Multi-Model Prediction of Climate Change and Its Impacts on Runoff in Snow- and Ice-Dominated Watersheds: Postprint

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Abstract

Snow and ice meltwater in glacier-covered watersheds exerts an important regulating effect on river runoff. Climate change influences the processes and quantitative variations of snow and ice meltwater, with river runoff processes and volumes changing correspondingly, the magnitude of which is related to glacier conditions within the watershed. By utilizing meteorological data output from CMIP5 climate models to drive watershed hydrological models, this study simulates and investigates the response of runoff to climate change for three rivers with different glacier coverage rates in the Tianshan region (Kumalak River, Manas River, and Kuqa River). The results demonstrate that with continued increases in future temperature and precipitation, snowmelt water increases in all three watersheds, whereas changes in ice meltwater are affected by glacier coverage area and vary inconsistently across watersheds. Runoff changes are primarily influenced by the combined effects of increased precipitation and variations in snow and ice meltwater; under future scenarios, runoff increases in all watersheds, by 5.8%–14.3% (Kuqa River), 2.9%–11.4% (Manas River), and 12.9%–47.1% (Kumalak River), respectively. Moreover, in watersheds with larger glacier coverage, the projected uncertainty range of runoff variability is more substantially influenced by ice meltwater. Projected changes in the intra-annual distribution of runoff and snow-ice meltwater for the three watersheds indicate that the advancement of spring snowmelt timing and increased snowmelt amounts result in greater spring runoff compared to the historical period. In summer, influenced by changes in snow and ice meltwater, the summer runoff peak decreases for the Kuqa and Manas Rivers, while it increases for the Kumalak River, and the projected uncertainty range of summer runoff changes is significantly larger than in other seasons.

Full Text

Multi-Model Prediction of Climate Change and Its Impact on Runoff in Snow-Ice Basins

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Abstract: Snow-ice meltwater in glacier-covered basins plays a crucial role in regulating river runoff. Climate change affects the processes and quantity of snow-ice meltwater, consequently altering river runoff regimes in ways that correlate with basin glacier coverage. This study employs meteorological data from CMIP5 climate models to drive a watershed hydrological model, simulating runoff responses to climate change for three rivers with different glacier coverage in the Tianshan region: the Kumaric River, Manas River, and Kuqa River. Results indicate that with continued future increases in temperature and precipitation, snowmelt will increase across all basins, while icemelt changes will vary inconsistently among basins depending on glacier area. Runoff changes are primarily influenced by the combined effects of increased precipitation and altered snow-ice meltwater. Under future scenarios, runoff in all three basins shows increases of 5.8%–14.3% (Kuqa River), 2.9%–11.4% (Manas River), and 12.9%–47.1% (Kumaric River). Basins with larger glacier coverage exhibit greater uncertainty ranges in projected runoff variations due to icemelt influences. Projected intra-annual distributions of runoff and snow-ice meltwater reveal that spring runoff increases in all basins compared to the historical period, driven by earlier and greater snowmelt. In summer, peak runoff decreases for the Kuqa and Manas Rivers due to snow-ice meltwater changes, while the Kumaric River shows increased peak flow. The uncertainty ranges for projected summer runoff changes are significantly larger than those for other seasons.

Keywords: climate change; climate model; hydrological model; glacier; runoff

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1.1 Study Area Overview

The Tianshan Mountains (39°–45°N, 69°–95°E) stretch across Xinjiang, China, and the Central Asian countries of Kazakhstan, Kyrgyzstan, and Uzbekistan. The entire Tianshan range can be divided into Central Tianshan, Western Tianshan, and Eastern Tianshan [Figure 1: see original paper]. This study selected the headwater regions of three rivers with different glacier coverage in the Tianshan area as representative basins to investigate climate change impacts on snow-ice hydrological processes and runoff regimes: the Kumaric River, Manas River, and Kuqa River. Basin locations and glacier distributions are shown in [Figure 1: see original paper], with characteristics summarized in . The Kumaric River Basin has the largest glacier area coverage at 21.0%, with runoff primarily supplied by snow-ice meltwater. The Manas River Basin has approximately 10.0% glacier coverage, with runoff supplied by summer rainfall and snow-ice meltwater. The Kuqa River has the smallest glacier area, with coverage of just 3.4%, and its runoff is mainly derived from summer rainfall.

