Economic losses from reduced freshwater under future climate scenarios: An example from the Urumqi River, Tianshan Mountains postprint

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Abstract

As important freshwater resources in alpine basins, glaciers and snow cover tend to decline due to climate warming, thus affecting the amount of water available downstream and even regional economic development. However, impact assessments of the economic losses caused by reductions in freshwater supply are quite limited. This study aims to project changes in glacier meltwater and snowmelt of the Urumqi River in the Tianshan Mountains under future climate change scenarios (RCP2.6 (RCP, Representative Concentration Pathway), RCP4.5, and RCP8.5) by applying a hydrological model and estimate the economic losses from future meltwater reduction for industrial, agricultural, service, and domestic water uses combined with the present value method for the 2030s, 2050s, 2070s, and 2090s. The results indicate that total annual glacier meltwater and snowmelt will decrease by 65.6% and 74.5% under the RCP4.5 and RCP8.5 scenarios by the 2090s relative to the baseline period (1980-2010), respectively. Compared to the RCP2.6 scenario, the projected economic loss values of total water use from reduced glacier meltwater and snowmelt under the RCP8.5 scenario will increase by 435.10$\$\times106and537.20\times106CNYinthe2050sand2090s,respectively,andthecumulativeeconomiclossvaluefor$
CNY. We also find that the industrial and agricultural sectors would likely face the largest and smallest economic losses, respectively. The economic loss value of snowmelt in different sectorial sectors is greater than that of glacier meltwater. These findings highlight the need for climate mitigation actions, industrial transformation, and rational water allocation to be considered in decision-making in the Tianshan Mountains in the future.

Full Text

Economic Losses from Reduced Freshwater Under Future Climate Scenarios: An Example from the Urumqi River, Tianshan Mountains

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Abstract: Glaciers and snow cover represent critical freshwater resources in alpine basins, yet they are projected to decline significantly due to climate warming, thereby affecting downstream water availability and regional economic development. However, assessments of economic losses caused by reductions in freshwater supply remain limited. This study projects changes in glacier meltwater and snowmelt in the Urumqi River of the Tianshan Mountains under future climate scenarios (RCP2.6, RCP4.5, and RCP8.5) using a hydrological model and estimates economic losses from meltwater reduction for industrial, agricultural, service, and domestic water uses through the present value method for the 2030s, 2050s, 2070s, and 2090s. Results indicate that total annual glacier meltwater and snowmelt will decrease by 65.6% and 74.5% under RCP4.5 and RCP8.5 scenarios, respectively, by the 2090s relative to the baseline period (1980-2010). Compared to the RCP2.6 scenario, projected economic losses from reduced glacier meltwater and snowmelt under RCP8.5 will increase by 435.10\$×10^{6}\$ CNY and 537.20\$×10^{6}\$ CNY in the 2050s and 2090s, respectively, with cumulative losses reaching approximately 2124.00\$×10^{6}\$ CNY by 2099. The industrial and agricultural sectors face the largest and smallest economic losses, respectively, while snowmelt losses exceed glacier meltwater losses across all sectors. These findings underscore the need for climate mitigation actions, industrial transformation, and rational water allocation in future decision-making for the Tianshan Mountains region.

Keywords: glacier meltwater; snowmelt; freshwater supply; water use; economic losses; future climate scenario; climate change; Tianshan Mountains

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1 Introduction

Glacier meltwater and snowmelt constitute significant freshwater resources globally, influencing water provisioning, hydroelectric power generation, and extreme weather events [?, ?, ?]. More than one-sixth of the world' s population depends on freshwater supplies from glaciers and seasonal snow cover [?, ?]. As global warming accelerates cryosphere decline, the extent of glaciers and snow cover will diminish, altering seasonal variation in meltwater runoff [?, ?, ?, ?]. This manifests as increased average winter streamflow and earlier spring peak flows in glacier- and snowmelt-dominated alpine basins under future climate scenarios [?, ?]. Consequently, climate change impacts on meltwater runoff will affect freshwater ecosystems, domestic water supplies, and sustainable socioeconomic development [?, ?, ?].

