouyang et al. (2013). Our simulations further disclosed that the rainfall rate must be greater than 1 cm/d for surface runoff from the forest land to occur although this runoff depends not only on rainfall rate and duration but also on soil moisture content and topography.

Analogous to the case of stream discharge, the daily water outflows from the watershed outlet increased with rainfall rate

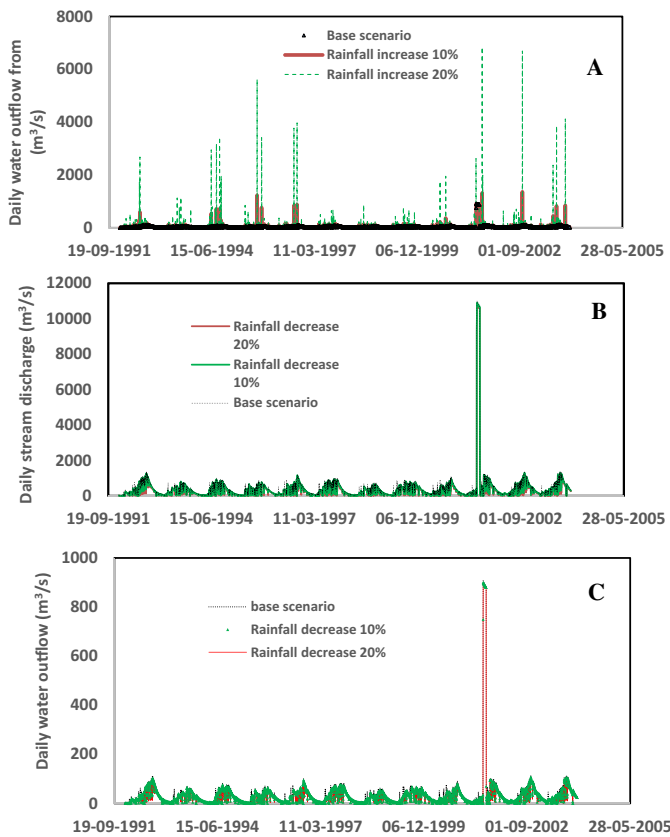


Fig. 6. Simulated daily water outflow (A) with rainfall increase and daily stream discharge (B) and water outflow (C) with rainfall decrease.

(Fig. 6A). The total water outflows for the entire 12-year simulation period were $1.7\text{E}+05$, $2.2\text{E}+05$, and $3.5\text{E}+05$ m^3/s , respectively, for base rainfall, increased 10% rainfall, and increased 20% rainfall. The 10 and 20% increases in rainfall rate increased the total water outflow by 1.3 and 2.1 times, respectively, which were similar to those for total stream discharge.

In contrast, the impacts of dry climate on daily stream discharge were less profound as compared to the case of wet climate (Fig. 5B vs. Fig. 6B). As an example, a decrease in rainfall rate by 10% decreased the stream discharge from 634 to 314 m^3/s (or about 2 times) on August 29, 1995, whereas a decrease in rainfall rate by 20% decreased the stream discharge from 634 to 144 m^3/s (or about 4 times) on the same date. In general, the total daily stream discharge for the entire 12-year simulation period were $2.0\text{E}+06$, $1.8\text{E}+06$, and $1.6\text{E}+06$ m^3/s , respectively, for the base rainfall, decreased 10% rainfall, and decreased 20% rainfall. The 10 and 20% decreases in rainfall rate decreased the total stream discharge by 1.1 and 1.3 times, respectively. Our simulations further demonstrated that the differences in surface water runoff from forest land under dry climate with reducing rainfall rates were trivial (figure not shown).

Annual stream discharge and water outflow through the JFL watershed at five different rainfall rates over a simulation period from 1992 to 2003 are shown in Fig. 7. This figure illustrates that the annual stream discharge increased with rainfall rate. Similar to the case of daily stream discharge, the increase in annual stream discharge was not proportional to the increase in rainfall rate (Fig. 7A). For example, a 20% increase in rainfall rate increased the annual stream discharges from 462,000 to 741,000 m^3/s (or 1.6 times) in 2001. A similar pattern was also observed for annual water outflow, i.e., as the rainfall rate increased, more water flowed out of watershed outlet (Fig. 7B).

