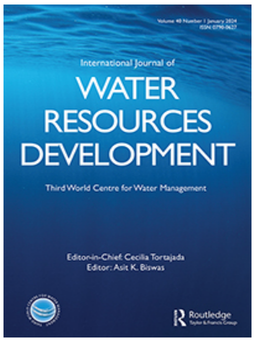

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Projecting conflict risk in transboundary river basins by 2050 following different ambition scenarios

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ABSTRACT

This study presents three global scenario projections of conflict risk in transboundary river basins by combining scenario projection data on risks identified in the existing literature. Under a business-as-usual scenario, 920 million people are projected to live in very high to high conflict-risk basins by 2050. In the low ambition scenario, this number decreases to 724 million people, while in the high ambition scenario, it decreases to 536 million. Large basins with specifically high conflict risk are the Juba–Shibeli, Lake Turkana, Indus and Irrawaddy. These findings hope to inform water diplomacy, conflict prevention and mitigation support for basins at risk.

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Transboundary river basins; scenario projections; hydropower dams; institutional resilience; conflict risk; ambition pathways

Introduction

Hundreds of rivers are shared by two or more countries. Using these shared rivers can lead to competition or conflict between riparian states. Recent examples of conflictive interaction include tensions in the Indus (Pakistan and India), the Euphrates–Tigris (Turkey, Syria and Iraq) and the Nile (Egypt, Sudan and Ethiopia) basins. Nonetheless, cooperation over these rivers overall prevails (Bernauer & Böhmelt, 2020; Wolf, 1999) and large-scale international violent conflicts or even war over shared waters have so far not happened (De Stefano et al., 2012; Yoffe et al., 2003).

Risks for conflict do nonetheless remain and potentially increase as populations grow, water use intensifies and the climate changes. It is therefore important to better understand the dynamics and conditions that can affect transboundary conflict and cooperation and the different factors that drive conflict and cooperation dynamics, as studied by various authors (Dinar et al., 2019; Link et al., 2016; Petersen-Perlman & Wolf, 2015; Schmeier, 2013). This is particularly important as these drivers are still insufficiently understood and prior research has sometimes led to inconclusive findings (Bernauer &

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Böhmelt, 2020) while being of great importance especially for understanding potential future conflict risk in shared basins and developing adequate policy responses.

Some scenarios investigating conflict risks in transboundary basins are already available (Farinosi et al., 2018; De Stefano et al., 2012, 2017), but all come with their own challenges. In this study we build on existing insights on conflict risk in transboundary basins to develop ambition scenarios on conflict risk in transboundary river basins. Ambition scenarios are potential futures reflecting certain levels of commitment in terms of policy or investments towards desired outcomes, such as reducing water stress. We adapt the framework developed by De Stefano et al. (2017) to develop three scenario projections for 2050 which are situated in the Shared Socioeconomic Pathway 2 (SSP2) (O'Neill et al., 2014) and Representative Concentration Pathways (RCP) 6.0 (van Vuuren et al., 2011). Combining scenario projection data and historical data, this multicriteria assessment combines information on the construction of mega-dams, institutional resilience and exacerbating hydroclimatic, governance and socio-economic risk factors. A definition of mega-dams is given in the third section. In the absence of full consensus on the drivers of conflict in transboundary river basins, it is neither possible nor desirable to accurately predict conflict in the long term. What can be done, though, is identifying basins where various risks are projected to compound, which therefore deserve heightened policy attention to prevent or mitigate conflict and strengthen cooperation early on.

Providing conflict risk projections for transboundary river basins is particularly timely and relevant in the context of rising hydroclimatic and socio-economic pressures in shared basins. In the coming decades, the hydrological impacts of climate change and rising human-induced water demand are projected to intensify water problems in many shared river basins (Munia et al., 2020). Often downstream water availability is dependent on upstream precipitation and water use patterns. Countries towards the downstream ends of transboundary rivers can thus become dependent on the water use policies of their upstream counterparts (Munia et al., 2018), while upstream countries can find their development needs and plans negatively affected by downstream opposition, possibly bearing an increasing risk of conflict that needs to be identified and addressed preventively.

Especially in the context of climate change, many small and large dams are planned to be constructed, mainly for hydropower purposes, mostly in parts of Latin America, Asia and Africa (Zarfl et al., 2015). The construction of dams, particularly large ones, can intensify existing tensions or create new ones (Link et al., 2016; Zeitoun et al., 2013; Zeitoun & Mirumachi, 2008), although this strongly depends on the way these dams will be constructed and managed, and on the existing socio-political context (De Stefano et al., 2017; Wolf et al., 2003). Besides the construction of dams, which has received most attention in the literature, planned and operating inter-basin water transfers, typically for irrigation purposes, might add to future tension between states in shared basins (Purvis & Dinar, 2020), although little research has been done towards the potential long-term impacts of these transfers and their implications for conflict.