Climate change affects not only hydrological processes and water resource systems but also regional water supply and demand [?, ?, ?, ?]. With expanding irrigation, socioeconomic development, and rapid population growth, water demand is projected to increase substantially [?, ?, ?, ?, ?]. For instance, water demand in South Asian river basins will rise rapidly in coming decades [?, ?]. In Xinjiang Uygur Autonomous Region, a semi-arid area of Northwest China, glacier meltwater and snowmelt are critical water resources, with demand expected to increase further [?, ?]. Simultaneously, future freshwater supply and availability will face challenges from rising temperatures and changing precipitation patterns.

Mountain regions serve as the world' s water towers, providing substantial and relatively constant freshwater resources for lowland river basins [?, ?, ?]. The Tibetan Plateau contributes 48.0% of the Indus River Basin' s annual discharge, with glacier meltwater accounting for 40.6% of total river flow [?, ?, ?]. In the upper Heihe River Basin of China' s Qilian Mountains, glacier meltwater and snowmelt contributed an average of 28.9% to total streamflow from 1960 to 2013 [?, ?]. Similarly, the Tianshan Mountains rely heavily on glacier meltwater and snowmelt due to their distance from oceans. Zhang et al. (2016a) found that glacial meltwater contributed 3.5% to 67.5% of runoff in several Tianshan catchments, averaging 24.0% during 1961-2007. However, the Tianshan Mountains' snow cover area has decreased significantly and glacier shrinkage has accelerated under warming [?, ?, ?, ?]. These changes will alter runoff quantity and water storage capacity in glacier- and snowmelt-dependent watersheds [?, ?], thereby affecting downstream water supply.

Remarkable reductions in freshwater supply under climate change will impact not only cryospheric processes and ecological environments but also cause substantial economic losses. In the Arctic, economic costs from reduced snow cover with global warming are estimated at 34.0$\$\times10^{\{9\}-650.0\times10}\{9\}\$$ USD for 2010-2100 [?, ?]. In the western USA, shifts from snowfall to rainfall will cause annual economic losses of 10.8$\$\times10^{\{9\}-48.6\times10}\{9\}\$$ USD [?, ?]. Moreover, snow mass loss values in western China will increase in the future [?, ?]. Xinjiang plays an irreplaceable strategic role in the "Silk Road Economic Belt" and constitutes the core area of the new Silk Road [?, ?]. Decreasing water resources will inevitably challenge construction of this economic belt' s core area. Additionally, freshwater supply provides essential direct and indirect services for human livelihoods, including domestic use and power generation [?, ?]. Consequently, cryosphere service valuation has gained widespread attention, including evaluations of glacier, snow, and permafrost services [?, ?, ?, ?, ?, ?, ?, ?].

Monetary valuation of freshwater resources is necessary for public and policymaker understanding of water supply changes' economic significance. This study uses the Urumqi River, located on the northern slope of the Tianshan Mountains and recharged primarily by precipitation, glacier meltwater, and snowmelt, as a case study. Previous research on the Urumqi River has focused on cryosphere processes, changes, and climate impacts [?, ?, ?, ?, ?, ?], with less emphasis on economic impacts and quantitative analyses of meltwater reduction. Therefore, this study (1) analyzes the relative contribution and characteristics of glacier meltwater and snowmelt to outlet streamflow in the 2030s, 2050s, 2070s, and 2090s using five global climate models and three representative concentration pathway (RCP) scenarios, and (2) reveals associated economic losses from meltwater reductions for industrial, agricultural, service, and domestic water uses based on present value assessment.