1.2 Data

The fundamental data required for model construction include: basin digital elevation model (DEM), soil properties, land cover, glacier data, meteorological data, and runoff observations. The DEM was derived from the ASTER Global Digital Elevation Model (ASTER GDEM) with 30 m resolution (http://gdem.ersdac.jspacesystems.or.jp/index.jsp), processed using ArcSWAT to generate sub-basin boundaries, river channels, elevation bands, and slope parameters. Soil data were extracted from the Harmonized World Soil Database, including soil names, layer numbers, texture, bulk density, and other properties. Soil available water capacity and saturated hydraulic conductivity were calculated using the Soil-Plant-Atmosphere-Water (SPAW) software. These soil parameters were then written into the user soil database of the SWAT model.

Land cover maps were obtained from the European Space Agency's 2009 GlobCover product with 300 m spatial resolution. Glacier data primarily came from the First Chinese Glacier Inventory dataset (http://westdc.westgis.ac.cn) and the Second Chinese Glacier Inventory dataset. For the Kumaric River Basin, whose headwaters lie mainly in Kyrgyzstan, glacier data were obtained from the AsiaCryoWeb Tien Shan Glaciers V1.0 (TSGV1) dataset. Glacier information includes geographic coordinates, area, length, orientation, start/end elevations, mean elevation, glacier type, and moraine type, with vector boundary data used as input for the GHRU method. Runoff data were obtained from monthly records in the *China Hydrological Yearbook*: the Xiehela Station for the Kumaric River (1961–2006), the Kensiwate Station for the Manas River (1964–2006), and the Langan Station for the Kuqa River (1961–2006).

Since meteorological stations are typically located at lower elevations and are sparsely distributed within the basins, lacking observations for high-altitude areas, this study additionally employed gridded meteorological datasets: the APHRODITE (Asian Precipitation–Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources) precipitation data and the PGMFD (Princeton Global Meteorological Forcing Dataset) temperature data. These datasets have been successfully applied in high-elevation regions of Central Asia, including the Tianshan, Karakoram, and Tibetan Plateau, where long-term observed climate data are scarce [21,38-40].

1.3 Hydrological Model

The SWAT-RSG model is suitable for simulating climate change impacts on snow-ice hydrological processes and runoff at basin and regional scales, and has achieved good performance in snow-ice basins of the Tianshan, Pamir, and Karakoram [20,41-42]. This study uses this hydrological model to simulate watershed hydrological processes in the study area. The model incorporates Glacier Hydrologic Response Units (GHRUs) [32] into the SWAT model [43], enabling simulation of snowmelt, icemelt, and rainfall-runoff processes at the watershed scale.

The GHRU method calculates mass balance for individual glaciers and simulates glacier dynamics using the volume-area scaling relationship [31]. Glacier mass balance calculations account for snow-to-ice conversion and meltwater refreezing as accumulation processes, and consider sublimation, snowmelt on ice, and icemelt as ablation processes. Snow and icemelt are calculated using the degree-day factor algorithm. Glacier runoff consists of snowmelt on ice, icemelt, and rainfall on ice components. Each GHRU is divided into elevation bands to account for elevation-dependent variations in precipitation and temperature. Detailed methodology is described in the literature [32].

1.4 Model Performance Evaluation Metrics

During model calibration and validation, comparisons between simulated and observed runoff employed the Nash-Sutcliffe Efficiency (NSE) and Percent Bias (PBIAS) metrics to assess the agreement between simulated and observed runoff processes and magnitudes. Following the criteria established by Moriasi et al. [45] for model performance classification (see), PBIAS primarily evaluates the quantitative deviation between simulated and observed runoff. The calculations are as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{k}(Q_{obs}^{i} - Q_{sim}^{i})^2}{\sum_{i=1}^{k}(Q_{obs}^{i} - Q_{mean})^2}$$

$$PBIAS = \left[\frac{\sum_{i=1}^{k}(Q_{sim}^{i} - Q_{obs}^{i})}{\sum_{i=1}^{k} Q_{obs}^{i}}\right] \times 100$$

where Q_{obs}^{i} is the observed runoff for the i-th time step, Q_{sim}^{i} is the simulated runoff, Q_{mean} is the mean observed runoff, and k is the length of the runoff series.