While physical changes have shown to be critical in the evolution of transboundary water interactions, these interactions are inherently political processes determined by the broader political context. The degree of cooperation and conflict typically depends on the broader historical and contemporary political context (Zeitoun & Mirumachi, 2008).

Existing research also suggests that one of the most indicative variables for conflict in shared river basins is a rapid or extreme change in the basin, such as through the development of physical infrastructure, in absence of sufficient transboundary institutional mechanisms to manage the effects of that change (Wolf et al., 2003). Formal agreements governing transboundary basins and river basin organizations (RBOs) have provided a framework for communication and negotiation with the intent to prevent potential disputes (De Stefano et al., 2017), and to develop and implement joint activities of water resources management (Schmeier, 2013). However, the presence of a treaty or an RBO does not mean the absence of conflict (Dinar et al., 2019). Even when treaties are in place and complied with, and RBOs function, future pressures from climate change, socio-economic developments and the construction of new dams may challenge the effectiveness and continuity of these arrangements.

In this study we provide insight into which shared river basins may face conflict risk as a result of the construction of hydropower dams, limited institutional resilience and hydro-climatic, governance and socio-economic pressures. We operationalize three scenarios with different ambition levels regarding local and transboundary water management and national governance. We argue that there is a research gap in identifying which transboundary river basins might be at risk of conflict in the long term. This research gap results in a knowledge gap for decision-makers, ultimately affecting conflict prevention. Bridging this research gap can spur discussion between different actors stimulating a shared understanding of long-term conflict risks (de Bruin et al., 2022). This in turn can increase awareness concerning the need and the specific instruments to be applied for conflict prevention or mitigation efforts between states sharing water resources as well as conflict-sensitive transboundary climate adaptation.

Framing conflict and cooperation in transboundary river basins

Defining conflict in transboundary river basins

In this study we define conflict in transboundary river basins as a situation in which two or more countries perceive that they possess mutually incompatible goals with regard to the use, development or protection of the water resources they share (conflict definition adapted from Mitchell, 1981). This definition allows for a broad interpretation of conflict over transboundary water resources, in contrast to other definitions that solely focus on violent conflict. Conflictual interactions between states could range from accusations, diplomatic tensions, economic sanctions to militarized interstate disputes (Bernauer & Siegfried, 2012). In the case of conflict in transboundary basins, the main concern is not primarily that of casualties due to armed conflict. A more stringent issue resulting from conflict in transboundary basins is the impact this can have on the environment as well as on socio-economic development, such as increasing water demand and pollution, ecological degradation as well as increased vulnerability to the impacts of climate change. Moreover, the absence of cooperation can lead to foregone benefits that could arise from joint activities such as flood management, the improvement of navigation, joint infrastructure projects and many more (Klaphake, 2005). Additionally, tensions between states over such issues can spill over into other sectors, compromising regional political or economic relations more generally (Keskinen et al., 2021). This together can create significant costs of non-cooperation (Pohl et al., 2017).

Views on conflict and cooperation over transboundary waters

The dominant discourse on conflict over transboundary water resources has changed over the years – as have assessments on whether the transboundary nature of many of the world's watercourses would come with a risk of increased conflict or a promising potential for cooperation.

At the end of the 1980s and in the early 1990s, water was increasingly perceived by scholars and politicians as a resource that held an inherent conflict potential. The 'water wars' theory was born, implying that water scarcity can and necessarily will lead directly to violent conflict or even war between nations (Myers, 1993; Starr, 1991). This was based on a broader debate on environmental security, which emerged in the context of shifting security priorities after the end of the Cold War. Starting with the publication of *Our Common Future* by the World Commission on Environment and Development (Brundtland, 1987), neo-Malthusian theories argued that the lack of access to or absolute scarcity of natural resources would be a cause of conflict at the local, national but also international level (Gleick, 1991; Homer-Dixon, 1994; Homer-Dixon et al., 1993). Water resources fit this line of reasoning, with scholars such as Starr (1991) arguing that water security would soon rank with military security, especially in the Middle East and Northern Africa, and Ashton (2002) concluding that water wars in Africa would be 'inevitable' by 2025 without preventive action.

