Impacts of rainfall and air temperature variations due to climate change upon hydrological characteristics: a case study

Ying Ouyang, Jia-En Zhang, Yide Li, Prem Parajuli and Gary Feng

ABSTRACT

Rainfall and air temperature variations resulting from climate change are important driving forces to change hydrologic processes in watershed ecosystems. This study investigated the impacts of past and future rainfall and air temperature variations upon water discharge, water outflow (from the watershed outlet), and evaporative loss in the Lower Yazoo River Watershed (LYRW), Mississippi, USA using the HSPF model. Four future climate change (i.e., rainfall and air temperature change) scenarios, namely the CSIROMK35A1B, HADCM3B2, CSIROMK2B2, and MIROC32A1B scenarios, were used as input data to perform simulations in this study. Results showed that monthly variations of water discharge, evaporative loss, and water outflow were primarily due to the monthly fluctuations of rainfall rather than air temperature. On average, for all of the four scenarios, a 6.4% decrease in rainfall amount resulted in, respectively, 11.8 and 10.3% decreases in water outflow and evaporative loss. Our study demonstrated that rainfall had profound impacts upon water outflow and evaporative loss. In light of this predicted future decrease in water outflow, water resource conservation practices such as reducing ground and surface water usages that help to prevent streams from drying are vitally important in mitigating climate change impacts on stream flow in the LYRW.

Key words | evaporative loss, HSPF model, rainfall, temperature, water outflow, watershed

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INTRODUCTION

Climate change is a long-term change in statistical distribution of weather patterns over periods of time that range from decades to millions of years (Houghton *et al.* 2001). Climate change over the last several decades has been linked to changes in hydrological characteristics, including increasing atmospheric water vapor content; modifying rainfall patterns, intensity and extremes; reducing snow cover and widespread melting of ice; and changing soil moisture, surface runoff, and stream discharge (IPCC 2008; NRC 2008). Over the 20th century, rainfall has increased over land in high northern latitudes, but has decreased from 10 °S to 30 °N since the 1970s. Globally, the area of land classified as very dry has more than doubled since the 1970s (IPCC 2008).

Estimates of hydrologic characteristics (e.g., stream discharge, overland flow, and surface evaporation) are central to climate change assessment, water resource management, water supply engineering, environmental protection, and ecological restoration. In climate vulnerability assessment, hydrologic characteristics are important indicators of water responses to the climate change. Climate variability and change exacerbate these hydrologic characteristics

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and add the uncertainty and instability to these characteristics. To mitigate the likelihood of future climate impact, water resource managers must be able to assess potential risks and opportunities, and where appropriate, implement practices for adapting to future climatic conditions (Sarewitz *et al.* 2000; Pielke & de Guenni 2004).

Back in frontier days, the Lower Mississippi River Basin (LMRB) was considered as a water-rich region that supported a high standard of living and biodiversity. In the past decades, this region has, however, experienced increasing water stress due to climate change, land use conversion, and population increase. Extensive usages of ground and surface water leading to overdrafts and declines in water resources have resulted in water shortages (Konikow 2013), which are increasingly common and are more likely to become severe in the future. Although much attention has been given to estimate climate change impacts upon streamflows (Nazif & Karamouz 2014; Tan *et al.* 2014), very few efforts have been devoted to assessing the impacts of climate change upon hydrologic characteristics in the LMRB. Kim *et al.* (2014) assessed impacts of bioenergy crops and climate change on hydrometeorology in the Yazoo River Basin (YRB), which is a sub-basin within the LMRB. These authors showed that climate change is likely to affect hydrometeorology more significantly than bioenergy crop production. However, no effort has been made to investigate the impacts of rainfall and air temperature variations due to climate change upon water discharge, water outflow, and evaporative loss in this basin. Therefore, a need exists to undertake this issue.

The goal of this study was to evaluate the potential impact of future climate change (i.e., rainfall and air temperature variation) upon hydrologic characteristics such as stream discharge, surface evaporation, and water outflow in the Lower Yazoo River Watershed (LYRW), Mississippi, USA using the US-EPA's BASINS-HSPF model. Our specific objectives were to: (1) develop a site-specific model for the LYRW based on watershed, meteorological, and hydrological conditions; (2) calibrate and validate the resulting model using existing field measured data and/or aggregated data; and (3) apply simulation scenarios to project the potential impacts of future climate change upon hydrologic characteristics in the LYRW.

MATERIALS AND METHODS

Study site

The LYRW is located in the southern part of the YRB within the LMRB with an area of 618 km^2 (Figure 1). The main reason for choosing this watershed was the availability of some field-observed data that are necessary for model calibration and validation. The YRB is the largest river basin in Mississippi, USA and has a total drainage area of about 34,600 km^2. The LYRW in the YRB primarily consists of 61% forest land and 31% agriculture land. The rest of land uses are urban, wetland, and surface water. The soil types for this watershed are primarily sand, loam, and clay (Guedon & Thomas 2004; MDEQ 2008; Shields *et al.* 2008).

Surface water pollution within the LYRW includes excess nutrients, sediments, heavy metals, and herbicides which come from both point and nonpoint sources, and are the result of storm water runoff, discharge from ditches

Figure 1 | Location of modeled area in the Lower Yazoo watershed, Mississippi.

and creeks, groundwater seepage, aquatic weed control, naturally occurring organic inputs, and atmospheric deposition (Nett *et al.* 2004; Pennington 2004; Aulenbach *et al.* 2007; Alexander *et al.* 2008; Shields *et al.* 2008). The degradation of water quality due to these contaminants has resulted in altered species composition and decreased overall health of aquatic communities within the LYRW. In addition, the high sediment deposition rates in the LYRW can interrupt river navigation.

Model description

Better assessment science integrating point and nonpoint sources (BASINS) is a multipurpose environmental analysis system for use by regional, state, and local agencies in performing watershed and water quality-based studies. This software makes it possible to quickly assess large amounts of point source and nonpoint source data in a format that is easy to use and understand (US-EPA 2010). The hydrological simulation program-FORTRAN (HSPF) is a comprehensive model developed by the U.S. Environmental Protection Agency (US-EPA) for simulating many processes related to water quantity and quality in watersheds of almost any size and complexity (Bicknell *et al.* 2001).

Data acquisition

Data collection for the LYRW (HUC 08030208) includes watershed descriptions, meteorological, and hydrologic data. Several agencies are active in the data collection efforts. Most of the data used in this study such as land use, soil type, topography, rainfall, and discharge are from National Hydrography Dataset, US Geologic Survey National Water Information System, and 2001 National Land Cover Data. These data can be downloaded directly from the Metadata Section of BASINS. Some stream discharge data within the basin were obtained from the local USGS monitoring stations (#07288955, #07289000, and #0728875070). These data were aggregated and disaggregated to better suit the average watershed conditions.