2.1 Study Area

The Urumqi River (43°00 -44°07 N, 86°45 -87°56 E), with elevations ranging from 1892 to 4461 m [Figure 1: see original paper], is located on the northern slope of the Tianshan Mountains in Xinjiang Uygur Autonomous Region, Northwest China. The basin originates from Urumqi Glacier No. 1 on the northern side of Tianger Peak No. II and flows northeastward. Influenced by westerly circulation, the region has a temperate continental arid climate. The river spans 214 km with a total area of 4684 km^2, flowing through Urumqi City, the political, economic, and cultural center of Xinjiang [?, ?, ?]. The Urumqi River provides essential water resources for the city. As Xinjiang' s largest economy, Urumqi City is located in the economic belt on the Tianshan Mountains' northern slope, which supports 56.0% of Xinjiang' s total GDP but accounts for only approximately 7.4% of its water resources [?, ?]. The drainage area above the Yingxiongqiao Hydrographic Station outlet is 924 km^2 with an average elevation of 3066 m. There are 124 glaciers above the outlet, covering a total area of 38 km^2 (4.1% of the watershed area). The basin' s annual average precipitation and streamflow are 526 mm and 2.42$×10^{8}$ m^3, respectively [?, ?].

2.2 Data Sources

Future climate data projections were obtained from Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models (1950-2099) [?, ?]. To address uncertainties in hydrological simulations from single climate models, we used five global climate model datasets (GFDL-ESM2M, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M, and HadGEM2-ES) after downscaling and bias correction for China [?, ?, ?]. Projections of future climate data and hydrological impacts were based on different greenhouse gas emission scenarios, for which RCP2.6, RCP4.5, and RCP8.5 were selected to represent low, moderate, and high emission pathways, respectively. The RCP8.5 scenario is expected to produce the most warming by 2100. For comparison with the baseline period (1980-2010), future time was divided into four periods: the 2030s (2020-2039), 2050s (2040-2059), 2070s (2060-2079), and 2090s (2080-2099). Water consumption data for Urumqi City's industrial, agricultural, service, and domestic sectors in 2016 were derived from the Xinjiang Statistical Yearbook [?, ?] and Xinjiang Water Resources Bulletin [?, ?]. Water prices for industrial, service, and domestic sectors in 2016 were collected from http://www.chinaxinjiang.cn/, while agricultural irrigation water prices were obtained from local farmers in Urumqi County.

2.3 Methodology

This study employed a distributed cryospheric basin hydrological model to simulate glacier meltwater and snowmelt contributions to streamflow in the Urumqi River under future climate scenarios. Detailed model descriptions and accuracy evaluations are available in Chen et al. (2018) and Zhang et al. (2021). A snow valuation model proposed by Sturm et al. (2017) assessed future economic losses from declining glacier melt and snowmelt for sectorial water uses. This method uses present value to quantify future losses in today' s currency, discounting future value by discount factor Di (a financial concept where future value decreases over time). The present value of meltwater losses in reference year i is expressed as:

$$V_i = P_i \times W_i \times D_i$$

where V_i (CNY) is the present value of meltwater losses in reference year i; P_i (CNY/m^3) represents water price in year i; W_i (m^3) is the water amount lost in a future year relative to year i; and D_i (%) is the discount factor associated with discount rate r (representing the rate at which future value declines relative to present level), calculated as: $D_i = 1/(1 + r)^i$ (where i is measured from the present (i=0) and increments to future years). Discount rates of 1%, 3%, and 6% are commonly used in climate studies [?, ?]. Li (2018) indicated that lower discount rates yield relatively high social costs of carbon, which tends to reduce emissions significantly. Therefore, under low greenhouse gas emission scenarios, resulting economic losses are less pronounced and corresponding discount rates are higher. Consequently, discount rates for RCP2.6, RCP4.5, and RCP8.5 scenarios are 6%, 3%, and 1%, respectively.

To calculate meltwater loss values across sectors, we assumed constant sectorial water use proportions over time, modifying the equation as:

$$V_i = P_i \times W_i \times D_i \times S_{ij}$$

where S_{ij} (%) is the percentage of jth sectorial water use relative to total water amount in reference year i. In this paper, the reference year is 2016, with calculated P and S values held constant. Since future years were divided into four periods (2030s, 2050s, 2070s, and 2090s), cumulative meltwater loss value (V_{cum}) for different periods is calculated as:

$$V_{cum} = \sum_{i=1}^{n} P_i \times S_i \times W_i \times D_i$$

Hydrological simulation and projection were performed using MATLAB software, while present value assessment of meltwater losses employed descriptive statistical analyses.