In the late 1990s, 2000s and early 2010s, the discourse shifted from a focus on conflict to a focus on cooperation, also influenced by a more general optimism in international relations that emphasized the benefits of the post-Cold War multilateral system and the ability of international institutions to peacefully solve conflicts. Observations, through projects gathering large-scale evidence across the world's basins (Wolf, 1999) as well as through specific case studies (Elhance, 1999; Turton, 2000), supported this renewed focus. Relatedly, the broader environmental security discourse became more and more criticized: the assumption that people – mostly in the Global South – will resort to violence in times of resource scarcity was increasingly seen as colonial and simplistic (Barnett, 2000). Moreover, the debate moved beyond the earlier dichotomy of conflict or cooperation, acknowledging that they can and in fact often do coexist (Zeitoun & Mirumachi, 2008) and that a great potential for cooperation exists that needs to be yielded for the benefit of riparian people and countries (Sadoff & Grey, 2005). Scholars have also increasingly taken into consideration the many possible intervening factors that can link shared water resources to conflictive or cooperative developments, with a particular focus on treaties and RBOs as international institutions that ensure peaceful cooperation (Kliot et al., 2001; Schmeier et al., 2016; Song & Whittington, 2004).

In recent years, hypotheses about increasing risks of conflict over transboundary water resources are re-emerging, largely in the context of the climate security debate (Boas & Rothe, 2016; Busby, 2021) but also considering an increasing scepticism towards international institutions and an increase in unilateral trends more generally in the international system. As the global concern shifted towards the potential security implications of climate change, scholars not only assessed its conflict potential within countries (e.g., von Uexkull & Buhaug, 2021), but – albeit to a significantly smaller extent – climate change's possible risk implications for transboundary rivers and their existing governance mechanisms (Dinar et al., 2019; Link et al., 2016; Petersen-Perlman et al., 2017). While results still vary, there seems to be some indication that increasing water variability due to climate change can indeed negatively affect cooperation and potentially lead to conflict. Nonetheless, intervening factors, such as the overall relations between riparian states (Link et al., 2016) or the role of RBOs in mitigating such conflict risks (Dinar et al., 2019; Kittikhoun & Schmeier, 2020; Milman et al., 2013), seem to still matter at least as much.

By defining the main risk of conflict between riparian countries as the absence of cooperation over a wide range of hydroclimatic and socio-economic developments, we turn away from the water war and climate security hypotheses.

Methodology

To assess which transboundary river basins might face conflict risk by 2050, we adapted the multi-criteria assessment as developed by De Stefano et al. (2017). The scenario projections in this study were based on three components: (1) the construction of new hydropower dams; (2) the institutional resilience of basins; and (3) hydroclimatic, governance and socio-economic conditions within countries. Since our study has a longer time horizon than De Stefano et al. (2017), we replaced and adapted the hydroclimatic data, hydropower dam construction and socio-economic indicators with data that were already available or specifically developed for this study. Scenario projections for the development of water treaties and RBOs do not exist. Therefore, we adapted the existence and characteristics of treaties fitting the three scenarios operationalized in this study.

The analysis was conducted at the basin-country unit (BCU) level (McCracken & Wolf, 2019). A BCU is the portion of a riparian country's land area within a certain transboundary river basin. To calculate the number of people living in BCUs by 2050, results from the future urban growth model 2UP (Koomen et al., 2023) were used.

Scenarios

Three ambition scenarios situated in SSP2 and RCP 6.0 were operationalized with various ambition levels regarding governance quality within countries, water management measures and institutional capacity in terms of water treaties and RBOs. SSP2 is understood as the middle-of-the-road scenario following the current trends in demographic and socio-economic developments without fundamental breakthroughs. Under RCP 6.0, total radiative forcing increases steadily to 3.5 W m^{-2} in 2050. Stabilization only begins at the end of the century. RCP 6.0 implies explicit climate policy intervention, and greenhouse gas emissions peak around 2060 and then decline until 2100.

The three scenarios included in this study are the business-as-usual (BaU), low ambition and high ambition scenarios. The BaU scenario follows the socio-economic and hydroclimatic baseline as derived from SSP2 and RCP 6.0 for the socio-economic and hydroclimatic indicators as well as for the construction of new hydropower dams. The indicator values for governance and institutional capacity in terms of water treaties and RBOs are the same in the BaU scenario as the most recent historical data, since no major changes are assumed in this scenario. The low and high ambition scenarios are more ambitious in terms of water (re) use efficiency, institutional capacity and governance quality within countries. In addition, the high ambition scenario assumes a different spatial configuration of the changing land use of SSP2, excluding the expansion of agriculture in areas that are protected on grounds of their biodiversity or vulnerable soils. At the scale of the BCUs, the shifts in land use are negligible, the effects of water measures (summarized in Table 3) and the operation of dams are more important. The improvements made per indicator are described below in detail.

Hydropower dams

For this study, we used projections of new hydropower dam construction in the SSP2-RCP 6.0 scenario following the method developed by Gernaat et al. (2017). This dam construction scenario is based on physical feasibility, energy yield and construction costs, and is restricted by several conditions. Construction is restricted by avoiding large reservoirs in urban areas due to high displacement costs, by excluding the first 200 km upstream of basin outlets of rivers to allow for shipping and other uses, and by excluding nature protected areas and areas in the vicinity of large bodies of water such as lakes and wide rivers. To avoid overlap between reservoirs, Gernaat et al. (2017) used an optimization method to prioritize hydropower dam sites with the lowest cost per kWh and reject upstream sites inundated by these dams. The economic potential was defined as net production costs lower than US$0.1/kWh. The new dams come on top of the existing dams from the GRAND (Lehner et al., 2011) and the GOODD (Mulligan et al., 2020) databases.

