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Assessing Impacts of Projected Climate Change on the Streamflow of Kesinga Catchment, India using the SWAT Model

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ABSTRACT: Climate change has significantly affected the hydrological cycle and future climate projections. Understanding the impacts of climate change on streamflow necessitates the examination of various climate scenarios using hydrological models. The present study used the Soil and Water Assessment Tool (SWAT) model to predict and project streamflow in a catchment. High-resolution future climate data from CSIRO-QCCCE-CSIRO and CCCma-CanESM2 models obtained from CORDEX are generated for impact assessment. The hydrological response of the catchment is assessed by dividing the future time scales into mid-century (2021-2050) and end-century (2071-2099) with two scenarios: Representative Concentration Pathway (RCP) 4.5 and 8.5. The climate projection results indicate an increase in both maximum (up to 3.7℃) and minimum (up to 2.9℃) temperatures, along with an expected increase in precipitation of up to 14.8%. Additionally, streamflow is projected to increase by up to 21% to 172% in the mid-century and decrease by 28% or increase by 160% in the end-century under different streamflow scenarios. The results of this study highlight the impact of climate change on streamflow in the Kesinga catchment and provide a scientific basis for adaptive management.

Keywords: Precipitation, Temperature, CORDEX, Future scenarios, SWAT model, streamflow.

INTRODUCTION

Water is a fundamental resource provided by nature to humanity and is susceptible to the effects of climate change (Ahmed *et al.,* 2020). It is essential for various human activities such as industry, domestic use, and agriculture, and its availability is affected by changes in precipitation patterns and increasing temperatures caused by climate change (David *et al*., 2004). Since the late 19th century, the Intergovernmental Panel on Climate Change has stressed with a very high degree of confidence that both land and ocean surface temperatures have risen within the range of 0.4–0.7°C (Nearing, 2005). This warming trend is attributed to human actions, primarily the burning of fossil fuels and deforestation.

The IPCC's fifth assessment incorporated four greenhouse gas concentration trajectories based on the Coupled Inter-Comparison Model Project Phase 5 (CMIP-5) climate change scenarios (Bhatta *et al.,* 2019). These four scenarios are RCP 2.6 (with radiative forcing peaking in the middle of the twenty-first century and decreasing to a level of 2.6 W/m²), RCP 4.5 (an intermediate scenario), and RCP 8.5 (a high scenario with radiative forcing reaching 8.5 W/m² before the 21st century) (Londhe and Katpatal 2020; Bisht *et al.,* 2020). Hydrological models incorporate data inputs derived from Global Climate Models (GCMs), including variables like precipitation and temperature projections (Azari *et al*., 2016; Bisht *et al.,* 2020). Accurate predictions of streamflow changes, which are directly linked to climatic variations and modifications, are essential for effective planning and management (Padhiary *et al.,* 2018). These predictions can help predict floods and droughts and support sustainable agriculture practices (Zuo *et al.,* 2016).

In this region, there have been limited previous studies addressing the impact of climate change on hydrological components. However, this study focuses on watershed streamflow prediction in the Kesinga catchment as part of its examination of climate change impacts using the calibrated/validation SWAT model. The evaluation of the SWAT model includes the consideration of future climate projections (2021-2099) for maximum/minimum temperature and precipitation, which are downscaled regional climate model (RCM) data from the Coordinated Regional Climate Downscaling Experiment (CORDEX) for the research region. The future scenarios involve the use of RCP 4.5

and RCP 8.5 emissions in conjunction with the 1973-2003 base period.