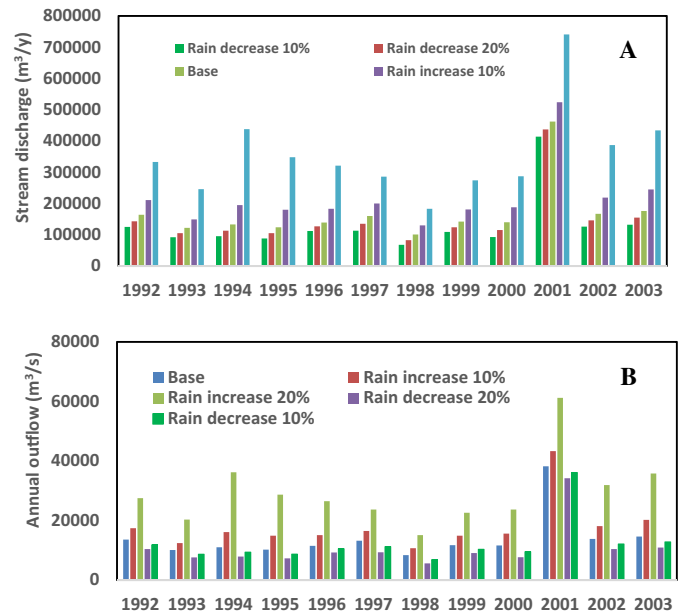


Fig. 7. Simulated annual stream discharge (A) and water outflow (B).

3.3. Impacts of storm intensification

Impacts of potential storm intensification due to climate change on annual stream discharge and surface water runoff from forest land at the JFL watershed are shown in Fig. 8. In this study, an intensified storm was obtained by taking 20% highest rainfall rates that are greater than 7 cm/d and increased them by 10%, and then the volume of rainwater from this storm is set to equal 10% of

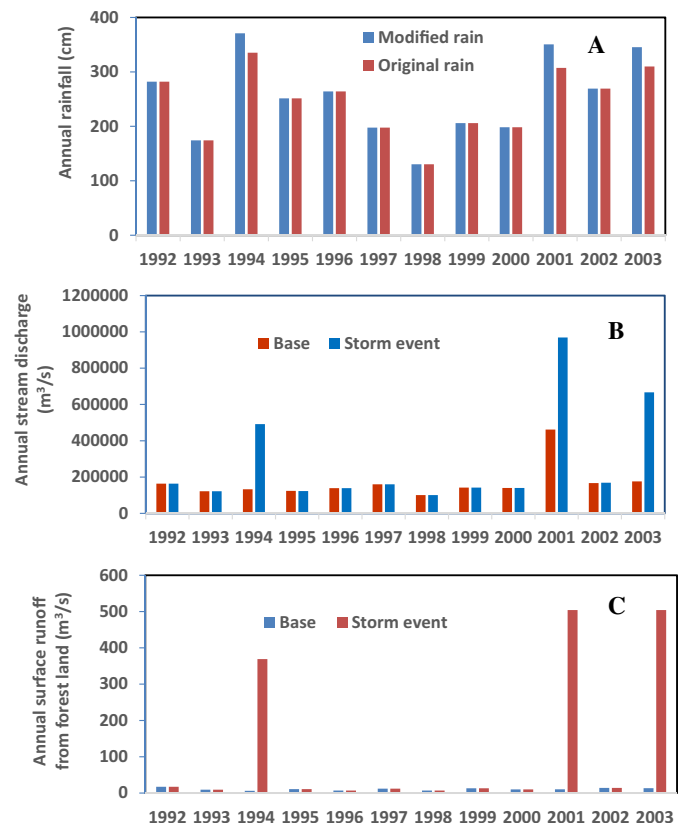


Fig. 8. Simulated annual rainfall (A), stream discharge (B), and surface runoff (C).

the total volume of rainwater from the entire 12-year simulation period. Based on this simulation condition, three intensified storms were identified in 1994, 2001 and 2003 (Fig. 8A).

In general, impacts of intensified storms on annual stream discharge were profound (Fig. 8B). A 10% increase in rain storm increased the annual stream discharge from $1.33\text{E}+05$ to $4.92\text{E}+05\text{ m}^3/\text{s}$ (3.7 times) in 1994, from $4.62\text{E}+05$ to $9.69\text{E}+05\text{ m}^3/\text{s}$ (2.1 times) in 2001, and from $1.76\text{E}+05$ to $6.67\text{E}+05\text{ m}^3/\text{s}$ (3.8 times) in 2003 (Fig. 8B). Result implied that future climate change driven by storm intensification could dramatically interrupted stream flows in this watershed. In contrast, impacts of intensified storms on annual surface runoff were tremendous (Fig. 8C). A 10% increase in rain storm increased surface runoff from 6.3 to $369\text{ m}^3/\text{s}$ (59 times) in 1994, from 10.4 to $504\text{ m}^3/\text{s}$ (48 times) in 2001, and from 13.6 to $504\text{ m}^3/\text{s}$ (38 times) in 2003 (Fig. 8C). This finding revealed that future climate change driven by extreme rain storms had much greater impacts on annual surface water runoff from forest land than on annual stream discharge at the JFL watershed.

