

Transboundary conflict from surface water scarcity under climate change

Received: 12 March 2024

Accepted: 20 August 2025

Published online: 01 September 2025



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Transboundary river basins (TRBs) are at risk of water scarcity-induced conflicts, especially given the rising water demand and impacts of climate change. Despite extensive efforts and some progress, the mechanisms linking water scarcity to conflicts in TRBs remain insufficiently understood, and identifying effective mitigation and adaptation strategies remains a challenge. In this study, we introduce a framework for predicting TRBs vulnerable to water scarcity-induced conflicts, based on the concept of water dependency, defined by monthly water scarcity. This framework successfully explains over 80% of the TRBs experiencing water scarcity-induced conflicts during 2005–2014. Our projections indicate that, without mitigation and adaptation measures, nearly 40% of global TRBs could face potential conflicts driven by water scarcity in 2041–2050, with hotspots in Africa, southern and central Asia, the Middle East, and North America. However, proactive measures such as intra-basin cooperation could reduce this proportion to less than 10%. This study underscores the urgency of increased investment and active stakeholder engagement to foster intra-basin cooperation and avert potential conflicts.

Water resources are vital for life, but their spatiotemporal distribution is increasingly impacted by climate change¹. Socio-economic development has also increased water demand over recent decades^{2,3}, and this trend is expected to continue^{4–6}. Consequently, some regions will face insufficient water resources to meet demand, resulting in water scarcity and conflicts that threaten human health, socio-economic development, and ecosystem stability^{7,8}.

Transboundary river basins (TRBs) account for approximately 60% of global water resources⁹. Unlike rivers confined within a single country, water availability in downstream countries within TRBs can be directly affected by upstream countries^{10,11}. To address water scarcity, cooperation between upstream and downstream countries is common in TRBs¹². However, such cooperation does not always effectively alleviate scarcity, especially under conditions of severe drought or increasing water demand. In these cases, tensions between upstream

and downstream countries may escalate, leading to conflict over shared water resources. Notably, cooperation and conflict coexist in about 20% of TRBs¹³. For instance, the state of Montana in the United States has called for a renegotiation of agreements with Canada, claiming Canadian farmers overuse water¹⁴. Similarly, international disputes over the Nile resurged in 2020 with the construction of the Grand Ethiopian Renaissance Dam, despite prior cooperation. Recent data suggest an increase in low-level conflicts, while cooperation may be declining¹⁵. Since 2017, the number of conflict events has exceeded cooperation events. The failure or renegotiation of water allocation treaties is likely to become more frequent as water scarcity intensifies^{16,17}. Therefore, predicting TRBs vulnerable to water scarcity-induced conflicts under extreme scenarios (i.e., without cooperation) is crucial, which can provide policymakers with insights into which TRBs require prioritized attention.

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Previous research has primarily examined relationships between water conflicts and explanatory variables such as water scarcity indices, water availability, water demand, treaties, population, and GDP¹⁸. However, no direct causal link between water scarcity and conflict has been established. One reason is that water-related conflicts can arise from various factors, including water pollution, flood control, geopolitics, and water scarcity, but most studies attempt to correlate water scarcity with all types of conflicts. Moreover, water scarcity alone does not necessarily lead to conflict; instead, poorly coordinated or inequitable responses between upstream and downstream countries can increase the risk of tensions and disputes¹⁹. Databases such as the Transboundary Freshwater Dispute Database (TFDD)¹⁴ have documented the causes of water scarcity-induced conflicts in detail. Conflicts can emerge from upstream regions when upstream actions—such as building dams or diverting water flows—further exacerbate water scarcity downstream. Conversely, downstream regions may trigger conflicts by demanding more water resources, challenging existing agreements, or seizing upstream water to alleviate local water scarcity. These examples highlight that conflicts are more likely to arise when downstream regions heavily depend on upstream water resources to alleviate local scarcity, leading to competition over upstream water resources and, consequently, a higher risk of conflict.

Previous research has also shown that greater external dependence on water resources correlates with a higher likelihood of conflict¹³. However, most studies define water dependency using annual water availability and withdrawal²⁰. This approach raises the question of whether water scarcity-induced conflicts are better linked to monthly water availability and withdrawal, given that conflicts can arise after just a few months of water scarcity¹⁴.

To mitigate future water scarcity-induced conflicts in TRBs, transboundary cooperation is critical. Additionally, measures such as taking a low-emission and resource-efficient development pathway, seawater desalination, and rainfed crop expansion can also help address water scarcity^{16,21,22}. However, most assessments of these measures are case-specific²³, and global-scale evaluations of optimal strategies remain limited.

The primary goal of this research is to investigate the mechanisms driving water scarcity-induced conflicts and identify TRBs at risk of such conflicts in the future, focusing on monthly water scarcity and water dependency. For maximum identification of vulnerable TRBs, this study assumes the absence of future intra-basin cooperation, as such cooperation remains uncertain. Therefore, the results in this study primarily highlight the TRBs vulnerable to conflicts due to the inherent pressure of water scarcity. After identifying TRBs facing potential water scarcity-induced conflicts, intra-basin cooperation is considered as a potential solution alongside climate change mitigation, seawater desalination, and rainfed crop expansion, with their effectiveness in mitigating future water conflicts thoroughly evaluated. Conflicts driven by geopolitics, environmental pollution, or other factors are excluded from this analysis. Following previous studies^{12,13}, conflict actions in this study include condemnation, criticism, economic hostile, political hostile, small scale military acts, declaration of war and other disputes between upstream and downstream countries.

Results

Modelling historical water scarcity and water scarcity-induced conflicts

To identify areas experiencing water scarcity, we applied the monthly water scarcity index (WSI). The WSI employed in this study is calculated as the ratio of total human water withdrawal to the available water resources, thus capturing the extent of anthropogenic pressure on water systems (see Methods section: “Water Scarcity Calculation”). During the historical period (2005–2014), approximately 35% of all sub-basin areas faced water scarcity for at least one month each year (Fig. 1a), affecting an estimated 750 million people (Supplementary

Table 2). Water-scarce sub-basin areas were primarily located in Asia and Africa (Fig. 1b), with hotspots in central and western Asia and northern Africa.

Notably, 24 sub-basin areas experienced water scarcity throughout the year (Supplementary Table 2), including those in the Colorado, Indus, and Rio Grande River Basins. These results align closely with previous research findings²⁴. The monthly distribution of sub-basin areas affected by water scarcity is presented in Fig. 1d, while the affected populations are detailed in Supplementary Table 2. It is also worth highlighting that water-scarce sub-basin areas were predominantly located in upstream regions of transboundary river basins (TRBs; Fig. 1c), potentially exacerbating downstream water challenges.

Water scarcity in downstream regions is heavily influenced by upstream inflows, increasing the likelihood of transboundary conflicts over water resources^{13,25}. Unlike previous studies that employed regression analyses to link all conflict events to various variables (e.g., water scarcity), we defined two types of water scarcity-induced conflicts—Type I and Type II—based on the usage rights of upstream runoff and the dependency of downstream regions on upstream inflow. Type I conflict represents a situation where downstream regions seek to increase their share of upstream runoff—either by disputing existing water allocation arrangements or attempting to secure additional upstream resources—in order to alleviate their own water scarcity. Type II conflict, by contrast, reflects upstream regions’ efforts to gain greater control over runoff through interventions such as water storage or diversion, which may exacerbate water scarcity downstream. TRBs facing either type of situation are considered at risk of potential water scarcity-induced conflict. These two types of conflicts are simulated by comparing the number of water-scarce months under varying assumptions of downstream water availability, including local runoff, natural discharge, and actual discharge (see Methods section: “Modelling Water Scarcity-induced Conflicts”).