It should be noted that past climate data, such as rainfall and air temperature, were obtained from weather stations and/or USGS monitoring stations in Vicksburg, Leland, and Belzoni within the YRB. These data were aggregated and adjusted to represent the entire basin conditions. The potential evapotranspiration data were computed based on air temperature using the WDMUtil package from the HSPF model. These local past climate data were used only for model calibration and validation purposes.

Four future climate change scenario data were used in this study. They are HADCM3B2 (Hadley Centre for Climate Prediction and Research), CSIROMK35A1B and CSIROMK35A1B (Australian Commonwealth Scientific and Research Organization Atmospheric Research), and MIROC32A1B (Center for Climate System Research, University of Tokyo National Institute for Environmental Studies and Frontier Research Center for Global Change). These data are monthly air temperature and rainfall for a period from 2001 to 2050, which were obtained from the Rocky Mountain Research Station, USDA Forest Service (http://www.treesearch.fs.fed.us/pubs/37123; http://www.treesearch.fs.fed.us/pubs/37119). These data were generated by General Circulation Models and Center for Climate System Research National Institute for Environmental Studies and Frontier Research Center for Global Change, University of Tokyo. The data were scaled to the 8-digit HUC watersheds for different regions. The YRB watershed is within the HUC 08030208 region. Descriptive statistics for the air temperature and rainfall data from 2001 to 2050 used in this study are given in Table 1. This table revealed that the total amount of rainfall was in the following order: CSIROMK35A1B > HADCM3B2 > CSIROMK2B2 > MIROC32A1B, whereas the magnitude of temperature was in the following order: MIROC32A1B > CSIROMK35A1B > CSIROMK2B2 > HADCM3B2. These four future climate change scenario data were used to project the impact of future climate changes upon water discharge, evaporative loss, and water outflow in the LYRW. These four climate change scenarios were chosen because they are considered as better scenarios to represent future climate conditions in the southeast USA (Marion *et al.* 2014).

Model development

In general, the development of a hydrological model in BASINS begins with watershed delineation. This process requires the set-up of a digital elevation model in the ArcInfo grid format, creation of stream networks in shape

Table 1 | Descriptive statistics of rainfall and air temperature data used in this study

Scenario	CSIROMK35A1B	HADCM3B2	CSIROMK2B2	MIROC32A1B
Rainfall (mm)				
Mean	122.29	116.46	113.47	99.21
Standard error	2.74	1.83	1.62	2.13
Median	97.30	106.10	108.00	87.45
Standard deviation	94.87	63.47	56.08	73.67
Minimum	0.00	0.00	0.00	0.00
Maximum	566.00	546.90	359.00	832.90
Sum	146,748.80	139,756.50	136,161.20	119,056.80
Air temperature (°C)				
Mean	20	20	20	21
Standard error	0.22	0.22	0.24	0.23
Median	20	20	20	21
Standard deviation	8	8	8	8
Minimum	2	4	0	4
Maximum	35	34	35	39

format, and creation of watershed inlets or outlets using the BASINS watershed delineation tool. Hydrologic models like HSPF require 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.

The HSPF model has a modular structure and is a lumped parameter model. 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 is 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. Detailed information about the structure and functioning of these modules can be found in the literature (Donigian & Crawford 1976; Donogian *et al.* 1984; Chen *et al.* 1998). 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, interflow and groundwater behavior. In the RCHRES module, section HYDR was utilized to simulate the hydraulic behavior of the stream.

The key steps in modeling a watershed with HSPF are the mathematical representation of the watershed, the preparation of input meteorological and hydrological time series, the estimation of parameters, and the calibration and validation process. The time series are fed to the model by utilizing a stand-alone program called the Watershed Data Management Utility program provided in BASINS.

Model calibration and validation

Model calibration is a process of adjusting input parameters within a reasonable range to obtain a match between field observations and model predictions, whereas model validation is a process of verifying the calibrated model by comparing field observations and model predictions without adjusting any input parameter values. In this study, the hydrologic component was calibrated for a 5-year period from 1 January 2000 to 31 December 2004. To obtain fewer uncertainties in the hydrologic calibration process, we only adjusted the values of the following six hydrologic parameters: LZSN, UZSN, INFILT, LZETP, INTFW, and IRC, which are defined in Table 2. These parameters are most sensitive to the HSPF model predictions (Donogian *et al.* 1984).

Table 2 | Input parameter values used in model calibration

Parameter	Value/Unit	References
LZSN (lower zone nominal storage)	5.08 cm	US-EPA 2000
UZSN (upper zone nominal storage)	0.25 cm	US-EPA 2000
INFILT (index to the infiltration capacity of the soil)	0.2	US-EPA 2000
LZETP (lower zone ET parameter)	0.5	US-EPA 2000
INTFW (interflow inflow parameter)	0.2	US-EPA 2000
IRC (interflow recession parameter)	0.3 day^{-1}	US-EPA 2000

Comparison of the observed and predicted annual water outflow (through watershed outlet) volume is given in Table 3. The annual differences in errors between the observed and predicted water outflow volumes were about 6% and were therefore acceptable (Bicknell *et al.* 2001). With the regression equation of prediction = 0.9713*observation and $R^2 = 0.978$, we determined that a very good agreement was obtained between the field observations and model predictions during the model calibration process.

Daily mean discharge data were used to examine peak flows graphically between the observations and the predictions (Figure 2). The peak flows between the observations and the predictions were good matches. The monthly mean discharges between the observations and the predictions were used for regression analysis. With the regression equation of predictions = 0.9248*observation and $R^2 = 0.9522$, we concluded that a very good agreement was obtained between the observations and the predictions during the model calibration process.

Table 3 | Comparison of the simulated and observed annual water outflow volumes during model calibration and validation processes

Year	Simulated outflow (m^3)	Observed outflow (m^3)	Percent difference
Model calibration			
2000	1,766,344,792	1,751,003,632	0.88
2001	2,046,344,979	1,924,378,378	6.34
2002	1,926,697,322	1,933,900,443	−0.37
2003	1,154,784,912	1,158,763,694	−0.34
2004	2,001,939,663	1,896,082,283	5.58
Total	8,896,111,668	8,664,128,430	2.68
Model validation			
2005	1,323,525,113	1,302,106,745	1.64
2006	1,325,992,075	1,354,454,618	−2.10
2007	1,203,754,108	1,190,249,632	1.13
2008	971,489,636	947,433,535	2.54
2009	1,958,767,828	1,823,795,811	7.40
Total	6,783,528,760	6,618,040,341	2.50

Comparison of annual water outflow between the observations and predictions for a period from 1 January 2005 to 31 December 2010 during the model validation process is given in Table 3 and Figure 2. The regression equation of predictions = 0.969*observation and $R^2 = 0.9987$ supported that a very good agreement was obtained between the model predictions and the field observations during the model validation process.