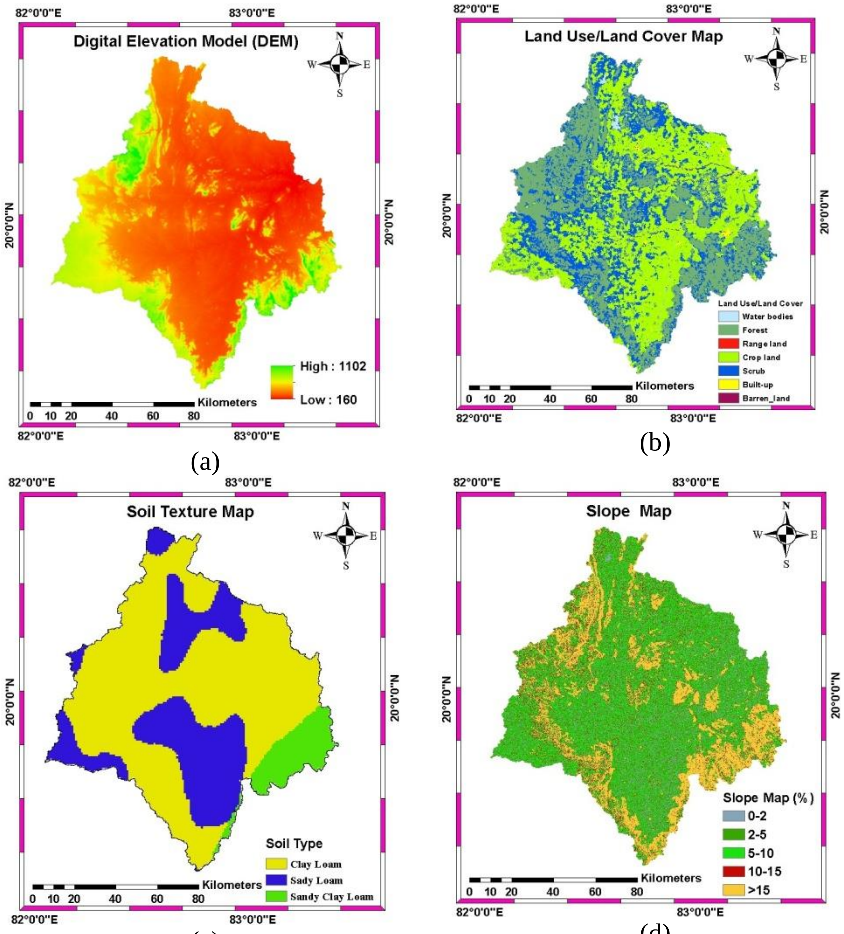
MATERIALS AND METHODS

Details of the study area. The selected study area, the Kesinga catchment, is situated in the middle part of the Mahanadi river basin in the state of Odisha, India. The catchment area covers approximately 11,855 km² with an annual rainfall of 1378.2 mm. During summer seasons the maximum temperature ranges from 25 to 45°C, while in winter, the minimum temperature varies from 11 to 27°C.

Soil and Water Assessment Tool (SWAT) model. The SWAT model is a long-term, semi-distributed hydrologic model that uses variable time intervals for computations. The watershed is divided into multiple sub-basins, each characterized by consistent climatic conditions. Furthermore, these sub-basins are subdivided into hydrological response units (HRUs), delineated based on homogeneous land use, slope, and soil type characteristics (Arnold *et al.*, 1995). SWAT incorporates a comprehensive water balance equation that accounts for various components, including precipitation, actual evapotranspiration, surface runoff, lateral flow, baseflow, percolation, and deep groundwater loss. The Soil Conservation Service Curve Number (SCS-CN) method estimates surface runoff by considering factors such as the area's hydrologic group, antecedent moisture content, and land use for each HRU. In this specific study, the SCS-CN method was utilized to simulate surface runoff (Neitsch *et al.*, 2011).

The model was calibrated and validated using the SWAT-CUP model with Sequential Uncertainty Fitting (SUFI-2) within the SWAT auto-calibration tool. Streamflow data for calibration and validation were obtained from gauging stations in the catchment area (Gathagu *et al.*, 2018).

SWAT model inputs. To assess catchment streamflow using the SWAT model, both temporal and spatial input data are required. The spatial data that SWAT relies on (Table 1) includes the Digital Elevation Model (DEM, Fig. 1a), land use/land cover map (Fig. 1b), slope map (Fig. 1c), and soil map (Fig. 1d). Long-term observed daily climatic data serve as the model's temporal or meteorological data.



(a) (b)

(c) (d)

Fig. 1. SWAT model input data (a) Digital Elevation Model (DEM) (b) Land use/Landcover map (c) Slope map (d) Soil map.

Climate change projection selection and study period. The daily meteorological data, rainfall, minimum and maximum temperatures, and hydrological data (daily discharge) for the baseline periods of 1973-2003 and 2000-2020, were obtained from the Central Water Commission (CWC) in Bhubaneswar, Odisha. Future climate data were derived from two Regional Climate Models (RCMs) combined with two emissions scenarios, RCP4.5 and RCP8.5, which represent medium and high emissions projected climate data. Bias correction and the extraction of CORDEX data for the projected climate data were performed using the CmHyd software (Rathjens *et al.*, 2016).