To validate our model, we compared TRBs simulated to face potential water scarcity-induced conflicts during 2005–2014 with historical records of such conflicts from datasets like TFDD and WCC^{14,26} (see Methods section: “Modelling Water Scarcity-induced Conflicts”). As illustrated in Fig. 2, the model successfully identified most TRBs that historically experienced water scarcity-induced conflicts (blue regions in Fig. 2), achieving a hit rate of 80.6%. However, some TRBs that experienced scarcity-induced conflicts—such as the Colorado, Ganges, Juba-Shibeli, Nu-Salween, Mekong, and Senegal River Basins—were not captured by the model (red regions in Fig. 2; Supplementary Table 4). Using the Monte Carlo method with 1000 experiments, we accounted for uncertainties in water availability and withdrawal (assumed to follow a normal distribution with a mean equal to the original value and a standard deviation of 0.5 times the original value). The results indicate that, for most TRBs—except the Juba–Shibeli and Colorado Rivers—the failure to reproduce water scarcity-induced conflicts is primarily due to uncertainties in the input data, rather than limitations of the modeling framework (see Supplementary Information, “Validation of the simulated basins facing potential water scarcity-induced conflicts”).

While the model overestimated potential conflicts in some TRBs (green regions in Fig. 2), resulting in a critical success index (CSI) of 0.42, this overestimation primarily occurred because the model assumed no cooperation. Of the 28 TRBs simulated to face potential water scarcity-induced conflicts but without historical records in 2005–2014, 24 showed evidence of cooperation (e.g., treaties or river basin organizations) in the TFDD dataset (Supplementary Table 5). Additionally, 19 of the 24 TRBs are not expected to face annual-scale water scarcity and indeed have the potential to achieve cooperation through reasonable intra-annual water allocation. For the remaining four basins without cooperation—Daoura, Dra, Baraka, and Kogilnik—the results of 1000 Monte Carlo experiments indicate that uncertainties in water availability and withdrawals contributed to the incorrect

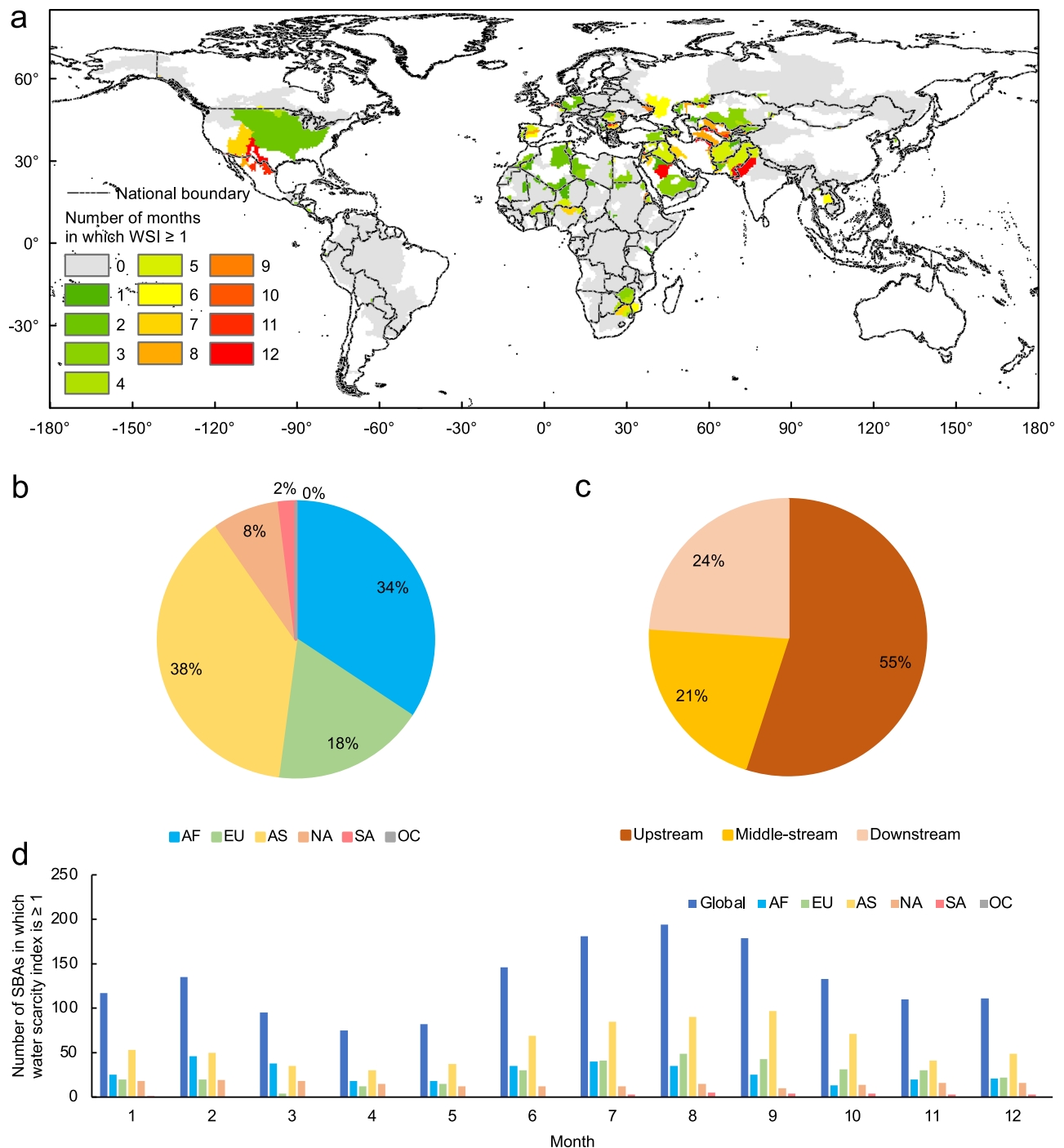


Fig. 1 | Transboundary water scarcity at monthly scale in 2005–2014. a Number of months in which the water scarcity index (WSI) ≥ 1 . The water scarcity index is the ratio of water withdrawal to available water resources. The white areas are regions without transboundary river basins. **b** Distribution of water-scarce sub-basin areas

(SBAs) across all continents (AF Africa, EU Europe, AS Asia, NA North America, SA South America, OC Oceania). **c** Distribution of water-scarce sub-basin areas in the upstream, middle-stream, and downstream parts of basins. **d** Number of sub-basin areas facing water scarcity in each month.

conflict predictions (see Supplementary Information, “Validation of the simulated basins facing potential water scarcity-induced conflicts”). Therefore, the absence of cooperation mechanisms in the model, along with uncertainties in water availability and withdrawal data, together contributed to the overestimation of conflicts.

Although cooperation is a mitigating factor, its occurrence in the future remains uncertain due to ongoing debates about the conditions required for cooperation²⁷. Additionally, cooperation does not guarantee the absence of water scarcity-induced conflicts, particularly during years with low water availability or under increasing pressures

from climate change, socio-economic developments, and new infrastructure projects^{19,27}. Given our study’s focus on maximizing the identification of TRBs facing potential scarcity-induced conflicts, cooperation was considered only as a potential solution and we have used post hoc to explain overestimations of water scarcity-induced conflicts.