SIMULATIONS

Four simulation scenarios, namely the CSIROMK35A1B, HADCM3B2, CSIROMK2B2, and MIROC32A1B scenarios, were performed for a simulation period of 50 years (2001–2050) in this study. The purpose of these scenario analyses was to project the potential impact of future climate changes (i.e., the rainfall and air temperature changes) upon hydrologic characteristics such as stream water discharge, surface water evaporation, and basin water outflow in the LYRW. In these four simulation scenarios, the only differences were the time series air temperature and rainfall variations. All other factors and conditions such as land uses, soil types, and topographies used in this study were kept the same for all of the four simulation scenarios. Characteristics of air temperature and rainfall from 2001 to 2050 are given in Table 1 and were briefly discussed in the data acquisition section above. Details of simulation results for each scenario are presented below.

Water discharge

Changes in monthly mean water discharge at the LYRW outlet (Figure 1) for the four simulation scenarios during a 10-year simulation period from 2011 to 2020 are given in Figure 3(a). In general, the monthly mean water discharge varied from year to year and from scenario to scenario. For example, the largest monthly mean water discharge

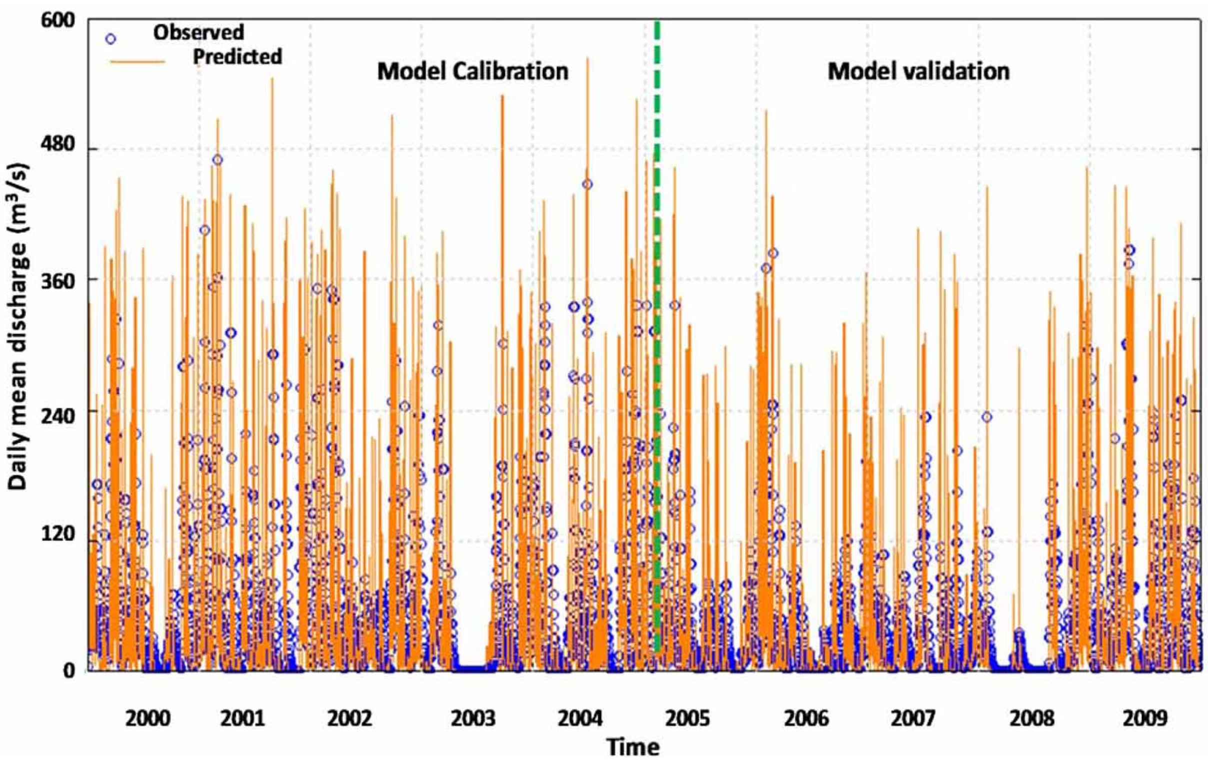

Figure 2 | Comparisons of the observed and predicted daily mean flow rates during model calibration and validation processes.

was 138 m^3/s for the MIROC32A1B scenario in 2016 and was 61 m^3/s for the HADCM3B2 scenario in 2012. The former was about 2.3 times larger than the latter. This was basically consistent with rainfalls for those scenarios (Figure 4(a)) because rainfall is a major driving force for stream discharge.

Figure 3(b) shows the annual sum water discharge for the four simulation scenarios during a 10-year simulation period from 2011 to 2020. Analogous to the case of monthly mean water discharge, the total annual water discharge for each scenario varied from year to year. The discharge was highly correlated to the annual rainfall. For example, a highest annual sum water discharge was obtained in 2016 for the MIROC32A1B scenario (Figure 3(b)), which occurred because there was a highest annual rainfall during the same time for this scenario (Figure 4(a)). A plot of the annual mean water discharge against the annual rainfall further confirmed this finding (Figure 5). There were very good positive correlations (R^2 ranged from 0.82 to 0.91) between the annual mean discharge and the annual rainfall for those four scenarios.

Variations in monthly maximum water discharge for the four simulation scenarios during a 10-year simulation period from 2011 to 2020 are given in Figure 6(a). Analogous to the case of the monthly mean water discharge, the largest monthly maximum water discharge (148 m^3/s) was observed for the MIROC32A1B scenario. This was the case because the MIROC32A1B scenario had the highest rainfalls (Figure 4(a)). Rainfall was a major driving force for stream water discharge. As the intensity of rainfall increased so was the rate of water discharge in the stream.

Figure 6(a) also revealed that the CSIROMK2B2 scenario had the lowest monthly maximum water discharge among the four simulation scenarios during most of the years for this simulation period. The largest monthly maximum water discharge for the CSIROMK2B2 scenario was 68 m^3/s, which was more than two-fold lower than that of the MIROC32A1B scenario. This occurred because the CSIROMK2B2 scenario had the lowest maximum rainfall (Table 1). It was, therefore, apparent that rainfall had positive effects on stream water discharge, i.e., the increase in the amount and maximum rainfalls was proportional to