We adapted the threshold for including hydropower dams as proposed by De Stefano et al. (2017). They defined dams as large if the dams divert quantities exceeding 100,000 m^3 per year and if these dams have over 10 MW in capacity. In our study, we solely assessed mega-hydropower dams with a capacity of > 400 MW to only include the largest projected hydropower dams in this study, since primarily large infrastructural changes in shared rivers affect conflict risk. Although there is not one shared definition of how to define dam sizes, and we acknowledge that 'mega' can have different meanings in different basins depending on hydrological and ecological characteristics, 400 MW capacity was defined as mega in several studies (García et al., 2021; Iannelli et al., 2017). To avoid confusion with the differing definition of large dams by the International Commission on Large Dams, we frame hydropower dams with a capacity of > 400 MW as mega-hydropower dams, rather than large hydropower dams. For all ambition scenarios, the same scenario projection was used in terms of when and where hydropower dams are constructed, but the operation of the dams differed per scenario. If there are no new hydropower dams in the BCU or upstream of it, a score of 1 (low) was given to that BCU. If there are one or more new large hydropower dams projected in the BCU or upstream of it, a score of 3 (high) was given.

Institutional resilience

Institutional resilience in shared river basins, in the form of treaties and RBOs that provide permanent platforms or mechanisms to peacefully address diverging water resources management issues instead of engaging in conflict, is found to contribute to the decrease of hydro-political conflict risk (Brochmann, 2012; De Stefano et al., 2012). Investigating the design of treaties, several studies have reported that the inclusion of specific features, such as reference to principles of international water

Table 1. Scoring institutional resilience per basin-country unit (BCU).

Component	Presence	Absence
Presence of at least one water treaty	0	1
Inclusion of a conflict resolution mechanism in the treaty	0	1
Adaptation/variability mechanism	0	1
Principle of no significant harm plus the principle of equitable and reasonable utilization	0	1
Presence of a river basin organization	0	1
Total possible value for a BCU	0	5

law conflict resolution mechanisms, treaty enforcement, and the delegation of authority to intergovernmental organizations, makes treaties more effective in preventing and mitigating conflicts (Brochmann, 2012; Tir & Stinnett, 2012). The same holds for RBOs, which institutionalize cooperation even further, therewith providing more and more stable mechanisms for preventing or addressing conflicts (Schmeier, 2013).

Climate change, urbanization and economic developments may change the game via increased risks as a result of increasing water variability, flooding and water stress. Some evidence points towards the importance of treaties and basin organizations in these changing conditions. For example, Zeitoun et al. (2011) found that increased water stress due to climate change is less likely to result in conflict when treaties are equipped with certain institutional design features. Tir and Stinnett (2012) found that the ability of treaties to adapt to increasing water stress resulting from climate change will depend on their institutional design. And Schmeier (2013) found that RBOs can mitigate conflict risks, even in challenging situations in which riparian countries disagree over fundamental water resources management questions.

The more and the better cooperation is institutionalized – through treaties and RBOs – the higher the ability of a basin and its riparian states to cope with conflict risks (Schmeier, 2013; Wolf et al., 2003). To account for the institutional resilience of a BCU, five components were scored, summarized in Table 1: first, whether a BCU has at least one water treaty, solely including the category 'major treaties'; second, whether the present treaty/treaties contain(s) conflict resolution mechanisms; third, whether the present treaty/treaties contain(s) adaptation or variability mechanisms; fourth, if the principle of no significant harm and the principle of equitable and reasonable utilization are included in the treaty/treaties; and last, whether an RBO exists in the BCU.

Data on the 250 independent water treaties negotiated between 1820 and 2007 were derived from the Transboundary Freshwater Treaties Database (TFDD), using the 2018 update (Giordano et al., 2014; International Freshwater Treaties Database, 2018). Treaties signed under colonial rule are excluded from the analysis because we are interested in treaties that still bind riparian countries, and not all colonial ones still do, depending on the treaty and treaty succession issues. We adapted the approach of De Stefano et al. (2012) to score the institutional resilience BCUs. The supplemental data online provides more details on this approach. The presence of an RBO was derived from the RBO Institutional Design Database under the TFDD (Schmeier, 2015). BCUs with 0 or 1 component are classified as high risk (risk score 3); the presence of 2 or 3 as moderate risk (risk score 2); and the presence of 4 or 5 as low risk (risk score 1). In the low ambition scenario, the total institutional resilience score was raised by 1, and in the high ambition scenario, the score was raised by 2.