Overall, the high hit rate (80.6%) demonstrates that the proposed method can effectively identify TRBs at risk of water scarcity-induced conflicts. Furthermore, the 1000 Monte Carlo simulations showed that uncertainties in water availability and withdrawal had minimal impact

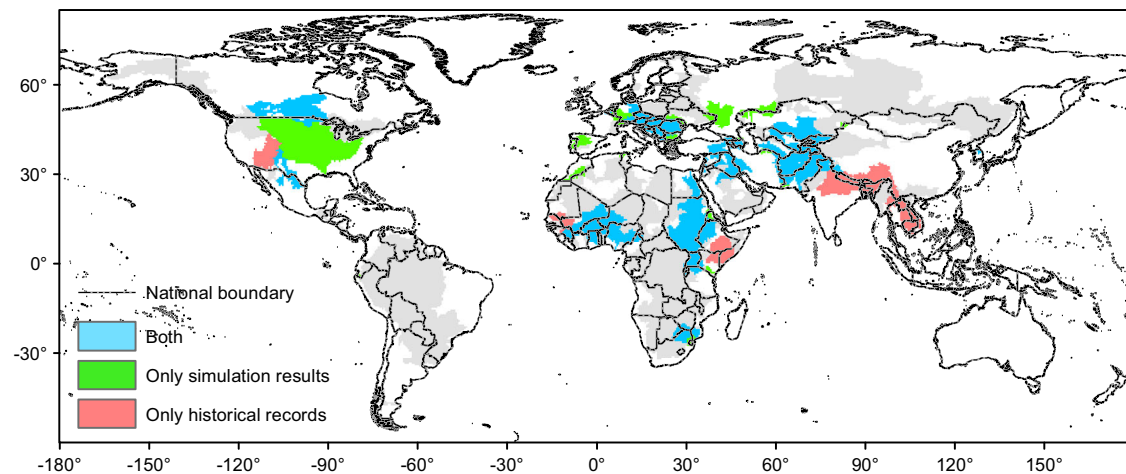


Fig. 2 | Validation of the transboundary river basins that were simulated to face potential water scarcity-induced conflicts in 2005–2014. The red, green, and blue regions represent, respectively: transboundary river basins with historical

conflicts but not simulated to face potential water scarcity-induced conflicts; those simulated to face such conflicts but without historical occurrences; and those in which conflicts were successfully simulated.

on the model's overall accuracy in predicting conflicts (see Supplementary Information, "Uncertainties").

Changes in water scarcity-induced conflicts

During 2005–2014, TRBs facing potential water scarcity-induced conflicts were primarily located in central and western Asia, eastern Europe, northern Africa, and North America. Notable examples include the Nile, Jordan, Tigris–Euphrates, Indus, and Rio Grande River Basins (Fig. 3a). It should be noted that while the Danube River Basin has established comprehensive transboundary water cooperation—particularly under the coordination of the International Commission for the Protection of the Danube River^{28,29}—it has not been entirely free from water-related disputes. According to the TFDD dataset, conflict events related to water scarcity occurred in the Danube Basin during 2005–2014, primarily associated with the Gabčíkovo–Nagymaros dam project.

Type I conflicts were the most prevalent form of water scarcity-induced conflicts (Fig. 3c), suggesting that these conflicts are primarily driven by increased freshwater demands from downstream regions. Central and western Asia experienced both types of conflicts, indicating a complex interplay of upstream and downstream pressures in these regions (Supplementary Fig. 10).

In the context of climate change and socio-economic development, future water scarcity is projected to intensify due to increasing water withdrawal (Supplementary Figs. 4–6). By 2041–2050, water scarcity is expected to intensify in most sub-basin areas, particularly in central and western Asia and southern Africa (Supplementary Figs. 7–9). The population exposed to water scarcity in TRBs is anticipated to rise substantially, reaching 1.8–2.3 billion—2–3 times the population affected during 2005–2014 (Supplementary Table 3).

If no mitigation and adaptation measures on water scarcity are implemented, the number of TRBs facing potential water scarcity-induced conflicts is projected to increase by 10–30% during 2041–2050 compared to 2005–2014, with 35–41% of TRBs globally likely to be affected (Figs. 3b, c). Central and western Asia are projected to face both upstream and downstream-driven conflicts (Supplementary Figs. 11–13), necessitating focused attention in these regions. Under all scenarios, South Asia, Southeast Asia, and Southern Africa are projected to emerge as new hotspots for water scarcity-induced conflicts, while some TRBs—such as the Elbe and Hamun-i-Mashkel/Rakshan—are expected to see a decline in conflict risk. Under SSP1-2.6, fewer TRBs in Europe (e.g., the Danube Basin) are projected to face conflicts (Supplementary Fig. 14), primarily due to reduced water

scarcity (Supplementary Fig. 7). In contrast, SSP3-7.0 indicates a sharp increase in the number of TRBs facing water scarcity-induced conflicts, largely driven by substantial rises in water withdrawal (Supplementary Fig. 5), with South America and parts of Europe emerging as regions of concern (Supplementary Fig. 15). Results from 1000 Monte Carlo simulations confirm minimal uncertainty in projections, with consistent trends across scenarios (Supplementary Fig. 29).

Potential solutions to mitigate water scarcity-induced conflicts

To reduce future water scarcity-induced conflicts, global-scale mitigation and basin-scale adaptation measures have been evaluated. The global mitigation measure is taking a low-emission and resource-efficient development pathway (i.e., SSP1-2.6 scenario). The basin-scale adaptation measures include intra-basin cooperation, spatio-temporal regulation of water supply and demand in sub-basin areas, seawater desalination, and expansion of rainfed crop planting. It should be noted that the cooperation we refer to primarily focuses on overcoming spatial and temporal mismatches between water supply and demand within sub-basin areas, meaning that the total annual surface water resources and withdrawal of the TRB remain unchanged.

Under SSP5-8.5, transboundary cooperation emerges as the most effective strategy, alleviating water scarcity in approximately 60% of affected sub-basin areas, with remaining water-scarce regions concentrated in central and western Asia (Supplementary Fig. 18). This indicates that through measures such as the construction of water transfer infrastructure, the establishment of basin-wide water allocation rules, and the development of joint water management platforms, the water resources within the TRB can be effectively utilized to address the spatiotemporal mismatches between water availability and demand across sub-basin areas. Spatiotemporal regulation of water supply and demand in sub-basin areas is the second most impactful measure, addressing water scarcity in 38% of sub-basin areas (Supplementary Fig. 19). The expansion of rainfed crops is effective in alleviating monthly water scarcity by up to three months in some regions, such as Central Asia and North America (Supplementary Fig. 20). Desalination is more geographically limited and can only reduce water scarcity by no more than six months in most regions (Supplementary Fig. 21). Under SSP3-7.0, transboundary cooperation remains the most effective solution to mitigate water scarcity and associated conflicts (Fig. 4c), underscoring the importance of collaborative efforts in addressing these challenges.