Model performance evaluation. The SWAT model performance was assessed using three simultaneous statistical criteria: Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970), percent bias (PBIAS), and root mean square error (RMSE) (Sorooshian *et al.*, 1993).

Table 1: SWAT input database.

Data type	Spatial resolution	Available sources
Digital Elevation Model (DEM)	30 m × 30 m	www.earthexplorer.usgs.gov
Land use/Land cover raster	30 m × 30 m	National Remote Sensing Centre (https://www.nrsc.gov.in/)
Soil map	0.5 km	Harmonized World Soil Database (HWSD) developed by (FAO) (http://www.fao.org/geonetwork/srv/en/metadata.show%3Fid=14116).
Hydrological data (2000–2020)	Station point data	Central Water Commission (CWC), Bhubaneswar
Climate projection data RCP4.5 (2021-2050) & RCP8.5 (2071–2099)	0.25° × 0.25°	CORDEX https://esg-dn1.nsc.liu.se/search/cordex/

RESULTS AND DISCUSSION

Model parameter sensitivity analysis of streamflow. For sensitivity analysis criteria ($p<0.05$) of streamflow, ten parameters for streamflow analysis were used as a model calibration (Table 2).

Projected climate change in the Kesinga catchment. The average minimum temperature in the Kesinga catchment is projected to be warmer, ranging from 19.9°C to 22.4°C during the mid-century (2021-2050) and 22.1°C to 23.3°C during the end-century (2070-2099) in RCP4.5 scenarios. Similarly, the average minimum temperature changes from 20.1°C to 23.0°C and 23.1°C to 25.7°C from the mid-century to end-century under RCP8.5 scenarios. The catchment maximum temperature is also expected to be warmer, changing from 31.2°C to 34.3°C and 33.3°C to 35.2°C, 31.7 to 35.0, and 33.9 to 37.6 from the mid-century to end-century under RCP4.5 and RCP8.5 scenarios. The highest percentage rise in maximum and minimum temperature is observed under RCP8.5 of the CSIRO-QCCCE-CSIRO model (Fig. 3 and 4).

During the mid-century (2021-2050), the mean annual rainfall increased by 14.8% in the RCP4.5 scenario of the CCCma-CanESM2 model. In the RCP8.5 scenarios, the mean annual rainfall increased by 8.2% during the mid-century. However, the CSIRO-QCCCE-CSIRO model with the RCP8.5 scenario indicated a decrease in average rainfall ranging from 1% to 10% from the mid-century to the end-century, as shown in Fig. 2.

The models CSIRO-QCCCE-CSIRO and CCCma-CanESM2, with RCP 4.5 and 8.5 scenarios, indicated an increase in average monthly minimum and maximum temperatures. Maximum and minimum temperatures reached their highest values in April and the lowest values from November to January. According to the CSIRO-QCCCE-CSIRO model, with both scenarios (RCP 4.5 and 8.5), the average minimum temperature for January was predicted to be 15.4°C and 18.3°C, respectively. The average minimum temperature for April in the RCP 4.5 and RCP 8.5 scenarios under the CCCma-CanESM2 model was recorded as 24.9°C and 27.8°C.

Table 2: Identified sensitive parameters for streamflow and adopted values in the study area

Rank	Parameters	Range	Adopted value	t-stat	p-value
Streamflow					
1	SURLAG	0.05 to 10	0.82	0.005	0.995
2	CH_N2	0 to 0.3	0.04	0.008	0.993
3	GW_DELAY	30 to 450	78.29	0.15	0.878
4	SOL_K	-0.8 to 0.5	0.17	-0.31	0.754
5	CH_K2	5 to 130	83.62	0.79	0.425
6	GWQMN	0 to 2	0.89	-0.82	0.413
7	ALPHA_BF	0 to 1	0.733	1.1	0.278
8	ESCO	0.8 to 1	0.94	1.54	0.124
9	SOL_AWC	-0.5 to 0.25	0.22	16.68	0
10	CN2	-0.2 to 0.2	-0.084	-32.3	0

These changes enhance the clarity and grammatical correctness of the text. Similarly, the CSIRO-QCCCE-CSIRO model predicted that, under the RCP4.5 and RCP8.5 scenarios, the maximum temperature for January could be 29.8°C and 32.9°C, respectively. The average maximum temperature in July under RCP4.5 and RCP8.5 of the CCCma-CanESM2 model was 39.9°C and 40.8°C, respectively. The projected monthly maximum and minimum temperatures for the RCP4.5 and RCP8.5 scenarios of the RCM models, including CSIRO-QCCCE-CSIRO and CCCma-CanESM2, are shown in Fig. 5.