Table 2. Calculation of exacerbating risk score.

Exacerbating factors →	a Water variability	b Water availability per capita	c Dependence on basin	d Education (proxy to conflict risk and adaptive capacity)	e Governance (proxy to conflict risk and adaptive capacity)	f Income (proxy to conflict risk and adaptive capacity)
Indicator → Score ↓	Projected coefficient of variation (CV)	M^3/person available per year	Water demand from basin (%)	Education projections SSP2 (years of education)	Governance (worldwide governance indicators WB 0–10)	SSP2 GDP per capita PPP (US$)
0	< 0.35	> 1000	< 30%	> 9	> 5.2	> $10,000
1	≥ 0.35	≤ 1000	≥ 30%	≤ 9	≤ 5.2	≤ $10,000

Note: GDP, gross domestic product; PPP, purchasing power parity.
Source: Adapted from De Stefano et al. (2017).

Exacerbating factors

Table 2 displays the indicators that were included to calculate the exacerbating risks and the applied thresholds for scoring BCUs. The indicators were selected based on insights from existing literature, particularly from De Stefano et al. (2017). Ten out of the 811 original BCUs were too small to represent their polygons faithfully at the raster resolution of 5 arc minutes at which the model results were available, and were excluded. This resulted in the exclusion of six other BCUs since these BCUs were the only ones left in the basin. Table S1 and S2 in the supplemental data online provide the names of the excluded BCUs. Table 2 presents how the score will be calculated per indicator. An overall BCU score of 0–2 is considered a low exacerbating risk (risk score 1); 3–4 as moderate risk (risk score 2); and 5–6 as high risk (risk score 3). Table 3 presents the scenario changes in the low ambition and high ambitions scenarios.

Hydroclimatic factors

Factors A–C are the hydroclimatic indicators that potentially exacerbate risk in BCUs. The indicators were derived from SSP2-RCP 6.0 model runs of PCR-GLOBWB (Sutanudjaja et al., 2018).

Factor A, water variability, was calculated by using the coefficient of variation (CV) of annual runoff. A threshold of 0.35 was defined, since rivers with a CV < 0.35 are defined as rivers with low interannual variability, following Adeloye (2012).

Factor B considers water availability per person, as a proxy for water stress in a BCU. People having access to < 1000 m^3 $person^{-1}$ $year^{-1}$ are considered water-stressed (Kundzewicz et al., 2007). Often, more water is available, but due to limited technical or institutional capacity and/or financial constraints, no more can be abstracted or provided. To account for this limited access to water resources, we defined water available for human consumption as 10% of all water available per capita in the BCU.

Factor C defines the water demand of a BCU that is dependent of a BCU on water stemming from the upstream transboundary river basin outside that country. River discharge is a reliable and accessible source of water and dependence on external inflow would make a BCU vulnerable to changes in the physical or socio-economic conditions upstream. Therefore, the inflow of external water was considered crucial if it provides 30% or more of the available water in a BCU.

Table 3. Scenario changes per indicator by 2050.

Exacerbating factors → Scenario ↓	a Water variability	b Water availability per capita	c Dependence on basin	d Education	e Governance	f GDP per capita PPP
BaU	SSP2-RCP 6.0	SSP2-RCP 6.0	SSP2-RCP 6.0	SSP2	2020 value	SSP2
Low	Dams are implemented as hydropower reservoirs, reducing the variability of the river discharge	Increased efficiency for new irrigated areas; moderately improved efficiency for domestic and industrial water demands; groundwater pumping capacity extrapolated into the future on the basis of the historic trend	Hydropower dams buffer more water, releasing it as a constant flow	SSP2	Low increase with log function	SSP2
High	Dams are implemented as water supply reservoirs, matching their release to the downstream demand of the BCU	Increased efficiency for new irrigated areas; strongly improved efficiency for domestic and industrial water demands; unlimited groundwater pumping capacity but extraction limited to renewable groundwater only	Hydropower dams buffer more water, releasing it as a constant flow	SSP2	High increase with log function	SSP2

Note: GDP, gross domestic product; PPP, purchasing power parity.

Domestic capacity: governance and socio-economic factors

Besides the hydroclimatic factors, conflict risk can increase due to the socio-economic and political conditions in a shared river basin and its respective riparian states. An important condition for transboundary cooperation is the domestic capacity to deal with water-related challenges, for which education, governance and economic capacity is required.

In the context of research analysing the influence of domestic factors on conflict and cooperation over shared water resources, Karreth and Tir (2018) show that states often fail to cooperate over shared water resources due to domestic situations in which there are incentives to prioritize national unilateral goals over cooperative behaviour. Such situations are often related to technical and institutional capacity and governance – with low levels of those indicating a limited ability of countries to act on domestic water problems (and thus limited adaptive capacity to change). Additionally, low education and governance levels represent a greater risk of conflict within countries (Besley & Persson, 2011; Brown, 2011; Mach et al., 2019). Factors D, education, and E, governance quality, were therefore used as proxy indicators for domestic capacity to deal with domestic water problems and internal conflict risk.