Our study further revealed that the coupled CAT-HSPF model is a very useful tool to modify historical rainfall data for projecting future rainfall pattern shifts and to analyze impacts of such variations on forest hydrological processes due to climate change. This tool is very important for the cases when the daily rainfall data obtained from General Circulation Model (GCM) predictions are not accurate due to the small scale watersheds.

4. Summary

A BASINS-HSPF-CAT modeling system was developed to assess impacts of potential rainfall variations due to climate change upon hydrological processes in Jianfengling tropical rainforest watershed, Hainan Island, China. The model was calibrated and validated using our field data with very good agreements prior to its applications. Three simulation scenarios were performed to investigate impacts of wet climate by increasing 20% of rainfall, dry climate by decreasing 20% of rainfall, and intensified storms upon daily and annual stream discharge, surface water runoff, and water outflow from the JFL watershed outlet.

Simulation results showed that increase in rainfall rate boosted daily and annual stream discharges although the percent increase in rainfall rate was not necessary proportional to the percent increase in stream discharge. Overall, the 10 and 20% increases in rainfall rate increased the total stream discharge by 1.3 and 2.1 times, respectively. Effects of rainfall rate on surface water runoff from forest land and water outflow from watershed outlet were very significant. Therefore, a potential future wet climate could have profound impacts on stream flow at the JFL watershed. Our simulations further disclosed that the rainfall rate must be greater than 1 cm/d for surface runoff from the forest land to occur although this runoff depends not only on rainfall rate and duration but also on soil moisture content and topography. In contrast, the impacts of dry climate on daily stream discharge were less profound as compared to the case of wet climate. Our simulations further demonstrated that the differences in surface water runoff from forest land under dry climate with reducing rainfall rates were trivial. Climate change driven by extreme rain storms could have much greater impacts on annual surface water runoff from forest land than on annual stream discharge at the JFL watershed. The approach used in this study would be able to extend to other regions in the world.

Further study is warranted to address impacts of potential air temperature changes upon hydrological processes. This information, in conjunction with impacts of rainfall changes on hydrological processes, would provide a more comprehensive answer to the question of how climate change affect water quantity in the JFL watershed.