Observed average precipitation data were compared with the projected climatic scenarios (RCP4.5 and RCP8.5) within the catchment. The CSIRO-QCCCE-CSIRO model, for both RCP4.5 and RCP8.5 scenarios, indicates that average precipitation increased by 25% and 16% in July.

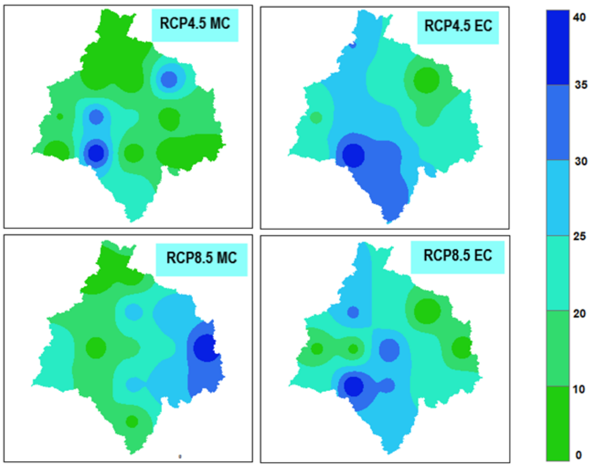


Fig. 2. Future Precipitation (%) changes in the MC (left), EC (right) under RCP4.5 (upper), RCP8.5 (lower).

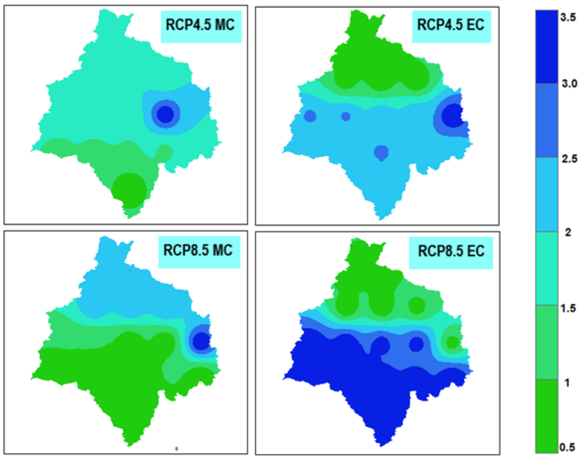


Fig. 3. Future minimum temperature (◦C) changes in the MC (left), EC (right) under RCP4.5 (upper), RCP8.5 (lower).

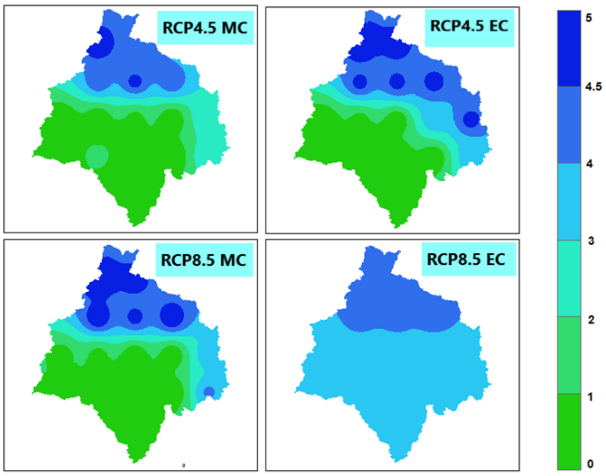


Fig. 4. Future maximum temperature (◦C) changes in the MC (left), EC (right) under RCP4.5 (upper), RCP8.5 (lower).