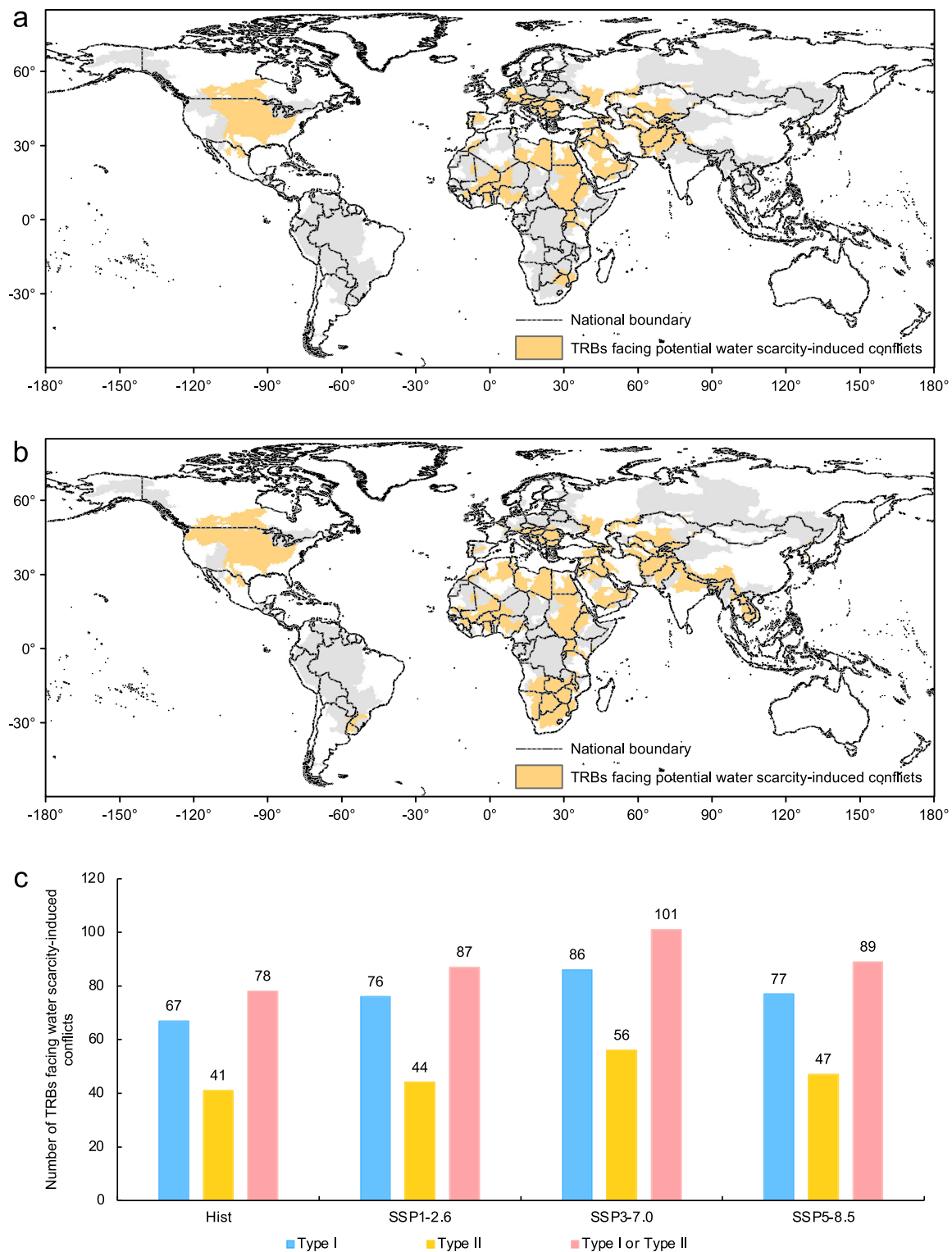


Fig. 3 | Simulated transboundary river basins (TRBs) facing potential water scarcity-induced conflicts in the historical (2005–2014) and future periods (2041–2050). **a** Simulated transboundary river basins facing potential water scarcity-induced conflicts in 2005–2014. **b** Simulated transboundary river basins facing potential water scarcity-induced conflicts in 2041–2050 under the SSP5–8.5

future scenario. **c** Number of transboundary river basins facing potential Type I and/or Type II conflicts. The blue and yellow bars represent the number of transboundary rivers basins facing potential Type I and Type II conflicts, respectively, while red bars indicate the number of transboundary river basins facing either Type I or Type II conflicts.

If all solutions are implemented simultaneously (i.e., under the SSP1-2.6 scenario with the adoption of other adaptation measures), the number of water-scarce sub-basin areas would be substantially reduced, with only 9.3% of all sub-basin areas projected to face water scarcity. These areas are primarily located in central and western Asia

(Fig. 4a), including river basins such as the Aral Sea, Tigris–Euphrates, and Helmand. This analysis assumes that in sub-basin areas where viable solutions exist, transboundary water conflicts would not be the immediate response. Consequently, the number of TRBs at risk of water scarcity-induced conflicts could be substantially reduced, with

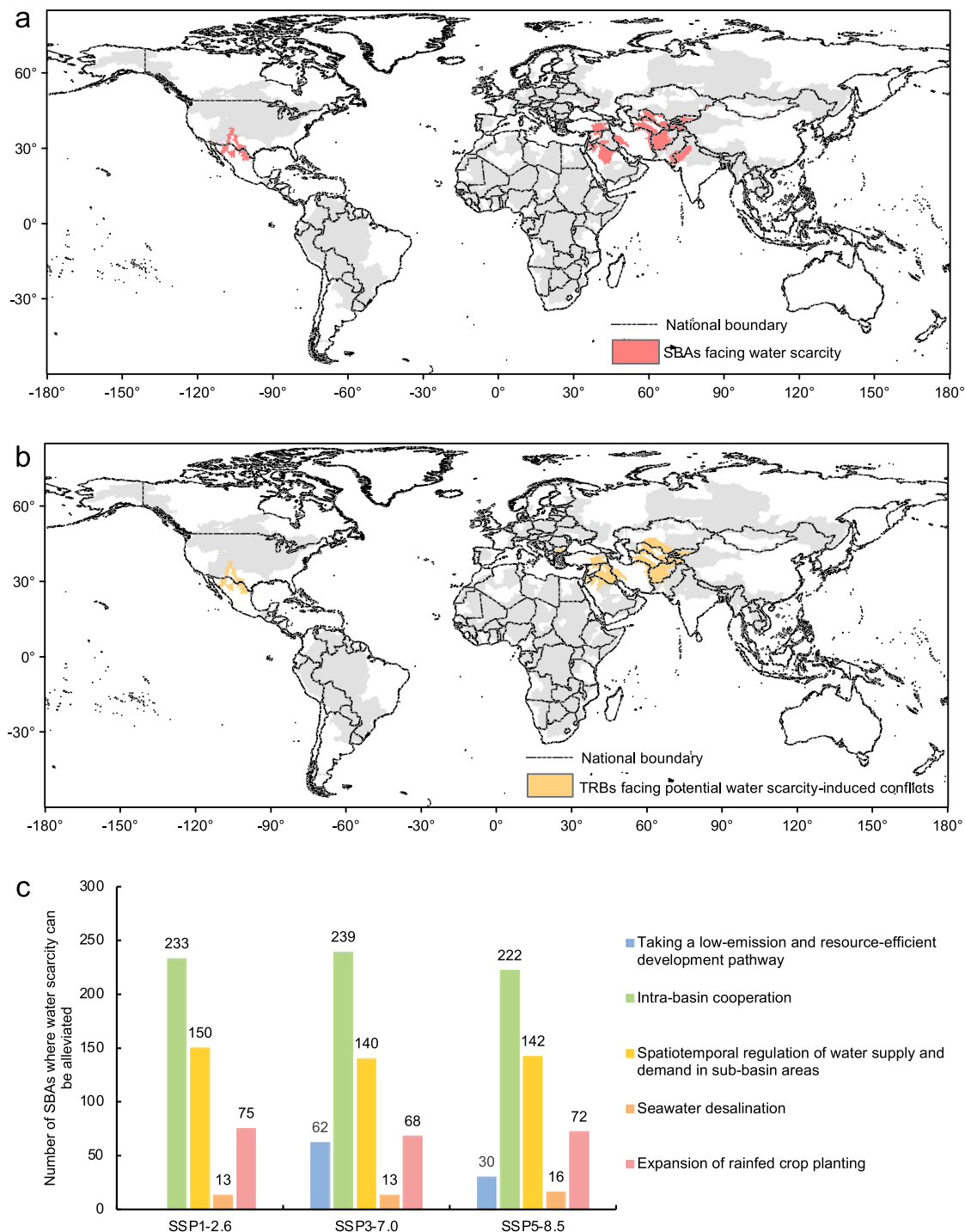


Fig. 4 | The potential solutions to water scarcity and water scarcity-induced conflicts in global transboundary river basins (TRBs). **a** Water scarcity in sub-basin areas (SBAs) after considering all solutions in 2050. **b** Transboundary river

basins facing potential water scarcity-induced conflicts after considering all solutions in 2050. **c** Number of sub-basin areas where water scarcity can be alleviated by different measures.

only 20 out of 246 TRBs projected to face such risks (Fig. 4b). These results suggest that, with coordinated efforts and the implementation of appropriate adaptation measures, potential conflicts between sub-basin areas could be effectively mitigated.