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References

- Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P., 2008. *Climate change and water*. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva, pp. 210.
- Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jobs, T.H., Donigan, A.S., 2001. *Hydrological Simulation Program – FORTAN, HSPF, Version 12, User's Manual*. National Exposure Research Laboratory, Office Of Research and Development, U.S. Environmental Protection Agency, Athens, Georgia 30605, March 2001.
- Brooks, R.T., 2009. Potential impacts of global climate change on the hydrology and ecology of ephemeral freshwater systems of the forests of the northeastern United States. *Climatic Change* 95, 469–483.
- Campbell, J.L., Driscoll, C.T., Pourmokhtarian, A., Hayhoe, K., 2011. Streamflow responses to past and projected future changes in climate at the Hubbard Brook Experimental Forest, New Hampshire, United States. *Water Resour. Res.* 47, W02514.
- Combalicer, E.A., Cruz, R.V.O., Lee, S., Im, S., 2010. Assessing climate change impacts on water balance in the Mount Makiling forest, Philippines. *J. Earth Syst. Sci.* 119, 265–283.
- Donigan, A.S., Imhoff, J.C., Bicknell, B.R., Kittle, J.L., 1984. *Application guide for hydrological simulation program-FORTAN (HSPF)*. EPA, Athens, GA. EPA-600/3-84-065.
- Huntington, T.G., Richardson, A.D., McGuire, K.J., Hayhoe, K., 2009. Climate and hydrological changes in the northeastern United States: recent trends and implications for forested and aquatic ecosystems. *Can. J. For. Res.* 39, 199–212.
- Li, Z., Huang, G., Wang, X.Q., Han, J.C., Fan, Y.R., 2016. Impacts of future climate change on river discharge based on hydrological inference: A case study of the Grand River Watershed in Ontario, Canada. *Sci. Total Environ.* 548–549, 198–210.
- Li, Y.D., Chen, B.F., Zhou, G.Y., others, 2002. *Research and Conservation of Tropical Forest and the Biodiversity – A special Reference to Hainan Island, China*. China Forestry Publishing House, Beijing (in Chinese).
- Luce, C.H., Vose, J.M., Pederson, N., Campbell, J., Millar, C., Kormos, P., Woods, F.R., 2016. Contributing factors for drought in United States forest ecosystems under projected future climates and their uncertainty. *For. Ecol. Manage.* 380, 299–308.
- Mouri, G., Nakano, K., Tsuyama, I., Tanaka, N., 2016. The effects of future nationwide forest transition to discharge in the 21st century with regard to general circulation model climate change scenarios. *Environ. Res.* 149, 288–296.
- NRC (National Research Council), 2008. *Hydrologic effects of a changing forest landscape*. National Research Council of the National Academies, The National Academies Press, Washington, D.C. 168 p.
- Ouyang, Y., Leininger, T.D., Moran, M., 2013. Impacts of reforestation upon sediment load and water outflow in the Lower Yazoo River Watershed, Mississippi. *Ecol. Eng.* 61, 394–406.
- Ouyang, Y., Leininger, T.D., Moran, M., 2015a. Estimating effects of reforestation on nitrogen and phosphorus load reductions in the lower Yazoo River Watershed, Mississippi. *Ecol. Eng.* 75, 449–456.
- Ouyang, Y., Zhang, J.E., Li, Y.D., Parajuli, P., Feng, G., 2015b. Impacts of rainfall and air temperature variations due to climate change upon hydrological characteristics: a case study. *J. Water Clim. Change* 6, 865–879.
- Tank, A.M.G., Zwiers, F.W., Zhang, X., 2009. *Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation*. Climate Data and Monitoring, WCDMP-No. 72, World Meteorological Organization, WMO-TD No. 1500.
- Trisurat, Y., Eawpanich, P., Kalliola, R., 2016. Integrating land use and climate change scenarios and models into assessment of forested watershed services in Southern Thailand. *Environ. Res.* 147, 611–620.
- US-EPA, 2009. *BASINS 4.0 Climate Assessment Tool (CAT): Supporting Documentation and User's Manual*. Global Change Research Program National Center for Environmental Assessment Office of Research and Development U.S. Environmental Protection Agency, Washington, DC 20460. EPA/600/R-08/088F.
- Xu, H., Li, Y.D., Tuo, T.S., Lin, M.X., Chen, D.X., Mo, J.H., Luo, W., Hong, X.J., Jiang, Z.L., 2009. Community structure characteristics of tropical montane rain forests with different regeneration types in Jianfengling. *Scientia Silvae Sinicae* 45, 14–20 (in Chinese).
- Zeng, Q.B., Li, Y.D., Chen, B.F., Wu, Z.M., Zhou, G.Y., 1997. *Tropical Forest Ecosystem Research and Management*. Chinese Forestry Press, Beijing, China (in Chinese).
- Zhang, X., Zwiers, F.W., Hegerl, G.C., Lambert, F.H., Gillett, N.P., Solomon, S., Stott, P.A., Nozawa, T., 2007. Detection of human influence on twentieth-century precipitation trends. *Nature* 448, 461–465.
- Zhou, Z., Li, Y.D., Lin, M.X., Chen, D.X., Xu, H., Tuo, T.S., Qiu, J.L., 2009. Climate changes characteristics over tropical mountain rainforest in Jianfengling during the recent 26 years. *Acta Ecol. Sin.* 29, 1112–1120 (in Chinese).

- Zhou, G.Y., Wei, X.H., Wu, Y.P., Liu, S.G., Huang, Y.H., Yan, J.H., Zhang, D.Q., Zhang, Q.M., Liu, J.X., Meng, Z., Wang, C.L., Chu, G.W., Liu, S.Z., Tang, X.L., Liu, X.D., 2011. Quantifying the hydrological responses to climate change in an intact forested small watershed in Southern China. *Glob. Change Biol.* 17, 3736–3746.
- Zhou, Z., Ouyang, Y., Qiu, Z.J., Zhou, G.Y., Lin, M.X., Li, Y.D., 2016. Evidence of climate change impact on stream low flow from the tropical mountain rainforest watershed in Hainan Island, China. *J. Water Clim. Change* (in press).