3.1 Projections of Glacier Meltwater and Snowmelt Changes

Projected changes in annual glacier meltwater and snowmelt in the Urumqi River are presented in Figure 2 [Figure 2: see original paper]. Both glacier meltwater and snowmelt exhibit decreasing trends across future periods under all RCP scenarios. Snowmelt declines faster under RCP8.5 than under RCP2.6 and RCP4.5, with mean projected amounts of 0.60\$$\times 10^{\{8\},0.52\times 10}\{8\}, and 0.43\times 10\hat{}\{8\}\$$ m^3 from 2017 to 2099, respectively. Glacier meltwater projections show no clear differences among the three RCP scenarios, decreasing to less than 0.21\$$\times 10\hat{}\{8\}\$$ m^3 by the end of the 21st century. Glacier meltwater contribution to outlet streamflow shows a slight decreasing trend during the projection period under all three scenarios, without significant inter-scenario differences (Fig. 3 [Figure 3: see original paper]). Snowmelt contribution rates also decline under different RCP scenarios, with faster decreases under RCP8.5 than under RCP2.6 and RCP4.5, averaging 22.9%, 20.4%, and 16.5% for 2017-2099, respectively.

Table 1 shows glacier meltwater and snowmelt changes in four 21st-century periods relative to the baseline (1980-2010) under RCP2.6, RCP4.5, and RCP8.5 scenarios. Total annual glacier meltwater decreases by 34.8%, 47.2%, 52.8%, and 55.1% in the 2030s, 2050s, 2070s, and 2090s under RCP2.6, respectively. Corresponding decreases reach 35.0%, 43.6%, 51.4%, and 54.6% under RCP4.5, and 34.8%, 42.7%, 50.5%, and 52.9% under RCP8.5. Notably, glacier meltwater declines faster in the 2070s and 2090s than in the 2030s and 2050s, with slightly greater decreases under RCP2.6 than under RCP4.5 and RCP8.5. Similar to glacier meltwater, total annual snowmelt is projected to decrease across all four periods. Under RCP2.6, snowmelt decreases by 57.4%, 63.1%, 61.5%, and 56.7% in the 2030s, 2050s, 2070s, and 2090s, respectively. Snowmelt declines faster under RCP4.5 and RCP8.5, with projected decreases of 57.4%, 66.2%, 68.7%, and 68.8% under RCP4.5, and 60.8%, 68.3%, 76.1%, and 80.8% under RCP8.5. Snowmelt in the 2070s and 2090s shows substantially greater decreases than in the 2030s and 2050s.

Total glacier meltwater and snowmelt in the 2030s, 2050s, 2070s, and 2090s decrease by 52.3%, 61.0%, 64.8%, and 65.6% under RCP4.5, respectively, and by 54.9%, 62.5%, 70.2%, and 74.5% under RCP8.5, respectively. Under RCP2.6, total meltwater reduction shows smaller variation across periods. Overall, glacier meltwater and snowmelt projected under all three RCP scenarios decline compared to the baseline period, with decreasing rates accelerating in the far future (after the 2050s).

3.2.1 Economic Losses of Meltwater for Various Sectorial Water Uses

Economic loss and gain values of glacier meltwater for the 2030s, 2050s, 2070s, and 2090s under RCP2.6, RCP4.5, and RCP8.5 scenarios were calculated based on present value in 2016 (Table 2). By the 2030s, economic gain values for various sectorial water uses range from 0.01$×10^{6}$ CNY for agricultural water use to 1.70$×10^{6}$ CNY for industrial water use across different RCP scenarios. However, estimated economic loss values range between 0.50$×10^{6}$ CNY (RCP2.6) and 20.00$×10^{6}$ CNY (RCP8.5) by the 2050s. Under RCP2.6 and RCP8.5, economic loss values increase by 0.20$×10^{{6}−32.70×10}{6}$ CNY by the 2070s and vary from 0.10$×10^{6}$ to 28.10$×10^{6}$ CNY by the 2090s. Generally, economic loss values by the 2070s exceed those of the 2050s and 2090s, except under RCP2.6. Industrial water use shows the greatest economic loss, totaling 80.60$×10^{6}$ CNY under RCP8.5 by the end of the 21st century, while agricultural water use shows the lowest loss at 6.47$×10^{6}$ CNY.