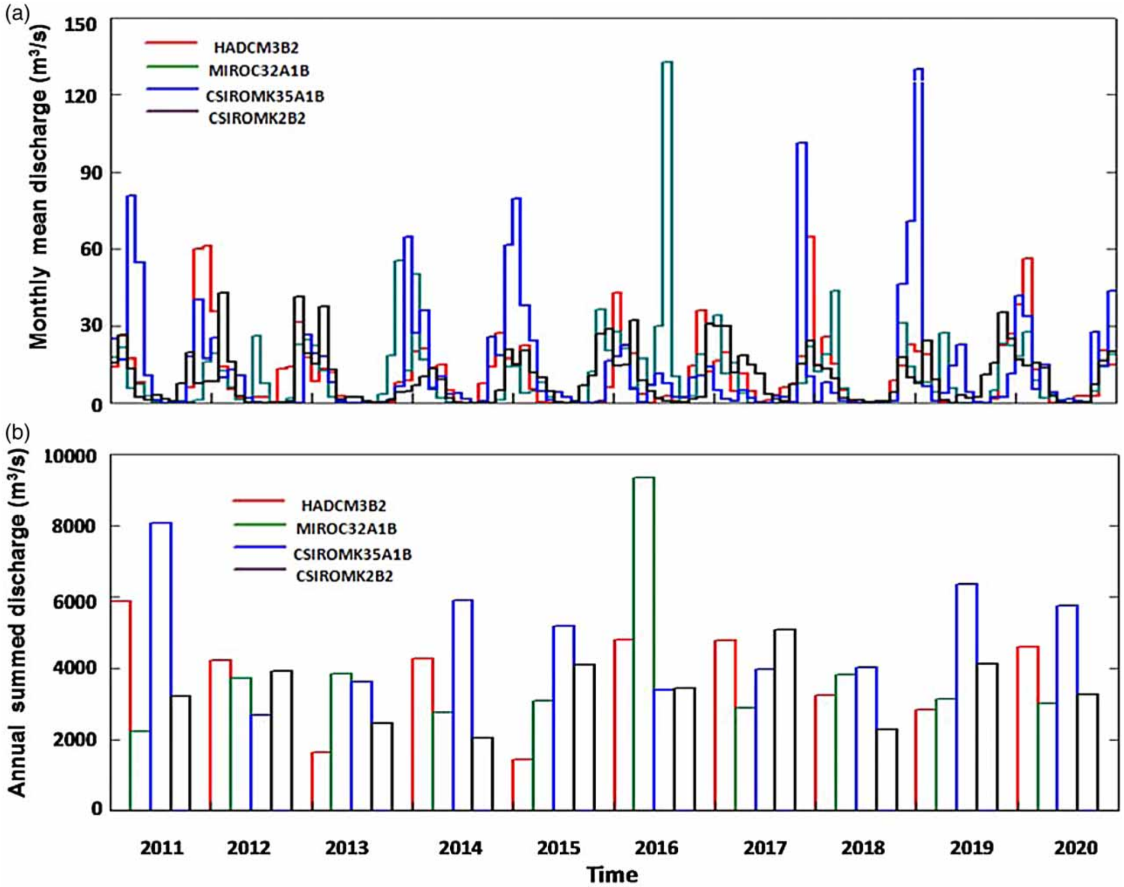

Figure 3 | Simulated and monthly mean (a) and annual sum (b) water discharge for the four simulation scenarios.

the increase in the magnitude and maximum stream water discharges.

Differences in monthly minimum water discharge for the four simulation scenarios during a 10-year simulation period from 2011 to 2020 are given in Figure 6(b). Similarly to the case of monthly maximum water discharge, the largest monthly minimum water discharge was 68 m^3/s for the MIROC35A1B scenario and was 67 m^3/s for the CSIROMK2B2 scenario. The former was slightly larger than the latter. This happened due to the same reason as for the case of the monthly maximum water discharge.

Table 4 lists the sum, mean, maximum, and minimum values of water discharge among the four simulation scenarios for a 50-year simulation period from 2001 to 2050. The 50-year sum of water discharge was in the following order: CSIROMK35A1B > HADCM3B2 > MIROC32A1B > CSIROMK2B2. For example, the 50-year sum of water discharge was 249,000 m^3/s for the CSIROMK35A1B scenario, but was 172,000 m^3/s for the CSIROMK2B2 scenario. The former was about 1.4 times larger than the latter as a result of greater amount of total rainfall for the CSIROMK35A1B scenario (Table 1). A similar order was observed for the 50-year mean water discharge.

Table 4 further reveals that the 50-year maximum water discharge was in the following order: CSIROMK35A1B > MIROC32A1B > HADCM3B2 > CSIROMK2B2. For example, the maximum water discharge was 161 m^3/s for the CSIROMK35A1B scenario, but was 81.8 m^3/s for the CSIROMK2B2 scenario. The former was 1.9 times larger than the latter. This occurred because the CSIROMK35A1B scenario had much higher maximum rainfall (Table 1).

Evaporative loss

Figure 7 shows the volumes of monthly mean, maximum, and minimum water evaporative loss for the four simulation