Discussion

This study has identified TRBs vulnerable to potential water scarcity-induced conflicts, based on the concept of water dependency, which is determined by the monthly water scarcity index across the sub-basin

areas of a TRB. This approach explains 80.6% of the TRBs that experienced water scarcity-induced conflicts during 2005–2014. In contrast, most prior studies have relied on multiple regression analyses correlating all types of historical conflict events with variables like water scarcity, to predict transboundary water conflicts¹⁸. Our research focuses exclusively on conflicts driven by water quantity, allowing for deeper insight into the relationship between water scarcity and transboundary conflicts. Additionally, previous regression methods often fail to explain the mechanisms underlying conflict outbreaks.

By emphasizing the dynamics between upstream and downstream regions, we distinguish two types of conflicts arising from competition for upstream runoff. This distinction offers a fresh perspective on the mechanisms behind water scarcity-induced conflicts. Type I conflicts occur when downstream regions attempt to secure greater usage rights over upstream runoff by challenging existing water allocation agreements or taking direct action to seize upstream water. These actions may alleviate water scarcity downstream and represent the predominant form of transboundary conflicts driven by water scarcity (Fig. 3c). This suggests that downstream regions will frequently contest water allocation treaties. Type II conflicts arise when upstream regions seek to retain greater control over upstream runoff through measures like water storage or diversion. These actions increase the number of months experiencing water scarcity in downstream regions. Our findings indicate that upstream infrastructure development, such as water storage facilities, may exacerbate water scarcity-induced conflicts.

The analysis projects that water withdrawals will increase in most sub-basin areas by 2041–2050, particularly under the SSP3-7.0 and SSP5-8.5 scenarios (Supplementary Figs. 4–6). Previous studies have highlighted water withdrawals as the primary driver of increased water scarcity^{16,30}. However, it is critical for TRBs to determine whether upstream or downstream withdrawals are the dominant contributor to downstream scarcity. To explore this, we categorized water availability and withdrawal into upstream water demand, local water demand, upstream runoff, and local runoff (see Supplementary Information, “Drivers for the changes in water scarcity”).

Our findings reveal that local water demand is the primary driver of downstream water scarcity for most sub-basin areas, while increases in upstream water demand have minimal impact (Supplementary Figs. 34–36). This insight is pivotal for preventing water conflicts, as rising downstream demand is likely to heighten competition for upstream runoff usage rights, potentially triggering disputes. This finding supports the conclusion that Type I conflict is the dominant form of water scarcity-induced conflict. For downstream regions, technical efficiency and policy interventions targeting demand-side pressures are crucial to alleviating local water scarcity.

Additionally, previous research has often overlooked the role of monthly variations in water availability by focusing on annual time-scales. Our monthly analysis underscores the importance of upstream and local runoff during specific months under the SSP1-2.6 and SSP5-8.5 scenarios (Supplementary Figs. 34, 36), particularly for TRBs in South and North America (e.g., the Amazon River). For these regions, improving seasonal forecasting and optimizing reservoir management are critical strategies.

Our projections identify potential TRBs facing water scarcity-induced conflicts in 2050. Without intervention, the number of TRBs vulnerable to such conflicts is expected to rise by 2041–2050, particularly in southern Africa under all scenarios. Notably, most regions in southern Africa experienced minimal water scarcity during 2005–2014. However, under the three scenarios for 2041–2050, reduced water availability and increased withdrawals (Supplementary Figs. 4–6) are projected to increase water-scarce months in the region (Supplementary Figs. 7–9). For example, in the SSP5-8.5 scenario, the Orange River basin, which experienced no water scarcity in 2005–2014, is projected to encounter water scarcity in midstream areas by 2041–2050. Similarly, water scarcity is expected to expand in the Zambezi and Okavango River basins, affecting both midstream and upstream areas. Increased midstream water scarcity is likely to intensify demands for upstream runoff, raising the risk of Type I conflicts. Well-designed policies must be promptly developed to address water scarcity and potential conflicts, particularly in midstream and downstream countries.

If comprehensive solutions (i.e., taking a low-emission and resource-efficient development pathway, intra-basin cooperation,

spatiotemporal regulation of water supply and demand in sub-basin areas, seawater desalination and expansion of rainfed crop planting) are adopted, only 20 TRBs—primarily in central and western Asia—are expected to face water scarcity-induced conflicts by 2041–2050. Among these solutions, transboundary cooperation is paramount. However, this study is based on an idealized assumption that water scarcity in all sub-basin areas within a TRB can be fully alleviated as long as the TRB does not experience water scarcity at the annual scale. In practice, achieving such comprehensive spatiotemporal redistribution of water availability and demand would require substantial investments in infrastructure, strong institutional coordination, and effective socio-political collaboration. For example, water-transfer projects involve complex cost-benefit analyses and cooperative decision-making. Third-party mediation mechanisms, public education, awareness campaigns, and community engagement are also essential to facilitate successful cooperation. Despite these simplifications, our findings underscore the potential of intra-basin cooperation to reduce local water scarcity and mitigate risks of transboundary conflict.

It should be noted that we did not consider all potential solutions. Firstly, we only considered basin-scale adaptation measures, without considering the external water resources beyond the TRB boundaries. Therefore, domestic water transfers, international virtual water trade, and similar external supply mechanisms were not considered. Moreover, quantifying the potential increase in surface water through adaptation measures (e.g., environmental legislation) on a global scale remains highly challenging. Consequently, we only considered measures that make optimal use of existing surface water resources within each TRB, as well as those that compensate for surface water shortages through alternative sources such as seawater and green water, rather than those that might increase total surface water resources. In regions such as Central and Western Asia (Fig. 4), where the measures proposed here may be insufficient to resolve water scarcity, additional strategies—including environmental legislation and international virtual water trade—are likely needed to achieve sustainable water management^{21,31,32}. Future research integrating refined regional socio-economic data could enhance assessments of these solutions.

Several uncertainties remain in this research. These include uncertainties related to GCMs, RCP–SSP scenarios, water availability and withdrawal data, water scarcity thresholds, and environmental flow requirement (EFR) values (see Supplementary Information, “Uncertainties”). While the study emphasizes the importance of monthly-scale analysis, the impact of water storage facilities on runoff simulations was not fully considered, leading to discrepancies with real monthly water resources. Also, due to the hydrological model's structural limitations and parameter inaccuracies, biases in the water availability data still exist in some regions³³, which may affect the assessment of water scarcity. Future research can incorporate methods such as machine learning to further improve the accuracy of runoff simulations³⁴. Groundwater, an important water source, was excluded in this study due to limited data availability and the uncertainty in projecting future groundwater use, which may result in a slight over-estimation of water scarcity³⁵. Future research should aim to improve the collection and sharing of groundwater data—especially at the transboundary basin scale—and support the development of integrated assessment frameworks that consider both surface and groundwater sources to better inform water management and adaptation planning. Another limitation of this study is that, due to the high uncertainty in predicting the future effectiveness or continuity of cooperation, existing or potential cooperation mechanisms—such as treaties and river basin organizations—were not incorporated into the model for predicting transboundary water conflicts. Future research could incorporate hypothetical future transboundary cooperation scenarios, exploring how varying degrees of institutional collaboration—ranging from minimal coordination to comprehensive treaties—may

influence the likelihood and severity of water conflicts. Despite these limitations and uncertainties, this study enhances the understanding of transboundary water scarcity and conflicts, offering critical insights for effective policymaking.