Table 3 presents economic loss values of snowmelt for various sectorial water uses across four periods under corresponding RCP scenarios. Snowmelt economic loss values exceed those of glacier meltwater because future annual snowmelt decline is much greater than glacier meltwater decline relative to 2016. Specifically, snowmelt economic loss values for sectorial water uses are estimated at 6.50$×10^{{6}−193.20×10}{6}$ CNY by the 2030s and 3.10$×10^{{6}−224.50×10}{6}$ CNY by the 2050s. By the 2070s and 2090s, estimated losses range from 0.90$×10^{6}$ CNY (RCP2.6) to 237.70$×10^{6}$ CNY (RCP8.5) and from 0.20$×10^{6}$ CNY (RCP2.6) to 222.80$×10^{6}$ CNY (RCP8.5), respectively. Particularly under RCP8.5, economic loss values for all sectorial water uses in the 2070s exceed those of other periods. The industrial sector faces the greatest economic loss, reaching 878.20$×10^{6}$ CNY under RCP8.5 over the 2020s–2090s period.

For total glacier meltwater and snowmelt economic loss values, sectorial water use values decrease by 6.40$×10^{6}$ CNY (RCP2.6) to 193.00$×10^{6}$ CNY (RCP8.5) and by 3.60$×10^{6}$ CNY (RCP2.6) to 244.60$×10^{6}$

CNY (RCP8.5) for the 2030s and 2050s, respectively (Tables 2 and 3). By the 2070s and 2090s, projected economic loss values vary from 1.10\$×10^{6}\$ CNY (RCP2.6) to 270.40\$×10^{6}\$ CNY (RCP8.5) and from 0.30\$×10^{6}\$ CNY (RCP2.6) to 250.80\$×10^{6}\$ CNY (RCP8.5), respectively. Moreover, each sector shows different results under the three RCP scenarios (Fig. 4 [Figure 4: see original paper]). Under RCP2.6, differences in average economic loss values among the four sectorial water uses are relatively small. Under RCP8.5, economic losses from glacier meltwater and snowmelt reduction exceed those under RCP2.6 and RCP4.5, with average losses for industrial, agricultural, service, and domestic water uses of 11.80\$×10$^{\{6\}, 0.90\times10}${6}, 5.20×10$^{\{6\}, and 7.70\times10}${6}\$ CNY, respectively.

3.2.2 Economic Losses of Meltwater for Total Water Use

In addition to sectorial water use estimates, we evaluated economic loss values of glacier meltwater and snowmelt for total water use under different RCP scenarios (Fig. 5 [Figure 5: see original paper]). Economic losses from glacier meltwater and snowmelt reduction under RCP2.6 and RCP4.5 are expected to decrease across the four future periods. Particularly under RCP2.6, economic loss values fall below 10.00\$×10^{6}\$ CNY. Under RCP8.5, economic loss values show increasing volatility, ranging from 419.70\$×10^{6}\$ CNY in the 2030s to 545.40\$×10^{6}\$ CNY in the 2090s. Cumulative economic loss values from total glacier meltwater and snowmelt reduction are shown in Figure 6 [Figure 6: see original paper]. Before 2030, cumulative economic losses increase slightly to 133.60\$×10$^{\{6\}, 174.10\times10}${6}, *and*249.40×10^{6}\$ CNY under RCP2.6, RCP4.5, and RCP8.5, respectively. By mid-21st century, cumulative losses rise to 267.40\$×10$^{\{6\}, 446.50\times10}${6}, *and*750.40×10^{6}\$ CNY under the three scenarios, respectively. By the end of the 21st century, cumulative economic loss under RCP8.5 increases faster than under RCP2.6 and RCP4.5, reaching an estimated total of 2124.00\$×10^{6}\$ CNY.