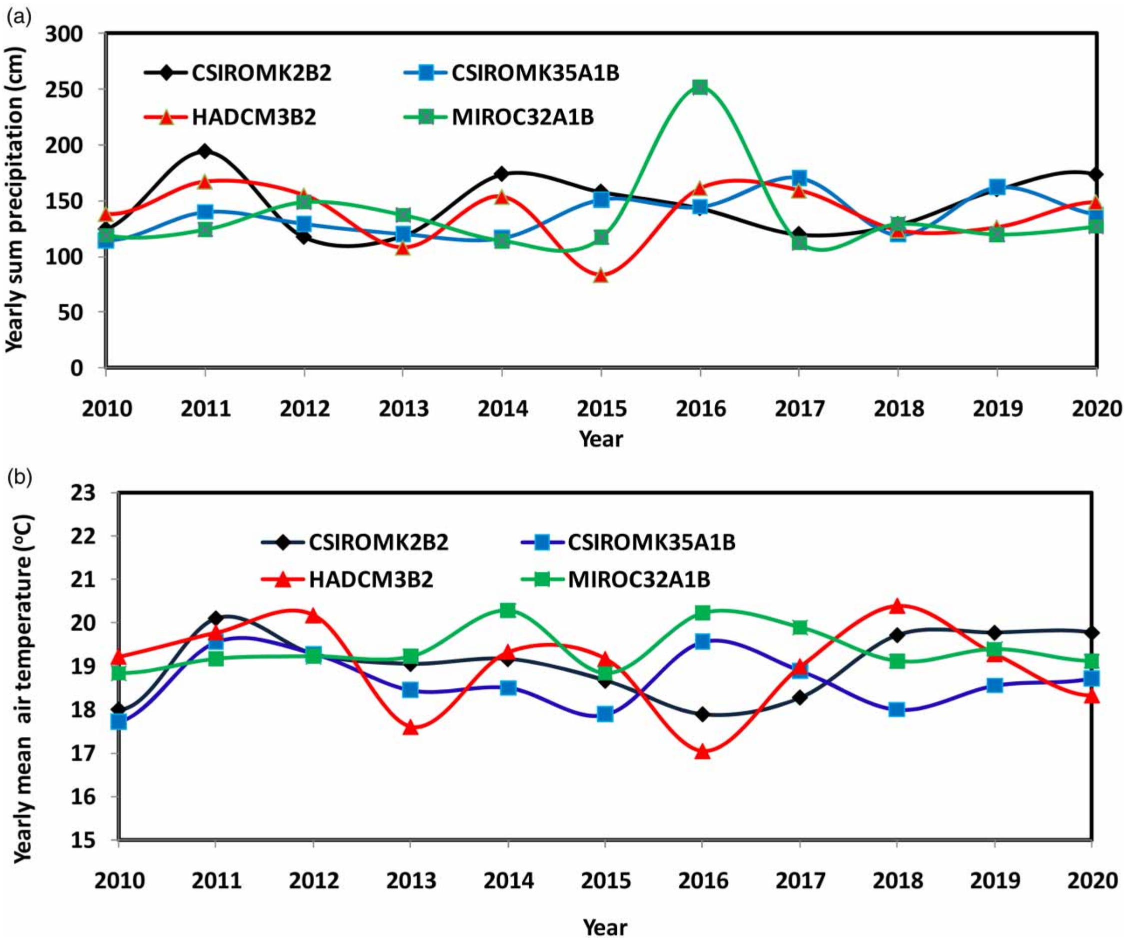

Figure 4 | Annual sum precipitation (a) and mean air temperature (b) for the four future climate charge scenarios. Precipitation and air temperature were used as input data for simulations.

scenarios during a 10-year simulation period from 2011 to 2020. These volumes varied from year to year as well as from scenario to scenario, and mixed results were obtained. There were two highest monthly mean evaporative losses during 2012 and 2016 for the MIROC32A1B scenario, during 2016 and 2019 for the CSIROMK35A1B scenario, and during 2017 and 2020 for the CSIROMK2B2 scenario, whereas there was only one highest monthly mean evaporative loss during 2014 for the HADCM3B2 scenario (Figure 7 (a)). The largest monthly mean evaporative loss was in the following order: MIROC32A1B (583 m^3) > CSIROMK35A1B (578 m^3) > HADCM3B2 (394 m^3) > CSIROMK2B2 (391 m^3). In general, the MIROC32A1B scenario had the highest air temperature for this simulation period (Figure 4(b)) and resulted in the largest monthly mean evaporative loss. Overall, we attributed these mixed results to variations in air temperature, rainfall, and soil moisture content during those particular years. It should be noted that the land uses such as agricultural and forest lands were kept the same for all of the four simulation scenarios used in this study.

Analogous to the case of monthly mean evaporative loss, the monthly maximum evaporative loss for each scenario varied from year to year (Figure 7(b)). The largest monthly maximum evaporative loss for those four simulation scenarios was in the following order: MIROC32A1B (717 m^3) > CSIROMK35A1B (677 m^3) > CSIROMK2B2 (517 m^3) > HADCM3B2 (467 m^3). This occurred because the MIROC32A1B scenario had the highest air temperature and rainfall (Figure 4). Higher air temperature and rainfall would result in larger maximum evaporative loss.

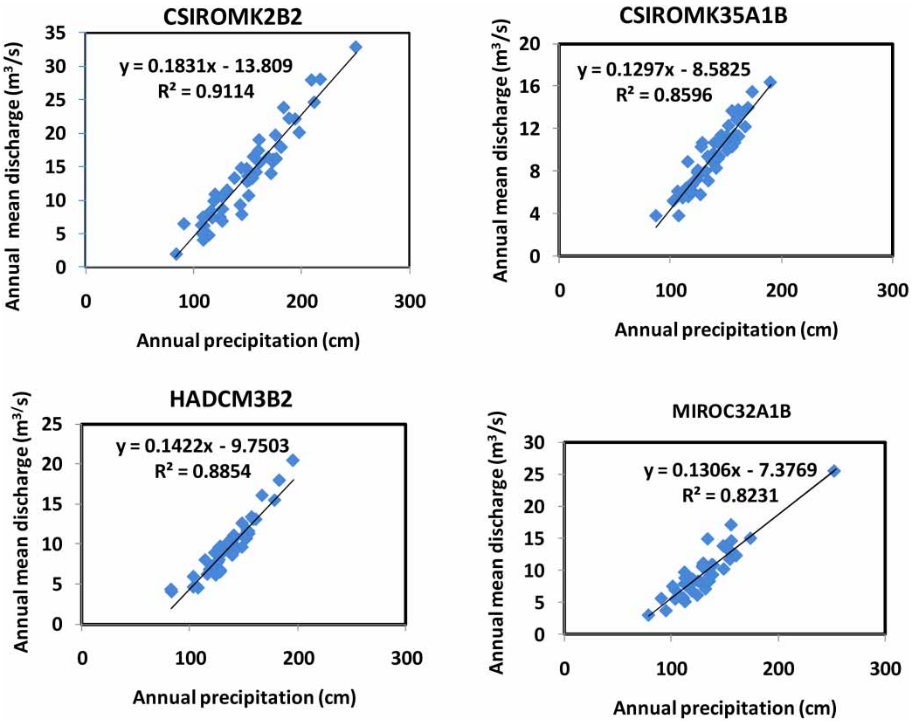

Figure 5 | Relationships of annual precipitation to annual mean water discharge among the four simulation scenarios.

Changes in monthly minimum evaporative loss for the four simulation scenarios during a 10-year simulation period from 2011 to 2020 are given in Figure 7(c). Similarly to the case of monthly maximum evaporative loss, the MIROC32A1B scenario had the highest and the HADCM3B2 scenario had the lowest monthly minimum evaporative loss for this simulation period. The largest monthly minimum evaporative loss was 511 m^3 for MIROC32A1B, but was 323 m^3 for HADCM3B2. This occurred because the MIROC32A1B scenario had higher air temperature and rainfall than the HADCM3B2 scenario.

Table 4 lists the sum, mean, maximum, and minimum values of water evaporative loss among the four simulation scenarios for a 50-year simulated period from 2001 to 2050. The 50-year sum of water evaporative loss was in the following order: CSIROMK2B2 (1.93×10^6 m^3) > HADCM3B2 (1.88×10^6 m^3) > CSIROMK35A1B (1.63×10^6 m^3) > MIROC32A1B (1.57×10^6 m^3). A similar order was observed for the 50-year mean water evaporative loss. Table 4 also shows that the 50-year maximum evaporative loss was in the following order: CSIROMK2B2 > CSIROMK35A1B > HADCM3B2 > MIROC32A1B. For example, the volume of maximum evaporative loss was 764 m^3 for the CSIROMK2B2 scenario, but was 598 m^3 for the MIROC32A1B scenario.

It should be kept in mind that the volumes of the sum, mean, maximum, and minimum evaporative loss for each scenario changes for different simulation periods due to the variations in air temperature and rainfall for each simulation period. Evapotranspiration is a complicated process, which depends not only on air temperature, rainfall, solar radiation, wind speed, and soil moisture content, but also on their combined effects, such as time intervals and durations when the high air temperature and rainfall occurred. In addition, land use pattern (agricultural and forestry) also plays an important role in evapotranspiration although this pattern was kept the same for all of the four simulation scenarios used in this study.

Water outflow

Changes in monthly mean water outflow through the LYRW outlet for the four simulation scenarios during a 10-year simulation period from 2011 to 2020 are given in Figure 8(a).