Methods

Data

Water scarcity includes physical water scarcity and social water scarcity³⁶. Physical water scarcity can be further divided into blue water scarcity and green water scarcity. Here, we focus on blue water scarcity.

The data used for this research consisted of (I) transboundary river basin (TRB) and sub-basin area data, (II) water availability data, (III) water withdrawal data, and (IV) population data. The TRB and sub-basin area data and upstream–downstream hierarchy were from Munia et al. (2018)²⁰ (Supplementary Fig. 1 and Supplementary Table 1). These data have a spatial resolution of 0.5°. The sub-basin areas were obtained by meshing raster maps of country and TRB boundaries of the same resolution (i.e., the area of a TRB within the boundaries of one of the riparian countries), giving 886 sub-basin areas in total. For instance, countries A, B, C share the same TRB and then the TRB can be divided into sub-basin area_A, sub-basin area_B, and sub-basin area_C.

The runoff data (surface runoff and baseflow) for the historical period (2005–2014) generated by Yang et al. (2021)³³ was used to represent the available water resources. The VIC hydrological model includes three soil layers. For the third soil layer, the VIC model combines the infiltration from the upper soil layers and groundwater recharge into baseflow. Therefore, following previous research¹⁰, the groundwater excluded as a freshwater source on the supply side in the VIC model are only the deep groundwater resources that do not feed the runoff and discharge estimates. Additionally, regarding the fulfillment of the groundwater abstraction, some models just take water from the baseflow³⁷. Therefore, the runoff from VIC model is widely used for water scarcity assessment^{25,38,39}. Here, we did not consider non-renewable groundwater, primarily because limited data availability on non-renewable groundwater use and the uncertainty in projecting its future trends³⁵. Additionally, as non-renewable groundwater resources decreasing, extraction costs will increase, potentially reducing reliance on non-renewable groundwater in some regions in the future⁴⁰. According to the findings of Hanasaki et al. (2018)³⁵, water extracted from non-renewable groundwater accounts for 5% of total use. To explore the impact of non-renewable groundwater on predicting water scarcity-induced conflicts, we subtracted 5% of the total water use and recalculated the TRBs facing water scarcity-induced conflicts in 2005–2014. The recalculated HR and CSI are equal to 74.2% and 0.40, respectively. Therefore, neglecting non-renewable groundwater has a minimal impact.

Yang et al. (2021) validated these runoff data against observed discharge at over 14,000 gauges³³. The overall Kling-Gupta Efficiency (KGE) of the monthly discharge is greater than 0.5 over 50% of the global stations. The pattern of the KGE values, even though the data consists of smaller basins and covers a longer period, is similar to that of previous global studies^{41,42}. Tu et al. (2024) have compared five of the latest global monthly runoff datasets across more than 26,000 stations worldwide⁴³. These datasets include CaMa-Flood⁴⁴, PCR-GLOBWB⁴⁵, WaterGAP⁴⁶, GloFAS-reanalysis⁴¹, and the dataset from Yang et al. (2021)³³. The comparison results show that none of the datasets consistently performs best across all stations, but the runoff data from Yang et al. (2021) performs best at approximately 40% of the stations. Therefore, the runoff dataset from Yang et al. (2021) is one of the best runoff datasets currently available. Due to the hydrological model's structural limitations, parameter inaccuracies, and biases in the forcing data, there is some uncertainty in the runoff data. We have performed 1000 experiments by the Monte Carlo method and the results show that the uncertainty in water availability has minimal

impact on the model's overall accuracy in predicting conflicts (see Supplementary Information, “Uncertainties”).

The original spatial resolution of the data was 0.05°, and was subsequently aggregated to 0.5°. The runoff data for the future period (2041–2050) were generated by the VIC model, with forcing data from Phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b). This project provides bias-corrected forcing derived from five global climate models (GCMs): GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. The initial future runoff data had a spatial resolution of 0.25°, and this was aggregated to 0.5°. This is because the resolution of the sub-basin areas is 0.5°, and thus if the VIC hydrological model was run at 0.5° resolution, there would only be one grid cell used to calculate the available water resources in the smallest sub-basin area (0.5°), and the result would be highly uncertain. The VIC hydrological model was, therefore, run at 0.25° resolution, meaning that there would be at least four grid cells used to calculate the available water resources in each sub-basin area. Due to the variability of individual reservoirs operating rules, and limited reservoir records for reservoirs' parameter estimation on the global scale⁴⁷, following previous research^{17,25,38,48}, here the reservoirs were not considered when using the VIC model to simulate water availability. Both historical and future water withdrawal datasets were from He et al. (2021)¹⁶ and aggregated to 0.5°. The water withdrawal data include agricultural, industrial, and domestic uses. These data are monthly values, with the future represented by the SSP1-2.6, SSP3-7.0, and SSP5-8.5 scenarios. The SSP1-2.6, SSP3-7.0 and SSP5-8.5 represent the sustainability, Regional Rivalry and Fossil-fuelled Development pathways, respectively⁴⁹. The population data were obtained from PBL Netherlands Environmental Assessment Agency, and are results from the new IMAGE model, version 3.2⁵⁰. Owing to the limitations of this dataset, the population of the historical period was represented by the population in 2015.

We chose 2005–2014 as the historical period because the historical period in CMIP6 models spans from 1850 to 2014, and we selected the most recent decade. We also have found that our model can effectively predict basins that experienced water scarcity-induced conflicts across different time periods (see Supplementary Information, “Sensitivity of results to the choice of historical period”). One additional reason for selecting 2005–2014 is that it represents a climatologically neutral decade—neither distinctly dry nor wet—thus minimizing potential bias in comparisons with future projections. Based on multiple reanalysis datasets, Dai (2021) found that global annual precipitation during this period was close to the long-term average for most regions, including key areas such as the Middle East and West Africa⁵¹. Similarly, runoff data from the G-RUN ENSEMBLE dataset show no clear trend toward drying or wetting since 2000⁵². We chose 2041–2050 as the future period mainly because we aim to project future water scarcity-induced conflicts around the middle of this century. The future period selection is consistent with previous research^{16,53}.

Water scarcity calculation

Previous research indicates that water scarcity assessments performed at a monthly compared to an annual scale markedly affect the outcomes of water scarcity assessments, while a sub-monthly resolution does not lead to very different results than monthly assessments⁵⁴. Therefore, we chose to assess water scarcity on a monthly scale. The water scarcity index (WSI), which is the ratio of water withdrawal to water resources, was used to measure the monthly water scarcity of each sub-basin area. The calculation formula is as follows:

Upstream:

$$WSI = \frac{WW_{\text{local}}}{WA_{\text{local}}} \quad (1)$$

Middle-stream and downstream:

$$WSI = \frac{WW_{local}}{WA_{local} + \sum_{i=1}^n (WA_{up,i} - WW_{up,i})} \quad (2)$$

where WW_{local} and WA_{local} denote local water withdrawal and water availability, respectively. $\sum_{i=1}^n (WA_{up,i} - WW_{up,i})$ represents the upstream inflow. If the upstream water withdrawal is larger than the upstream water availability, the upstream inflow is set to 0. In addition, there are no generalizable relationships between water resources and environmental impacts for large-scale water scarcity assessments, and thresholds of EFR obtained from case studies are not often transferable across different hydrological regimes or habitat types⁵. Besides, the EFR calculated by different methods differ from each other globally⁵⁵. Following previous research^{2,24,30,36}, the EFR has been subtracted from the total available water resources by assuming a fixed percentage of water resources for EFR. Pastor et al. (2014) found that EFR ranged between 25–46% of mean annual water resources globally among different methods⁵⁵. Following previous research^{2,36}, the EFR here is represented by 30% of the water resources of each river basin. The impact of EFR on water scarcity and water scarcity-induced conflicts is described in the Supplementary Information section “Uncertainties”. We adopted the value of 1.0 as the threshold to identify a water-scarce sub-basin area^{16,56}.