Low levels of education can have an indirect impact on conflict via socio-economic exclusion of the less educated as well as low political inclusion (Barakat & Urdal, 2009; Brown, 2011). Barakat and Urdal (2009) find that conflict risk increases in areas where youth bulges are high and secondary education is low. The threshold for secondary education set on nine years by Barakat and Urdal (2009) has been adopted for our study. For education, the SSP2 country projections by the Wittgenstein Centre were used (Wittgenstein Centre for Demography and Global Human Capital, 2018).

For governance, the composite governance indicator composed of the worldwide governance indicators (WGI) project was used scaled from 0 to 10 per country (Kaufman & Kraay, 2021). In the BaU scenario, the governance value was kept constant over the years, taking the 2020 value for 2050. The threshold for governance was set on 5.2 representing a threshold for increased conflict risk (based on an analysis by Visser et al., 2019). In the low and high ambition scenarios, the governance quality per country was logarithmically increased. Countries with low 2020 governance values faced a higher increase than countries with high values. The formula below describes the governance value (G_t) based on the governance of five years ago (G_{t-5}) and had two criteria: (1) the high ambition scenario had a higher increase than the low ambition scenario, therefore the C, a constant value, is 1.5 for the high and 0.8 for the low ambition scenario; and (2) countries could not exceed a governance value of 10:

$$G_t = C * (1 - \ log\ (G_{t-5}) + G_{t-5})$$

In addition to education levels and governance capacity in a country, the economic situation is likely to determine whether and how it will be able to deal with water-related challenges (Yoffe et al., 2003). Factor F, gross domestic product (GDP) per capita in purchasing power parity (PPP), was therefore used as another indicator to reflect the domestic situation's contribution to transboundary conflict risk. GDP per capita PPP provides a proxy for adaptive capacity and vulnerability to natural hazards, and countries with lower GDP per capita tend to be more vulnerable to economic and environmental shocks and have relatively low levels of human assets (Hallegatte et al., 2016, 2020). Hallegatte et al. (2020) found that people living in low-income countries are significantly less protected from natural hazards due to limited infrastructure than people living in richer countries. Most countries with low protection capacity had a GDP per capita PPP of < US$10,000. Besides being a proxy for low adaptive capacity and vulnerability, a low GDP per capita has been linked to more transboundary conflict (Yoffe et al., 2003). For GDP per capita, the SSP2 country projections by the Organisation for Economic Co-operation and Development's (OECD) ENV-Growth model were used (Dellink et al., 2017). These data were divided by population projections of the SSP2 scenario to gain GDP per capita PPP (Samir & Lutz, 2017).

Calculating overall risk scores

To calculate the overall composite conflict risk per BCU, we combined the scores of the three different dimensions:

$$Overall\ conflict\ risk = Dam\ risk\ score\ (1-3)\ x\ Institutional\ resilience\ score\ (1-3)\ x\ Exacerbating\ risk\ score\ (1-3)$$

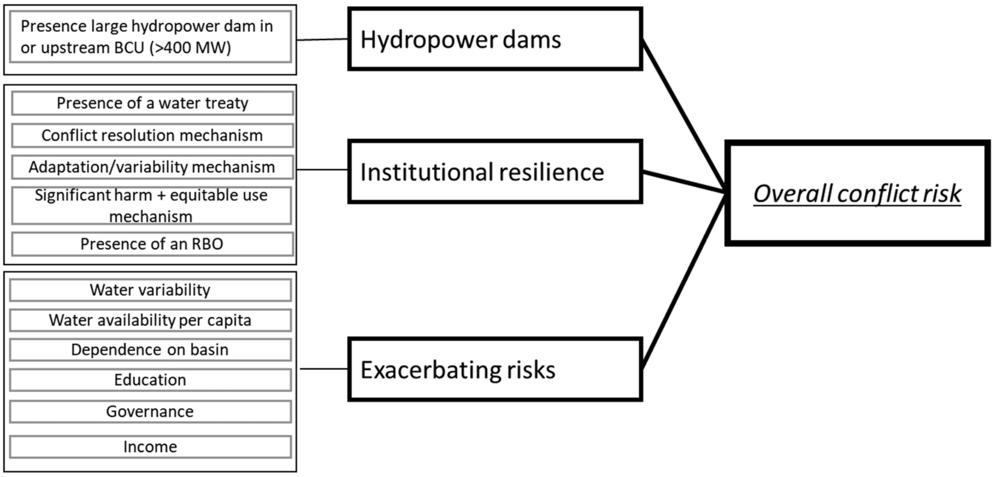

Figure 1. Conceptual diagram presenting the indicators used to develop the scenarios.