4.1 Implications of Climate Change for Glacier Melt and Snowmelt

Climate change will significantly affect regional river flow regimes, particularly in high-altitude mountain regions where glacier- and snow-dominated meltwater constitutes a key component of total basin runoff [**?**, **?**, **?**]. Future changes in climate variables (temperature and precipitation) will directly influence runoff projections under different greenhouse gas emission scenarios. Su et al. (2017) found that underestimating temperature and precipitation creates greater uncertainty in discharge projections for China' s upper Yangtze River. Our projected decreasing trend in annual glacier meltwater in the Urumqi River aligns with Zhang et al. (2016b), who found faster glacier melt decreases under RCP8.5 than under RCP2.6 and RCP4.5. However, our results show no clear differences among the three RCP scenarios for glacier meltwater or its contribution rate to total runoff. These results may stem from uncertainties in climate projections affecting glacier meltwater estimates, particularly regarding precipitation change impacts [?, ?, ?]. As Soleimani et al. (2017) emphasized, precipitation projections are generally less robust than temperature projections due to more complex local processes. In this study, both annual temperature and precipitation are projected to increase under future climate scenarios (Fig. 7 [Figure 7: see original paper]). Although glacier retreat accelerates under RCP8.5 due to faster temperature increases, retreat is decelerated by general precipitation increases under high greenhouse gas emission scenarios, ultimately leading to insignificant differences in glacier runoff across scenarios. Beyond climate models, runoff projection uncertainty also relates to hydrological models and downscaling approaches. Vetter et al. (2014) indicated that hydrological models and GCMs contribute to streamflow projection uncertainty in China’ s upper Yellow River Basin. Similarly, for China’ s upper Yangtze River, discharge projection uncertainty stems mainly from GCMs, followed by hydrological model effects [?, ?]. A recent study on Urumqi Glacier No. 1 in the Tianshan Mountains found that different climate change scenarios can create substantial projection uncertainty [?, ?]. Therefore, integrative uncertainty assessments are essential for future simulations.

For Urumqi River snowmelt estimation, future prediction uncertainty is relatively small due to minor uncertainties in future temperature variation. Mean annual temperature under RCP2.6 is projected to increase by 1.48°C, 1.91°C, 1.79°C, and 1.68°C in the 2030s, 2050s, 2070s, and 2090s relative to the baseline period, respectively, with the greatest increase expected by mid-21st century. Temperature increases faster under RCP4.5 and RCP8.5 than under RCP2.6. Undoubtedly, future temperature increases will lead to earlier snowmelt and reduced winter snow accumulation, resulting in less runoff during the snowmelt season [?, ?, ?, ?]. Additionally, temperature increases during certain future periods will cause shifts toward liquid precipitation, producing decreasing snowmelt trends under all three RCP scenarios. Wang et al. (2010) and Lutz et al. (2014) similarly found that air temperature increases accompany snowmelt runoff decreases in various glacier- and snowmelt-affected areas.

4.2 Implications of the Evaluation

In recent decades, population growth, economic development, and climate change impacts have intensified conflicts between water supply and demand [?, ?, ?, ?]. Resulting water shortages have affected industrial and agricultural production and domestic water use, threatening environments and ecosystems [?, ?, ?]. Research indicates that future agricultural irrigation water demand in Northwest China will increase, but runoff increases will not meet irrigation needs [?, ?]. With scarce annual precipitation in Xinjiang, water shortage has become a major factor limiting regional social and economic development [?, ?]. However, total annual water consumption and per capita water consumption in Xinjiang have generally increased since 2000, while water consumption per 1.00$×10^{4}$ CNY GDP has decreased [?, ?]. Significant regional differences exist in Xinjiang, with each area developing characteristic industrial structure systems over time. As Urumqi City is located in the economic belt on the Tianshan Mountains' northern slope, its secondary and tertiary industries have developed rapidly through prioritized development of high-tech zones and industrial parks [?, ?]. Although Urumqi City' s water use per 1.00$×10^{4}$ CNY GDP is the lowest in northern Xinjiang, local irrigation water utilization coefficients and industrial water reuse rates are not high, with agricultural water use exceeding 60.0% of total water consumption [?, ?].