1.5 Climate Model Selection and Statistical Downscaling

Global climate models are essential tools for studying climate change mechanisms and projecting future climate change impacts on hydrological processes

[46]. The CMIP5 (Coupled Model Intercomparison Project Phase 5) includes climate change projections from multiple modeling centers under four Representative Concentration Pathway (RCP) scenarios: RCP2.6, RCP4.5, RCP6.0, and RCP8.5. These outputs include meteorological variables such as temperature and precipitation spanning 1850–2100 at annual, monthly, and daily resolutions. Since RCP6.0 is similar to RCP4.5 and many models did not provide RCP6.0 results, this study considers only three representative concentration pathways: RCP2.6, RCP4.5, and RCP8.5, downloading corresponding monthly temperature and precipitation data from 39 climate models .

Statistical downscaling is a primary method for converting climate model output to watershed-scale meteorological data [47]. This study employs the delta method [48] to downscale precipitation and temperature data from model grids to each meteorological station. This method directly establishes relationships between model simulation results and surface climate variables, is relatively simple, and its reliability increases with the spatial resolution of CMIP5 models.

2.1.1 Runoff Simulation Performance

presents runoff evaluation results for the three rivers. During the calibration period, the difference between simulated and observed mean annual runoff was small for all rivers, within approximately 2%–5%. During the validation period, the difference was within about 5%–10%. According to the evaluation criteria of Moriasi et al. [45], all rivers achieved "good" performance standards during both calibration and validation periods, except for the Kuqa River's PBIAS. [Figure 2: see original paper] shows simulated monthly runoff versus observed monthly runoff for the three rivers. Overall, the model adequately reproduces the interannual and intra-annual variations of observed runoff in the study basins.

2.1.2 Glacier Area Changes

Simulated glacier area changes show that from 1961–2006, glaciers in the Kumaric, Manas, and Kuqa River basins retreated by 31.5–35.5%, 19.0–19.8%, and 34–49%, respectively. Compared with observed data from the AsiaCryoWeb TSGV1 dataset, the simulated glacier area retreat shows small differences, with observed retreats of 35.5%, 19.8%, and 31.5% for the three basins. Under all three RCP scenarios, projected glacier area changes increase with emission scenario intensity, and the model adequately reflects historical glacier area variations across the basins.

2.2 Future Temperature and Precipitation Changes in the Basins

Under RCP2.6, RCP4.5, and RCP8.5 scenarios, the ensemble mean temperature from 39 climate models shows an increasing trend in all basins, with greater warming under higher emission scenarios [Figure 3: see original paper]. The temperature increase ranges are 1.8–1.9°C, 2.5–3.0°C, and 6.0–6.3°C for the near-term and far-future periods under the three scenarios, respectively. These values are slightly lower than the projected 2.0–3.3°C increase for China's average temperature under the same scenarios [49], primarily because the study basins are located in high-altitude glacier-covered regions. Precipitation shows relatively small interannual variation differences across scenarios and basins [Figure 3: see original paper]. Statistical analysis indicates that precipitation increases in all basins during future periods compared to the historical period, though with small magnitude increases .

2.3.1 Interannual Variation

Under RCP2.6, RCP4.5, and RCP8.5 scenarios, runoff in all three basins increases compared to the historical period, though the trends are not entirely consistent with precipitation changes. Ice meltwater changes vary across periods, scenarios, and basins. The Kumaric and Kuqa Rivers show the greatest changes in the far-future period under the RCP8.5 scenario, with increases of 208.2% and decreases of 65.1%, respectively. The Manas River shows the greatest reduction in the far-future period under RCP2.6, decreasing by 37.9%. Since precipitation changes are small across scenarios, and the RCP8.5 scenario produces the greatest temperature increase and consequently the most significant runoff and snow-ice meltwater changes, this analysis focuses on the impacts of snow-ice meltwater on future runoff under RCP8.5 for basins with different glacier coverage.