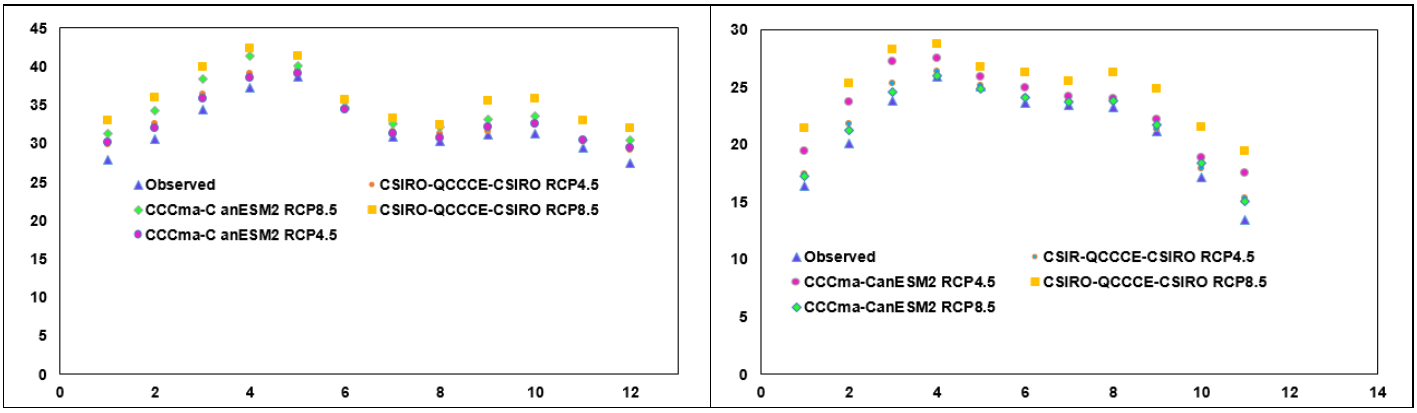


Fig. 5. Average monthly minimum and maximum changes for climate scenarios, RCP 4.5 and RCP 8.5 of the RCM climate models, CSIRO-QCCCE-CSIRO and CCCma-C anESM2.

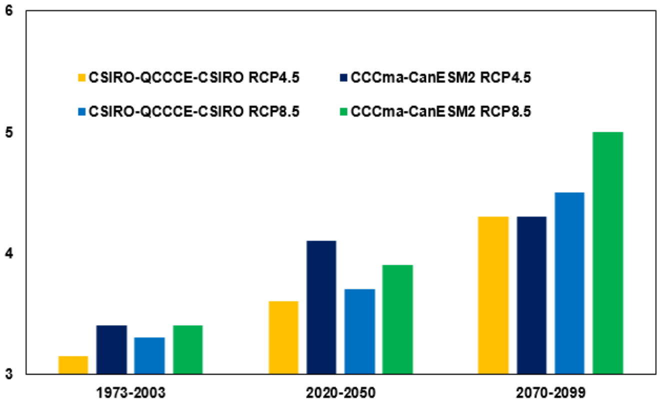


Fig. 6. Average monthly changes in precipitation for climate scenarios, RCP 4.5 and RCP 8.5 of the RCM climate models, CSIRO-QCCCE-CSIRO and CCCma-C anESM2

On the other hand, average rainfall decreased by 15% and 23% in November under RCP4.5 and RCP8.5 of the CSIRO-QCCCE-CSIRO model. In contrast, average precipitation increased by 31% in July and 14% in August in the RCP4.5 and RCP8.5 scenarios of the CCCma-CanESM2 model, while a decreasing trend of 10% and 8% was observed in November and December in the RCP4.5 and RCP8.5 scenarios of the CCCma-CanESM2 model, as shown in Fig. 6.

SWAT model calibration and validation results. In the monthly streamflow modeling using the SWAT model, the model's performance was classified as 'excellent.' This classification was based on the model achieving a Nash-Sutcliffe Efficiency (NSE) greater than 0.86, a Relative Streamflow Routing (RSR) value lower than 0.91, and a Percent Bias (PBIAS) less than 9%, as demonstrated in Fig. 7.

Climate change impacts on streamflow. The hydrological response of the catchment to changes in the climate was studied using two projected time windows: the mid-century (MC) from 2021 to 2050 and the end-century (EC) from 2071 to 2099. The reference (baseline) period was from 1973 to 2003.