Uncertainty resulting from GCMs

To reduce the uncertainty resulting from GCMs as much as possible, we followed a similar procedure to He et al. (2021)¹⁶ and bias-corrected the ISIMIP3b data using historical runoff data generated by Yang et al. (2021)³³. The calculation formula is as follows:

$$WA_{i,m,s}^{2041-2050} = WA_{i,m}^{2005-2014} \times \frac{WA_{i,m,s}^{2041-2050}}{WA_{i,m,s}^{2005-2014}} \quad (3)$$

where i , m , and s denote different sub-basin areas, months, and scenarios, respectively. $WA_{i,m,s}^{2041-2050}$ denotes the corrected water availability. $WA_{i,m}^{2005-2014}$ denotes the water availability in 2014 from a 10-year ordinary least squares regression from 2005 to 2014 based on the runoff generated by Yang et al. (2021). $WA_{i,m,s}^{2005-2014}$ and $WA_{i,m,s}^{2041-2050}$ denote the multi-year average runoff from 2005 to 2014, and from 2041 to 2050, respectively, generated from the average simulation results from five ISIMIP3b datasets. Smoothing through regression can avoid the results of water scarcity being influenced by the available water resources in a given year (i.e., filtering annual anomalies). At the same time, the regression value also represents, to some extent, the true available water resources in each year.

In addition, to measure the consistency between the results generated by the different GCMs, we used the coefficient of variation (CV) index given by:

$$CV = \frac{\sigma}{\mu} \quad (4)$$

where σ and μ denote the standard deviation and average value, respectively, of all GCM simulation results.

Modeling water scarcity-induced conflicts

The water availability of the downstream is affected by local runoff, upstream runoff and upstream withdrawal. The key water source contested between upstream and downstream regions is the upstream runoff. If the water scarcity of the downstream regions is dependent of the upstream inflow, the actions that alter the usage rights over the upstream runoff can trigger water conflicts. We, therefore, compare the number of months in which $WSI \geq 1$ when downstream water

availability is calculated using local runoff, natural discharge (local runoff + upstream runoff), and actual discharge (local runoff + upstream runoff - upstream water withdrawal). Two types of water scarcity-induced conflicts were defined (Supplementary Fig. 2): (I) If the number of months in which $WSI \geq 1$ calculated based on actual discharge is larger than that based on natural discharge in the water-scarce downstream region, the conflict is easy to break up. This reflects the downstream region's desire to obtain greater usage rights over the upstream runoff by challenging existing water allocation agreements or seizing upstream water, aiming to alleviate its own water scarcity. In this case, the conflict is proactively initiated by the downstream region. For instance, following a drought event, the state of Montana in the U.S., located downstream, has called for a renegotiation of its agreement with upstream Canada¹⁴. To simulate TRBs with Type I water scarcity-induced conflicts, the term $WW_{up,i}$ in Formula 2 is set to zero to calculate the WSI based on natural discharge. (II) If the number of months in which $WSI \geq 1$ calculated based on local runoff is larger than that based on actual discharge in the water-scarce downstream region, the conflict is easy to break up. This reflects that the upstream region seeks to gain greater usage rights over the upstream runoff by implementing measures such as water storage and diversion to retain the runoff within the upstream region. Cutting off the upstream runoff exacerbates water scarcity downstream, with the conflict being initiated by the upstream region. For example, the Ataturk Dam in Turkey controls the flow of the Tigris and Euphrates rivers, and the Turkish government has been accused of withholding water by Syria and Iraq⁵⁷. To simulate TRBs with Type II water scarcity-induced conflicts, the term $\sum_{i=1}^n (WA_{up,i} - WW_{up,i})$ in Formula 2 must be set to zero to calculate the WSI based on the local runoff. We assume that at least one additional month of water scarcity could trigger water conflicts because even one additional month of scarcity can have a profound impact on downstream regions (see Supplementary Information, “The assumption for predicting water scarcity-induced conflicts”). Additionally, the TFDD dataset has documented some water scarcity-induced conflicts occurring after just one additional month of water scarcity¹⁴. For example, Bangladesh has accused India in 2005 because it got less water than what it was supposed to get in January under the water distribution treaty with India. Also, the Iraq has accused the Turkey's plans to cut the flow of Euphrates River for one month in 1989.

Although cooperation measures such as treaties are recognized as critical tools for reducing transboundary water conflicts⁵⁸, given the uncertainty in whether future cooperation will materialize, and the observation that conflicts can still emerge even in TRBs with well-established cooperation mechanisms, cooperation was not included as a variable in our conflict prediction^{19,27}. Cooperation measures are considered solely as potential solutions to future water scarcity and conflicts (see Methods section: “Potential Solutions to Water Scarcity”).

Because the judgment of whether TRBs with water scarcity-induced conflicts or not is based on the regression values of water availability and withdrawal in 2014, the aim of our research is to predict the TRBs that face potential water scarcity-induced conflicts rather than to reproduce the time series of water scarcity-induced conflict events on the global scale. This is in line with previous research^{19,59}. To examine whether the simulated TRBs facing potential water scarcity-induced conflicts actually experienced conflicts during the historical period, we compare all simulated TRBs that face potential water scarcity-induced conflicts with all conflictive TRBs recorded in the TFDD¹⁴ from 1999 to 2008 and Water Conflict Chronology (WCC)²⁶ from 2005 to 2014. The TFDD provides records of transboundary water conflict and cooperation events, categorized by type and intensity using the Basin at Risk (BAR) scale. A BAR value below 0 indicates a conflict event. BAR values range from -1 to -7, representing escalating levels of conflict—from mild verbal expressions of discord to

declarations of war. Accordingly, our study classifies TFDD events as conflicts based on their BAR scores. The TFDD database has also labeled the major causes of each water conflict event. The vast majority of water scarcity-induced conflicts are marked as “water use”, “water quantity”, or “hydropower”. Conflicts related to water environment, flooding, and fisheries have their own specific labels, such as “flood control”, “water quality”, “pollution”, and “fishing”. Since the TFDD database explicitly marks the causes, we primarily determine whether the conflict was caused by water scarcity based on these labels, and we do not consider multiple contributing factors. According to the TFDD database, 34 basins experienced water conflicts during the historical period, of which 31 basins (91.2% of the basins with water conflicts) experienced water scarcity-induced conflicts. Two indicators, the hit rate (HR) and critical success index (CSI), were used to measure reliability. These indicators are calculated as follows:

$$HR = \frac{A_0 \cap A_T}{A_T} \times 100\% \quad (5)$$

$$CSI = \frac{A_0 \cap A_T}{A_0 \cup A_T} \quad (6)$$

where A_0 denotes all of the TRBs that were simulated to face potential water scarcity-induced conflicts, and A_T denotes all of the recorded conflictive TRBs in the historical period. Note that, here, only the water scarcity-induced conflicts recorded in the historical database are considered. The conflicts generated by geopolitics, environmental pollution, flood control, and other factors were not selected. For instance, the construction of the waterworks projects on the Elbe River has faced opposition from Czech and German environmental groups in 2001¹⁴. This is the water conflicts generated by environmental pollution. Nepalese protest the Indian dyke project because it would flood Nepalese land¹⁴. This is the water conflicts generated by flood control.