Figure 1 presents all the indicators used in this study. Based on the overall risk score per BCU, ranging from 1 to 27, the BCUs were categorized into different relative risk groups: low: 1–4; moderate: 6; high: 9, 12 high; and very high 18, 27. To illustrate the results, the overall risk indications were mapped.

To derive at an aggregated risk score per river basin, the following steps were taken. First, only basins were included where at least one BCU was projected to be at (very) high risk. Second, the overall risk indicator per BCU was weighted based on the population in that specific BCU and the wider basin. Third, the relative scores were added up to derive at a basin-wide average. Finally, a differentiation was made between relatively small basins (< 10 million people) and large basins (> 10 million people). We excluded basins in which over 90% of the population lives in one of the BCUs.

Results

New hydropower dams

A total of 94 new hydropower dams with a capacity of > 400 MW are projected to be constructed between 2021 and 2050, of which 80 are in transboundary basins. The locations of these new dams are presented in Figure 2. The new dams are mostly clustered in Asia: the Ganges–Brahmaputra–Meghna (25 dams), Salween (11 dams), Irrawaddy (seven dams), Indus (three dams), Mekong (three dams) and Kaladan (three dams). But also in Africa (e.g., the Nile, 11 dams) and South America (e.g., the Amazon, six dams) new hydropower dams are projected to be build. By 2050, a total of 1.9 billion people will live in or downstream one of the 43 BCUs with new mega-hydropower dams, affecting 43 BCUs in total.

Institutional resilience

Figure 3 presents the risk scores for institutional capacity in the BaU, low and high ambition scenarios. From the 4.4 billion people living in BCUs by 2050, 1.1 billion people

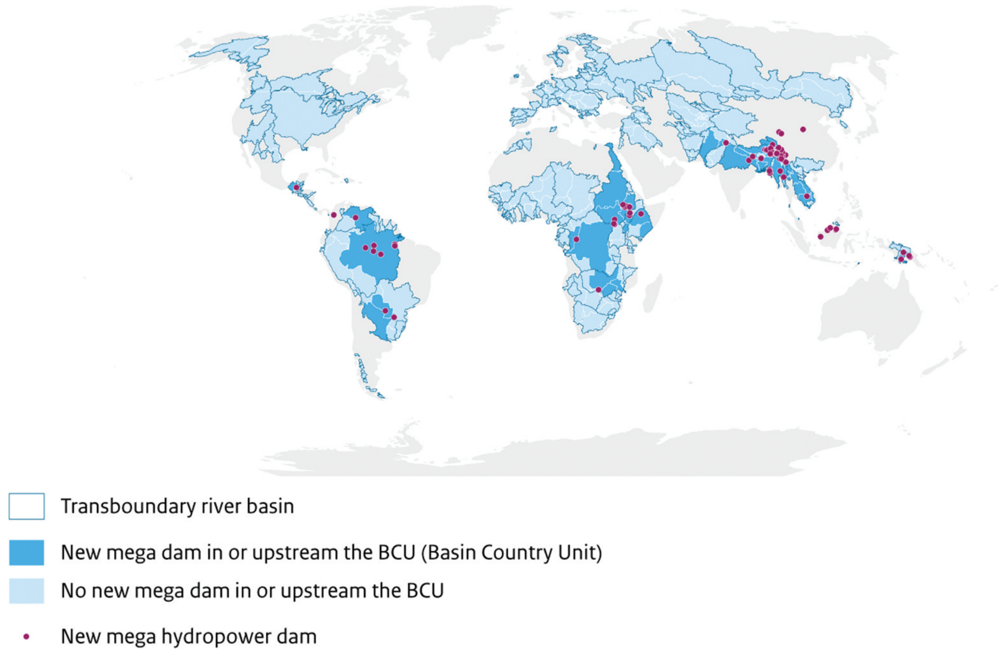

Figure 2. Projected locations of new hydropower dams in transboundary river basins between 2021 and 2050.
Note: Blue areas represent transboundary river basins; and white demarcations represent the basin-country units (BCUs) in the basins. Readers of the print issue can view the figures in colour online at https://doi.org/10.1080/07900627.2023.2184650

would live in a high risk BCU in terms of institutional resilience. This number decreases to respectively 723 million and zero in the low and high ambition scenarios. Most people, 2.4 billion people, are projected to live in low risk BCUs in the BaU scenario, which increases to, respectively, 3.0 billion and 3.3 billion in the low and high ambition scenarios. Overall, Asia has the most BCUs with a high-risk score considering institutional resilience, but also large parts of African transboundary river basins are not covered by treaties nor governed by RBOs.