2.3.2 Intra-Annual Distribution

Projected spring runoff increases in all basins compared to the historical period, primarily due to earlier and greater snowmelt peaks. Summer peak runoff timing shows no significant shift, but peak magnitudes change differently across basins with varying glacier coverage [Figure 5: see original paper]. In the Kumaric River, summer snowmelt decreases in both future periods, but peak runoff increases due to significantly enhanced icemelt during summer. Notably, the recent-period maximum runoff exceeds the far-future maximum under this scenario, inconsistent with icemelt changes, likely because pronounced warming increases summer evapotranspiration. The Manas River shows reduced summer peak runoff in both future periods, while the Kumaric River (with the largest glacier coverage) shows increased peak flow. The uncertainty ranges for projected summer runoff changes are substantially larger than for other seasons.

2.4 Uncertainty in Projection Results

Uncertainty in watershed hydrological simulations primarily originates from input data, hydrological model structure, and model parameters [55,56]. Previous studies have evaluated the model's performance using historical hydrological and glacier change data, achieving satisfactory standards. Climate model outputs of future meteorological data, serving as driving factors for the hydrological model, constitute a significant source of uncertainty in projected watershed hydrological results [57]. Research demonstrates that multi-model ensemble means better represent observed trends than individual models [50]. This study employs 39 climate models for annual and monthly scale projections, with the full range of results representing uncertainty from different climate model inputs.

At the annual scale [Figure 6: see original paper], basins with larger glacier coverage show greater uncertainty ranges in projected runoff changes, more strongly influenced by icemelt. Ice meltwater uncertainty ranges are generally larger in the near-term than far-future period, and larger under RCP8.5 than RCP4.5. Basins with greater glacier coverage exhibit larger icemelt uncertainty ranges. [Figure 6: see original paper] shows the uncertainty ranges for intra-annual runoff changes projected by the 39 climate model-driven hydrological model. Projected summer runoff uncertainty ranges are markedly larger than those for other seasons and annual averages, primarily due to significant summer icemelt changes [Figure 5: see original paper]. Basins with different glacier coverage show distinct uncertainty ranges, with larger glacier coverage producing greater uncertainty ranges for projected summer runoff changes across both future periods and scenarios. The increasing dispersion among the 39 climate models may lead to more extreme hydrological events, particularly under the RCP8.5 scenario where uncertainty ranges for runoff changes are largest.

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3. Conclusions

Using the SWAT-RSG hydrological model driven by downscaled climate model data, this study projects changes in snow-ice meltwater and runoff under RCP2.6, RCP4.5, and RCP8.5 scenarios for basins with different glacier coverage, examining runoff responses to future climate change and associated uncertainties. The main conclusions are:

1. With future temperature and precipitation increases, runoff in all basins shows an increasing trend. However, the intra-annual and interannual variations differ significantly among basins with different glacier coverage. The Kumaric River Basin, with the largest glacier coverage, is most sensitive to climate change, with runoff primarily influenced by snow-ice meltwater changes. Runoff increases significantly with emission scenario intensity, with summer runoff substantially higher than historical values. In contrast, the Kuqa River Basin, with minimal glacier coverage, shows runoff trends consistent with precipitation changes, exhibiting reduced summer runoff.

2. The 39-model ensemble includes the majority of climate models, with the ensemble mean reflecting projected hydrological changes from most models and the uncertainty range indicating potential variability in regional hydrological processes. Basins with larger glacier coverage exhibit greater uncertainty in runoff projections due to icemelt influences, with uncertainty

ranges largest under the extreme RCP8.5 scenario. Uncertainty ranges for runoff changes in highly glaciated basins are consistent with icemelt uncertainty, showing larger ranges in the near-term than far-future period. For basins with minimal glacier coverage, runoff uncertainty ranges gradually increase across future periods, related to precipitation uncertainty.

While this study employs a 39-model ensemble to reduce uncertainty from using single or few climate models, further uncertainty analysis is needed to address inherent climate model uncertainties and the effects of different ensemble approaches, thereby improving the accuracy of climate change impact assessments on watershed hydrological processes.

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Note: Figure translations are in progress. See original paper for figures.