Potential solutions to water scarcity

To explore whether the future transboundary water scarcity and water scarcity-induced conflicts can be alleviated in the future, we considered five potential solutions based on existing solutions to water scarcity^{16,21,22,60}: taking a low-emission and resource-efficient development pathway, intra-basin cooperation, spatiotemporal regulation of water supply and demand in sub-basin areas, seawater desalination and expansion of rainfed crop planting (Supplementary Fig. 3). Among these, taking a low-emission and resource-efficient development pathway represents a global mitigation measure, while the rest are adaptation strategies implemented at the river basin scale. Intra-basin cooperation and spatiotemporal regulation of water supply and demand in sub-basin areas aim to adjust the intra-annual distribution of water use and availability within the TRBs and sub-basin areas, respectively, without altering the annual total water use or water resources. Seawater desalination and expansion of rainfed crop planting represent efforts to tap into alternative water sources to compensate for surface blue water scarcity. Groundwater extraction is also a common practice to alleviate surface water shortages. However, the proportion of groundwater abstraction relative to total water use is available for only a limited number of countries³⁵, and projecting this proportion into the future remains highly uncertain. As a result, it is difficult to robustly quantify the role of groundwater extraction in alleviating water scarcity across individual TRBs. Consequently, groundwater was not included among the adaptation measures in this study.

Among the above solutions, taking a low-emission and resource-efficient development pathway was evaluated by comparing simulation results under the SSP3-7.0/SSP5-8.5 scenarios with those under SSP1-2.6, which represents the lowest growth in emissions, population, and cropland area, and the highest water-use efficiency^{4,16}. SSP1-2.6

reflects global mitigation efforts, not basin-scale mitigation. If sub-basin areas no longer face water scarcity under SSP1-2.6, this pathway is considered effective for mitigating water scarcity in those regions.

Regarding basin-scale adaptation, monthly water scarcity within sub-basin areas can initially be addressed through internal regulation, without relying on external water sources. Spatiotemporal regulation of water supply and demand is considered as a feasible solution if (1) the sub-basin area is not water-scarce on an annual scale (i.e., annual WSI < 1), and (2) upstream regulation does not worsen conditions downstream (i.e., does not trigger Type II conflicts). This approach includes supply-side options (e.g., water storage and redistribution) and demand-side strategies (e.g., dynamic water pricing, scheduling of water use). These measures do not change total annual water availability or withdrawal of the sub-basin area, but instead target mismatches between when and where water is available and needed. If the annual WSI of a sub-basin area is projected to be less than 1 in the future, then the number of months with WSI ≥ 1 in that sub-basin area will be set to zero.

Water scarcity in sub-basin areas can also be alleviated through cooperation with other sub-basin areas within the TRB. We assume that the availability of sufficient water resources is the basis for intra-basin cooperation. Therefore, if the entire TRB in which the water-scarce sub-basin areas are located does not face water scarcity on an annual scale, intra-basin cooperation can be identified as a potential solution for all the water-scarce sub-basin areas in the TRB. Accordingly, the transboundary cooperation we refer to includes a range of measures aimed at overcoming the spatial and temporal mismatches between water availability and demand in sub-basin areas. Typical cooperation actions include construction of water transfer facilities, hydrological data and forecast sharing, establishment of basin-wide water allocation rules, economic compensation and water trading mechanisms, joint water management platforms, and legal and institutional mechanisms for dispute resolution. The annual water scarcity index of the entire TRB can be calculated by dividing the annual water availability of the whole TRB by the annual water withdrawal of the whole TRB. Similarly, a WSI greater than 1 is considered to indicate water scarcity. If the projected annual WSI of the TRB is less than 1, the number of months with WSI ≥ 1 will be set to zero across all sub-basin areas within the TRB.

Desalination can be a potential solution for coastal sub-basin areas. Hanasaki et al. (2016) identified desalination-dependent regions by integrating hydrometeorological and socioeconomic data with historical desalination activity⁶¹. We adopted their AUSD (Area Utilizing Seawater Desalination) dataset for 2050 under SSP1, SSP3, and SSP5. For these regions, following Hanasaki et al. (2016)⁶¹, we assumed that industrial and municipal water withdrawals are fully met by desalinated seawater. Therefore, industrial and municipal water withdrawals in areas utilizing seawater desalination were set to zero, and the WSI of each sub-basin area was recalculated accordingly. The potential reduction in water scarcity by seawater desalination was then assessed by comparing the recalculated WSI values with the original estimates.

Another approach to compensate for surface blue water scarcity is the enhanced utilization of green water. Chouchane et al. (2020) found that expanding rainfed crop planting and optimizing cropping patterns could reduce global agricultural blue water consumption by up to 20%⁶². Similarly, Su et al. (2024) reported that increasing the rainfed area for wheat and maize in China could lead to a 15.1% reduction in agricultural blue water use⁶³. Therefore, in sub-basin areas where green water is not projected to decline significantly (2041–2050), we assumed a 20% reduction in agricultural water withdrawals and recalculated WSI to estimate the effect on future water scarcity. The trend of the green water resources is detected by the Mann-Kendall Trend Test at the 0.05 confidence level. Because green water is not the main object of this research, for simplicity, green water resources were represented by total evapotranspiration⁶⁴.

Subsequently, transboundary conflicts were recalculated using the adjusted water withdrawal data and WSI following the implementation of the above solutions, to explore whether future water scarcity-induced transboundary conflicts could be alleviated through the potential solutions to water scarcity.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The transboundary river basin data used in this study is publicly available from <https://doi.org/10.5194/hess-22-2795-2018-supplement>. The water withdrawal data used in this study is publicly available from <https://github.com/zfliu-bnu/Urban-water-scarcity>. The ISIMIP3b data is publicly available from <https://data.isimip.org>. The Transboundary Freshwater Dispute Database (TFDD) dataset is publicly available from <https://transboundarywaters.science.oregonstate.edu/content/international-water-event-database>. The Water Conflict Chronology (WCC) dataset is publicly available from <https://www.worldwater.org/water-conflict/>. The water scarcity index calculated in this study has been deposited in the Figshare database (https://figshare.com/articles/dataset/Water_scarcity_index/28120880)⁶⁵.

Code availability

The code of VIC hydrological model is available at <https://github.com/UW-Hydro/VIC/releases>. The Python scripts used in the calculation of water scarcity index are available at <https://doi.org/10.5281/zenodo.10807445>⁶⁶.

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Acknowledgements

This work was jointly supported by the National Key Research and Development Program of China (2024YFE0106700 & 2022YFC3002901) (H.L.) and the National Natural Science Foundation of China (42371340) (H.L.). The computing support is from the High Performance Computing Centre of Tsinghua University.

Author contributions

H.L. and R.J. designed the study. R.J. conducted the calculations. R.J., H.L., D.C., and K.Y. analyzed the results. R.J. created the figures. R.J. wrote the first draft of the manuscript. H.L., D.C., K.Y., D.G., G.H., and F.T. reviewed and edited the manuscript before submission.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41467-025-63568-y>.

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Peer review information *Nature Communications* thanks Guenter Bloeschl, Charalampos Skoulidakis and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. A peer review file is available.

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