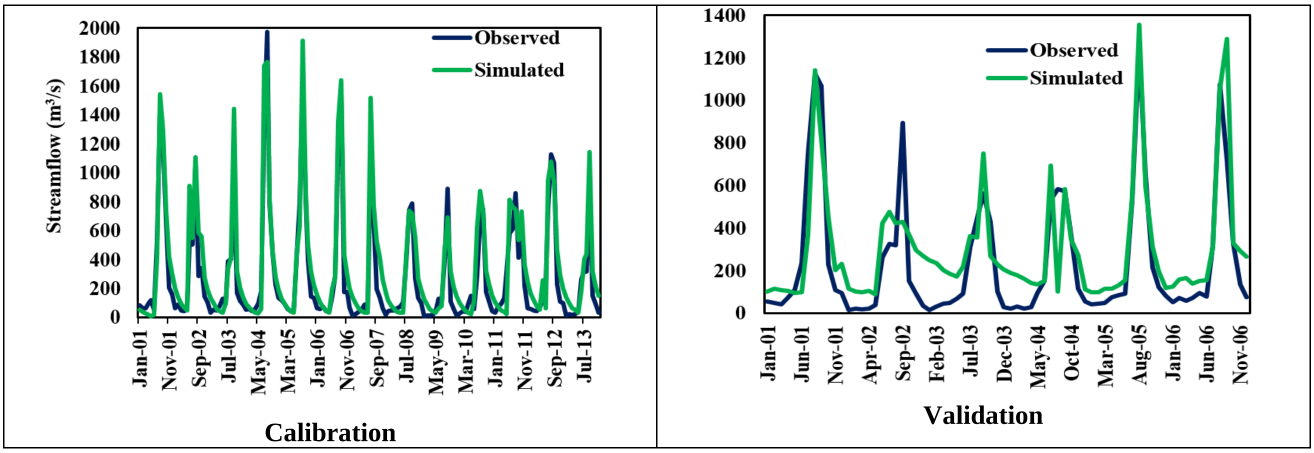


Fig. 7. Comparison between observed and simulated streamflow during calibration and validation at Kesinga catchment.

Streamflow changes during the MC increased by 21% to 172%. However, the average streamflow for the EC decreased by 28% or increased by up to 160%. The highest average monthly streamflow was observed in August in the CSIRO-QCCCE-CSIRO model under RCP4.5 and RCP8.5. On the other hand, the maximum streamflow for the average monthly flow was observed during November. The projected percentage change in streamflow during the transition from MC to EC with RCP4.5 and RCP8.5 scenarios using the RCM models CSIRO-QCCCE-CSIRO and CCCma-CanESM2 is presented in Table 6.

Table 3: Summary of streamflow changes (percentage) during MC (2021-2050) and EC (2070-2099) under RCP 4.5 & 8.5 of CORDEX-RCM models: CSIRO-QCCCE-CSIRO and CCCma-CanESM2.

CORDEX-RCM model	Scenario	Mid-century (2021-2050)	End-century (2070-2099)
CSIRO-QCCCE-CSIRO	RCP4.5	21	112
	RCP8.5	-28	160
CCCma-CanESM2	RCP4.5	172	92
	RCP8.5	70	-11

CONCLUSIONS

This study adopted a methodology to enhance SWAT streamflow projections for future climate change scenarios at regional scales. The estimation of watershed-scale streamflow using the SWAT model involved the integration of climate change factors at the regional scale, including the use of Digital Elevation Models (DEMs). A DEM was generated by removing topographic elements from high-resolution data and replacing them at the Hydrologic Response Unit (HRU) level. The SWAT model was then employed to evaluate the effects of climate change using future scenarios from RCM models under two RCP scenarios. The average streamflow values over 30-year periods exhibited significant changes under the future projected RCP climate change scenarios derived from two CORDEX-RCM models, as predicted by the SWAT model. Consequently, the streamflow values for the end of the century were notably different from the observed values. Monthly average streamflow values typically increased during June and August, while they decreased in February and March. Changes in precipitation patterns, surface temperature, and streamflow primarily drove the hydrological changes within the catchment. Furthermore, the climate models developed in this study hold significant value for the formulation of effective watershed management and mitigation strategies for the middle and end of the century, aimed at minimizing the impacts of climate change.

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Conflict of Interests. None.

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