Based on Urumqi City' s 2016 industrial structure, our predicted economic loss values for glacier meltwater and snowmelt are higher for industrial and service sectors and lower for agriculture. Correspondingly, Wang' s (2019) 2030 water input-output table projected that industrial and service sector water uses will exceed agricultural water use, with agricultural water consumption tending to decrease. Considering current sectorial water use structure impacts on the economy, developing high-efficiency water-saving irrigation and promoting agricultural transformation are needed to achieve agricultural modernization [?, ?, ?, ?]. In recent years, Urumqi City has launched water conservation campaigns. Improved citizen awareness and water price adjustments will enable more rational water resource use. For sustainable economic and environmental development, Urumqi City should prioritize high-tech and tertiary industries [?, ?]. The city has already established Asia' s largest wind power plant, making rapid new and clean energy development more conducive to industrial transformation.

Our results show that economic loss values for glacier meltwater and snowmelt under RCP8.5 increase by 435.10$×10^{6}$ and 537.20$×10^{6}$ CNY in the 2050s and 2090s, respectively, compared to RCP2.6. Undeniably, economic loss values are more pronounced under high greenhouse gas emission scenarios. In contrast, economic loss values tend to decrease under lower emission scenarios, partly due to different discount rates (the discount factor decreases over time), with lower emission scenarios corresponding to higher discount rates that cause faster economic value decline. Conversely, economic loss values are much greater under high emission scenarios, resulting in decreasing trends under RCP2.6 and RCP4.5 but increasing trends under RCP8.5. Additionally, since our present value approach uses 2016 as the reference year, we focus on economic loss values relative to the reference year rather than direct market value from meltwater provisioning. Results emphasize that active, effective measures to reduce carbon emissions and minimize mid-21st century warming will facilitate greater economic loss reductions. Wu et al. (2020) similarly demonstrated that curbing carbon emissions can reduce snow cover loss economic value.

5 Conclusions

Quantifying the economic significance of declining freshwater supplies is crucial for water resources management and decision-making. This study quantitatively assessed economic losses from future meltwater reduction for sectorial water uses based on glacier meltwater and snowmelt simulations in the Urumqi River, Tianshan Mountains. Results show that compared to the baseline period, total glacier meltwater and snowmelt in the 2030s, 2050s, 2070s, and 2090s decrease by 52.3%, 61.0%, 64.8%, and 65.6%, respectively, under RCP4.5, and by 54.9%, 62.5%, 70.2%, and 74.5% under RCP8.5. Correspondingly, economic loss values for various sectorial water uses are projected to decrease under RCP2.6 and RCP4.5 from the 2030s to 2090s. Under RCP8.5, economic loss values increase from 419.70$×10^{6}$ CNY in the 2030s to 545.4$×10^{6}$ CNY in the 2090s, with cumulative economic losses reaching 2124.00$×10^{6}$ CNY by the end of the 21st century. Snowmelt economic loss values exceed glacier meltwater losses across all four future periods. The industrial sector faces the highest economic losses, while agriculture faces the lowest. Based on these results, climate mitigation and adaptation actions—such as curbing CO_2 emissions and promoting clean energy—should be actively implemented to reduce future meltwater loss economic values. Local differential water pricing should be adopted to improve water resource utilization efficiency. Future research will assess cryosphere meltwater economic losses in other basins within the Tianshan Mountains' northern slope economic belt by combining future climate scenarios and socioeconomic pathways, enabling more reasonable water availability and sustainable development.

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