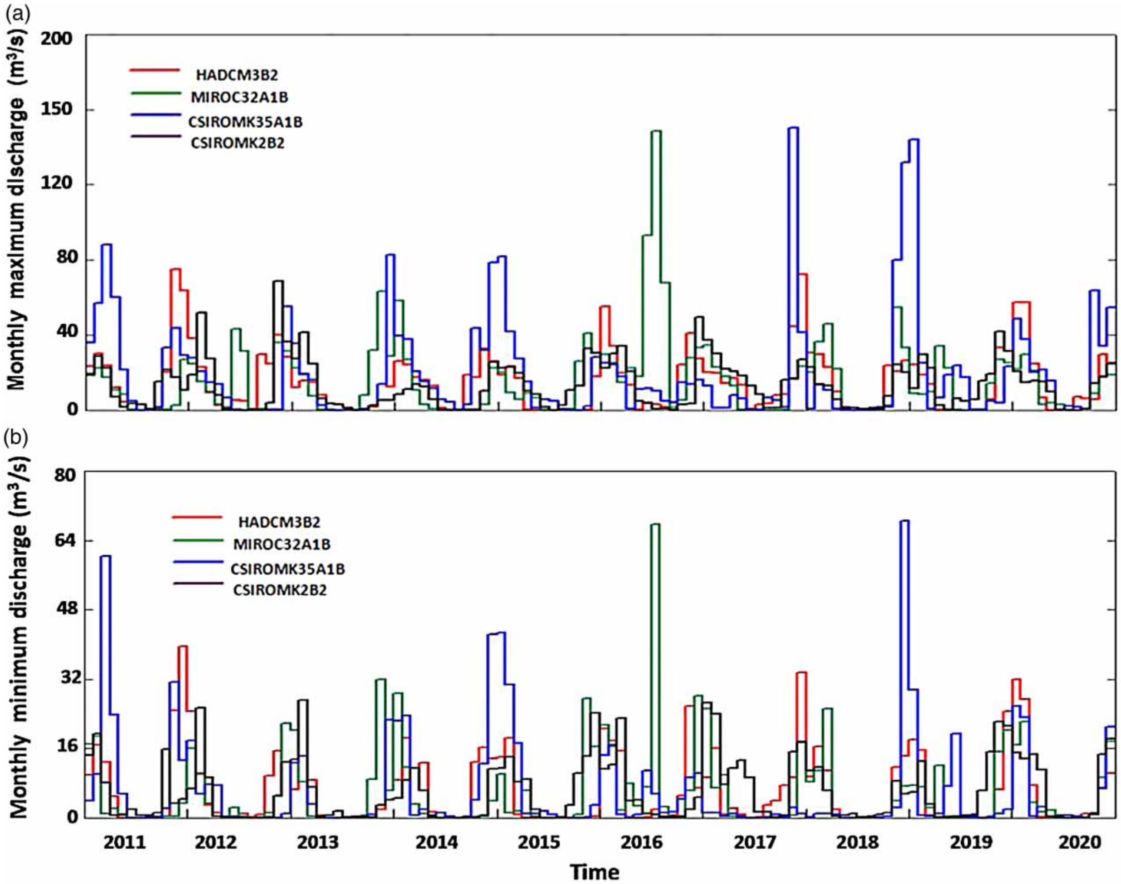

Figure 6 | Simulated monthly maximum (a) and minimum (b) water discharge among the four simulation scenarios.

Analogous to the case of water discharge and evaporative loss, the volumes of water outflow varied from year to year and from scenario to scenario. The largest monthly mean water outflow during this period was 478,000 m^3 for MIROC32A1B, but was 133,000 m^3 for CSIROMK2B2. The former was 3.6 times larger than the latter. This occurred because the MIROC32A1B scenario was wetter (higher rainfall) while the CSIROMK2B2 scenario was drier (lower rainfall) during this period (Figure 4(a)).

Figure 8(b) shows the volumes of the monthly maximum water outflow for the four simulation scenarios during a 10-year simulation period from 2011 to 2020. Similarly to the case of the monthly mean water outflow, the MIROC32A1B scenario had the largest monthly maximum water outflow (534,000 m^3). This was the case because the MIROC32A1B scenario had the highest rainfall during this simulated period (Figure 4(a)). Rainfall is a major controlling factor for water outflow. An increase in rainfall would result in an increase in water outflow.

Differences in monthly minimum water outflow for the four simulation scenarios during a 10-year simulation period from 2011 to 2020 are given in Figure 8(c). A similar pattern was obtained as that in the case of the monthly maximum water outflow. That is, the largest monthly minimum water outflow was found in 2016 for scenario MIROC32A1B and in 2013 for CSIROMK2B2. The former (243,000 m^3) was about 2.6-fold larger than the latter (41,300 m^3). This occurred for the same reason as for the case of the monthly maximum water outflow.

Table 4 lists the sum, mean, maximum, and minimum values of water outflow among the four simulation scenarios for a 50-year simulation period from 2001 to 2050. The 50-year sum water outflow was in the following order: CSIROMK35A1B > HADCM3B2 > CSIROMK2B2

Table 4 | The sum, mean, maximum, and minimum values of water discharge, evaporative loss, and water outflow among the four scenarios for a 50-year simulation period

Scenario	HADCM3B2	MIROC32A1B	CSIROMK35A1B	CSIROMK2B2
	Flow (m^3/s)			
	50-years simulation (2001–2050)			
Sum	177,000	174,000	249,000	172,000
Mean	9.71	9.55	13.6	9.43
Maximum	98.5	148	161	81.8
Minimum	0	0	0	0
	Evaporative loss (m^3)			
	50-years simulation (2001–2050)			
Sum	1.88×10^6	1.57×10^6	1.63×10^6	1.93×10^6
Average	103	86.1	89.5	106
Maximum	603	598	717	764
Minimum	0	0	0	0
	Water outflow (m^3)			
	50-years simulation (2001–2050)			
Sum	6.18×10^8	6.05×10^8	7.96×10^8	6.06×10^8
Average	33,800	33,100	43,600	33,200
Maximum	2,160,000	2,150,000	2,160,000	2,160,000
Minimum	0	0	0	0

> MIROC32A1B. Table 4 further reveals that the 50-year maximum water outflow had the same order as that of the sum water outflow. It is, therefore, apparent that the rainfall had tremendous effects on water outflow.

Past and future comparison

The impact of rainfall upon evaporative loss and water outflow between the past 10 years (2001–2010) and the future 10 years (2011–2020) for each simulation scenario is given in Table 5. This table shows that the sum and mean values of rainfall from the past 10 years to the future 10 years were decreased for all of the four simulation scenarios, which had resulted in decreasing evaporative loss and water outflow. For example, a 14.49% decrease in the sum of rainfall from the past 10 years to the future 10 years had resulted in a 25.81% decrease in the sum of water outflow for the CSIROMK35A1B scenario. Similar water outflow patterns were observed for other scenarios. As the sum of rainfall decreased from the past 10 years to the future 10 years, the sum of evaporative loss also decreased for most of the simulation scenarios except for the CSIROMK2B2 scenario. Our simulations suggested that the total amount of rainfall had profound impacts upon water outflow and evaporative loss in the LYRW.

Analogous to the case of the sum of rainfall, a decrease in mean rainfall from the past 10 years to future 10years had resulted in a decrease in mean water outflow. For example, a 7.62% decrease in mean rainfall from the past 10 years to the future 10 years had resulted in 10.74% and 12.68% decreases, respectively, in evaporative loss and water outflow for the HADCM3B2 scenario. On average, for all of the four scenarios, a 6.4% decrease in rainfall resulted in a 11.8% decrease in water outflow and 10.3% decrease in evaporative loss.

Unlike the case of the sum and mean rainfalls, there were no apparent correlations between the maximum rainfall and maximum water outflow. It seems that maximum water outflow through the basin outlet could also depend on topography and stream channel matrix. In addition, the impact of air temperature on evaporative loss cannot be deduced from this study. This is because evapotranspiration is a complex process, which is governed not only by air temperature, but also by rainfall, vegetation, and soil

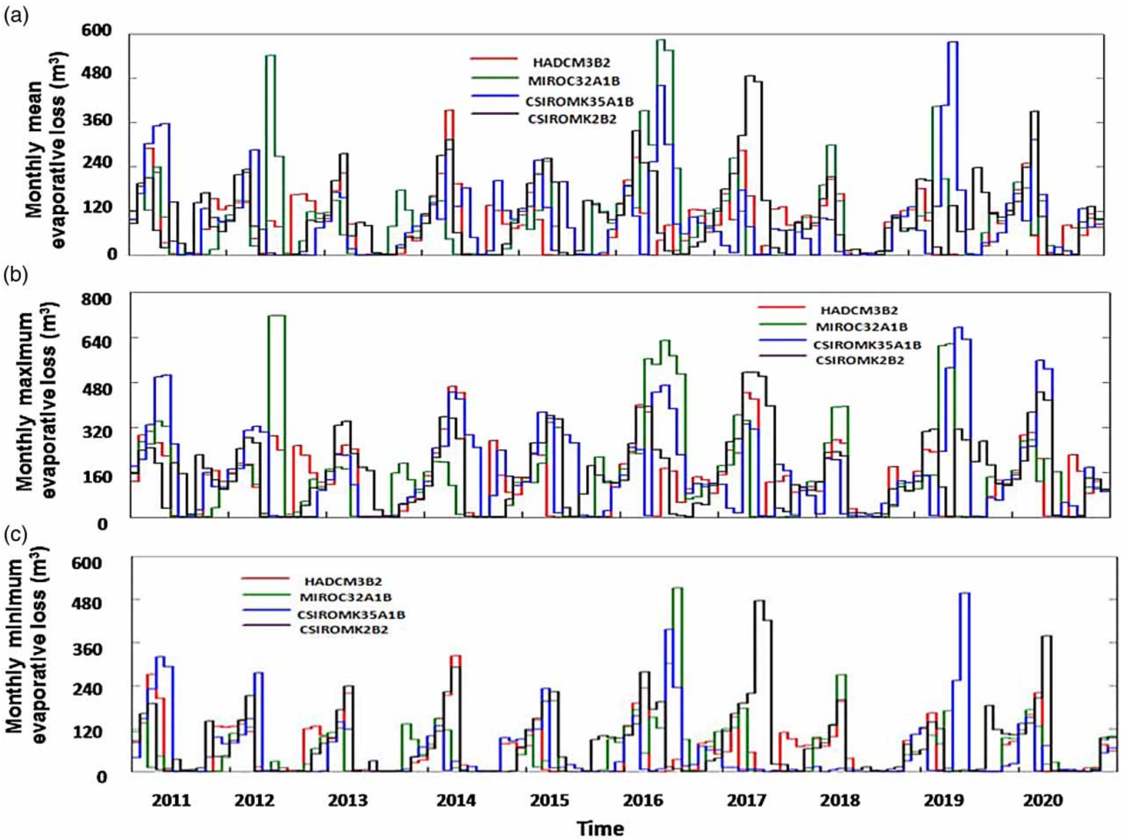

Figure 7 | Simulated monthly mean (a), maximum (b), and minimum (c) evaporative loss among the four simulation scenarios.

moisture content. A plot of our simulated evaporative loss against air temperature did show any good correlations for all of the simulation scenarios (figure not shown). These correlations could be masked by the rainfall. To compare the impact of air temperature on evaporative loss between the past 10 years and the future 10 years, simulations must be performed with changing air temperature but with the same rainfall for the past and future 10 years. This is not the case in this study. Further study is thus warranted to undertake this issue.

SUMMARY

In this case study, impact of future climate change upon water discharge, evaporation, and outflow in the LYRW, Mississippi was examined using the US EPA's BASINS-HSPF model. The model was calibrated using 5-year (2000–2004) local measured and aggregated data and validated using another 5-year (2005–2010) local measured and aggregated data prior to its applications. Very good agreements were obtained between the model predictions and the field observations during model calibration and validation.

Four simulation scenarios were then performed to investigate the water discharge, evaporative loss, and water outflow in response to rainfall and air temperature over a 50-year period from 2001 to 2050. They were CSIROMK35A1B, HADCM3B2, CSIROMK2B2, and MIROC32A1B scenarios. The future climate change data (i.e., air temperature and rainfall) for these four simulation scenarios were obtained from the Rocky Mountain Research Station, USDA Forest Service for LYRW (HUC 08030208).

In general, the monthly water discharge, evaporative loss, and outflow varied from year to year as well as from scenario to scenario, which was primarily due to the monthly fluctuations in rainfall. There were very good positive correlations (R^2 ranged from 0.82 to 0.91) between the annual mean discharge and the annual rainfall for those four scenarios.

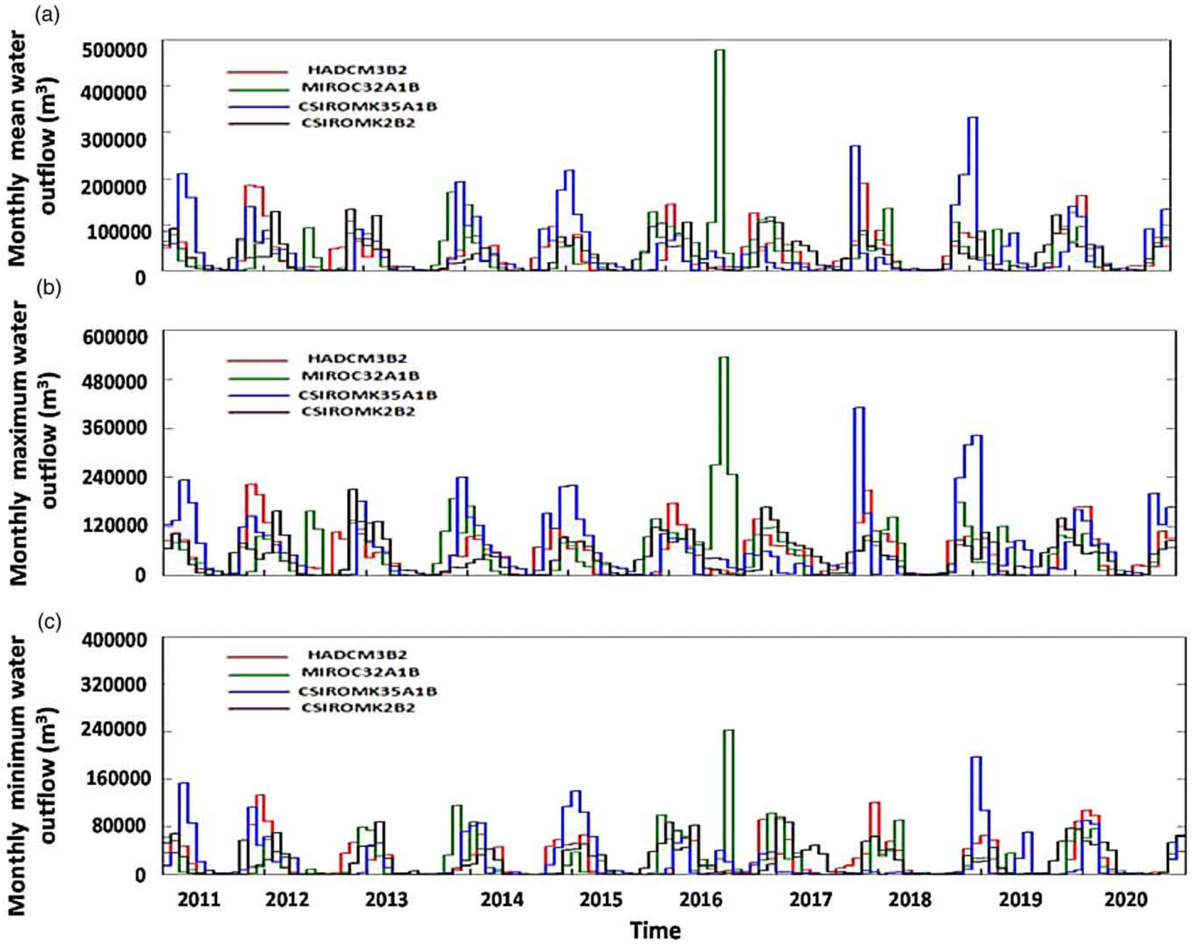

Figure 8 | Simulated monthly mean (a), maximum (b), and minimum (c) water outflow among the four simulation scenarios.

Table 5 | Comparison of the sum and mean values for rainfall, evaporative loss, and water outflow between the past and future 10 years

	Precipitation (cm)			**Evaporative loss (m^3)**			**Water outflow (m^3)**		
Scenario	**Past 10 years (2001–2010)**	**Future 10 years (2011–2020)**	**% Change**	**Past 10 years (2001–2010)**	**Future 10 years (2011–2020)**	**% Change**	**Past 10 years (2001–2010)**	**Future 10 years (2011–2020)**	**% Change**
	Sum								
HADCM3B2	1,478	1,374	−7.58	339,000	306,000	−10.78	146,000,000	130,000,000	−12.31
MIROC32A1B	1,397	1,374	−1.66	365,000	348,000	−4.89	135,000,000	133,000,000	−1.50
CSIROMK35A1B	1,646	1,438	−14.49	456,000	344,000	−32.56	195,000,000	155,000,000	−25.81
CSIROMK2B2	1,387	1,369	−1.30	351,000	378,000	7.14	127,000,000	120,000,000	−5.83
	Mean								
HADCM3B2	0.0169	0.0157	−7.62	92.8	83.8	−10.74	40,000	35,500	−12.68
MIROC32A1B	0.0160	0.0157	−1.78	99.9	95.2	−4.94	37,000	36,300	−1.93
CSIROMK35A1B	0.0188	0.0164	−14.73	125	94.1	−32.84	53,300	42,300	−26.00
CSIROMK2B2	0.0158	0.0156	−1.30	96.2	104	7.50	34,800	32,700	−6.42

The sum, mean, maximum, and minimum values of water discharge, evaporative loss, and water outflow for those four simulation scenarios varied with simulation periods. For a 50-year simulation period, the sum and mean water discharges were in the following order: CSIROMK35A1B > HADCM3B2 > MIROC32A1B > CSIROMK2B2, whereas the maximum water discharge was in the following order: CSIROMK35A1B > MIROC32A1B > HADCM3B2 > CSIROMK2B2; the sum and mean water evaporative losses were in the following order: CSIROMK2B2 > HADCM3B2 > CSIROMK35A1B > MIROC32A1B, whereas the maximum evaporative loss was in the following order: CSIROMK2B2 > CSIROMK35A1B > HADCM3B2 > MIROC32A1B; and the sum, mean, and maximum water outflows were in the following order: CSIROMK35A1B > HADCM3B2 > CSIROMK2B2 > MIROC32A1B. We attributed the discrepancies to the highly nonlinear and dynamic variations in rainfall for different simulation periods.

Comparison of simulation results between the past 10 years (2001–2010) and the future 10 years (2011–2020) showed that the sum and mean rainfalls from the past 10 years to the future 10 years decreased for all of the four simulation scenarios, which had resulted in decreased evaporative loss and water outflow. On average, for all of the four scenarios, a 6.4% decrease in rainfall resulted in a 11.8% decrease in water outflow and 10.3% decrease in evaporative loss. Our simulations suggested that the total amount of rainfall had profound impacts upon water outflow and evaporative loss in the LYRW.

The impact of air temperature on evaporative loss cannot be deduced from this study. This is because evapotranspiration is a complex process, which is governed not only by air temperature, but also by rainfall, vegetation, and soil moisture content. A plot of our simulated evaporative loss against air temperature did show any good correlations for all of the simulation scenarios. These correlations could be masked by the rainfall. To compare the impact of air temperature on evaporative loss between the past 10 years and the future 10 years, simulations must be performed with changing air temperature but with the same rainfall for the past and future 10 years.

Further study is thus warranted to investigate the impact of the percentage changes in future air temperature, rainfall, and forested land upon water discharge, evaporative loss, and water outflow in the LYRW. This could be accomplished by changing one of three input parameters (i.e., air temperature, rainfall, and forested land) while keeping the other two input parameters unchanged for those four simulation scenarios. It should be pointed out that although the air temperature and rainfall data from those four scenarios generated from the General Circulation Models have been widely used around the world, caution should be given to validating their accuracy using local observations when such observations are available.

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