Exacerbating factors

Figure 4 presents the exacerbating risks for the BaU, low and high ambition scenarios. In the BaU scenario, 749 million people live in high risk BCUs in terms of exacerbating factors by 2050, a combination of hydroclimatic, political and socio-economic factors. Especially transboundary river basins in Africa face high exacerbating risks. Large river basins with several BCUs at high risk include: the Nile (Eritrea, Ethiopia, Rwanda, Uganda), Juba (Ethiopia, Kenya, Somalia), Niger (Burkina Faso, Mauritania and Niger), Zambesi (Mozambique, Malawi), Volta (Benin and Togo) and Lake Turkana (Ethiopia, South Sudan, Uganda). In Asia, especially BCUs in Afghanistan and Pakistan are at risk, including the Indus, Harirud, Helmand and Aral Sea. In the low ambition scenario, fewer people are living in BCUs at high risk compared with the exacerbating factors, 596 million people. In

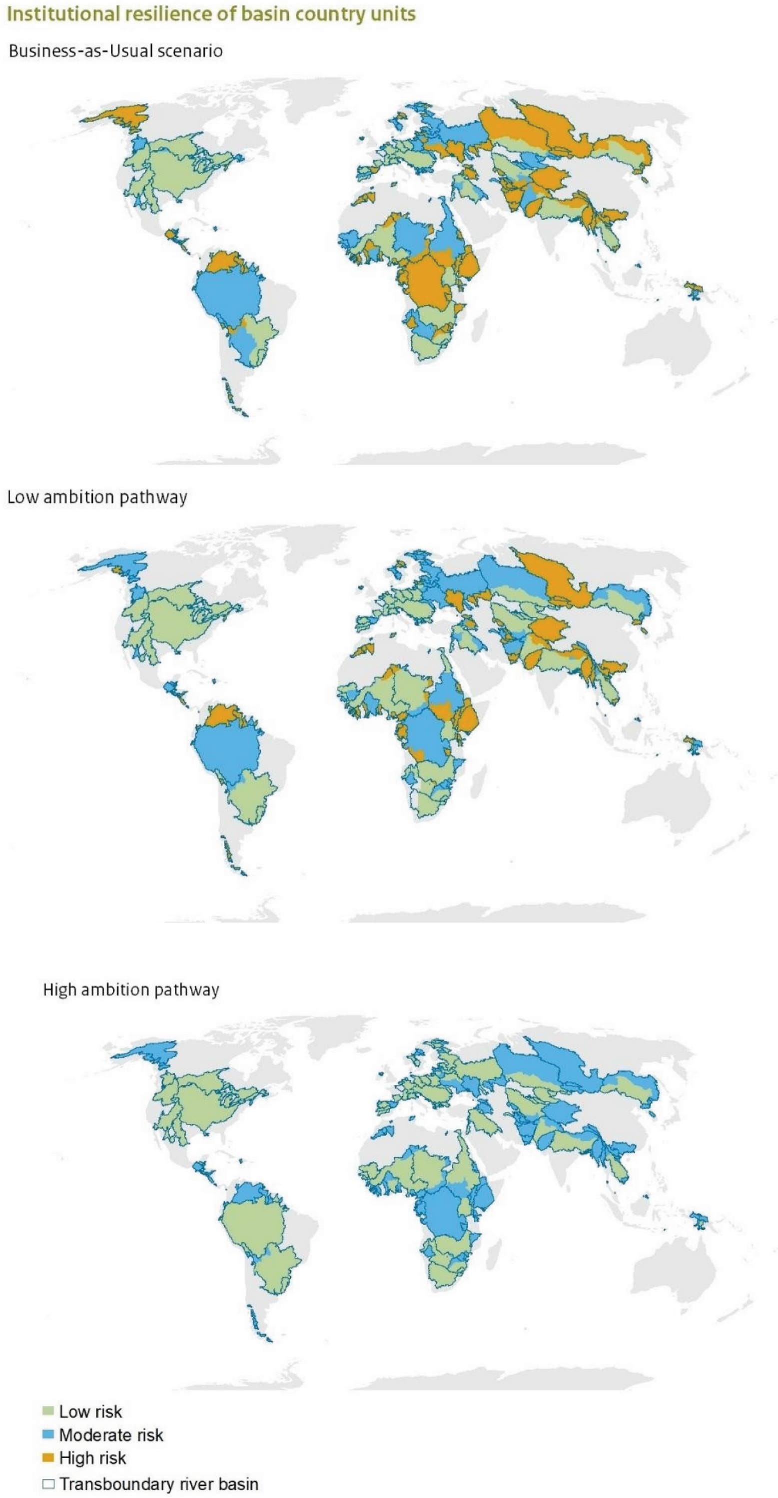

Figure 3. Projected institutional resilience risk score per basin-country unit (BCU) institutional resilience for the business-as-usual (BaU), low ambition and high ambition scenarios.

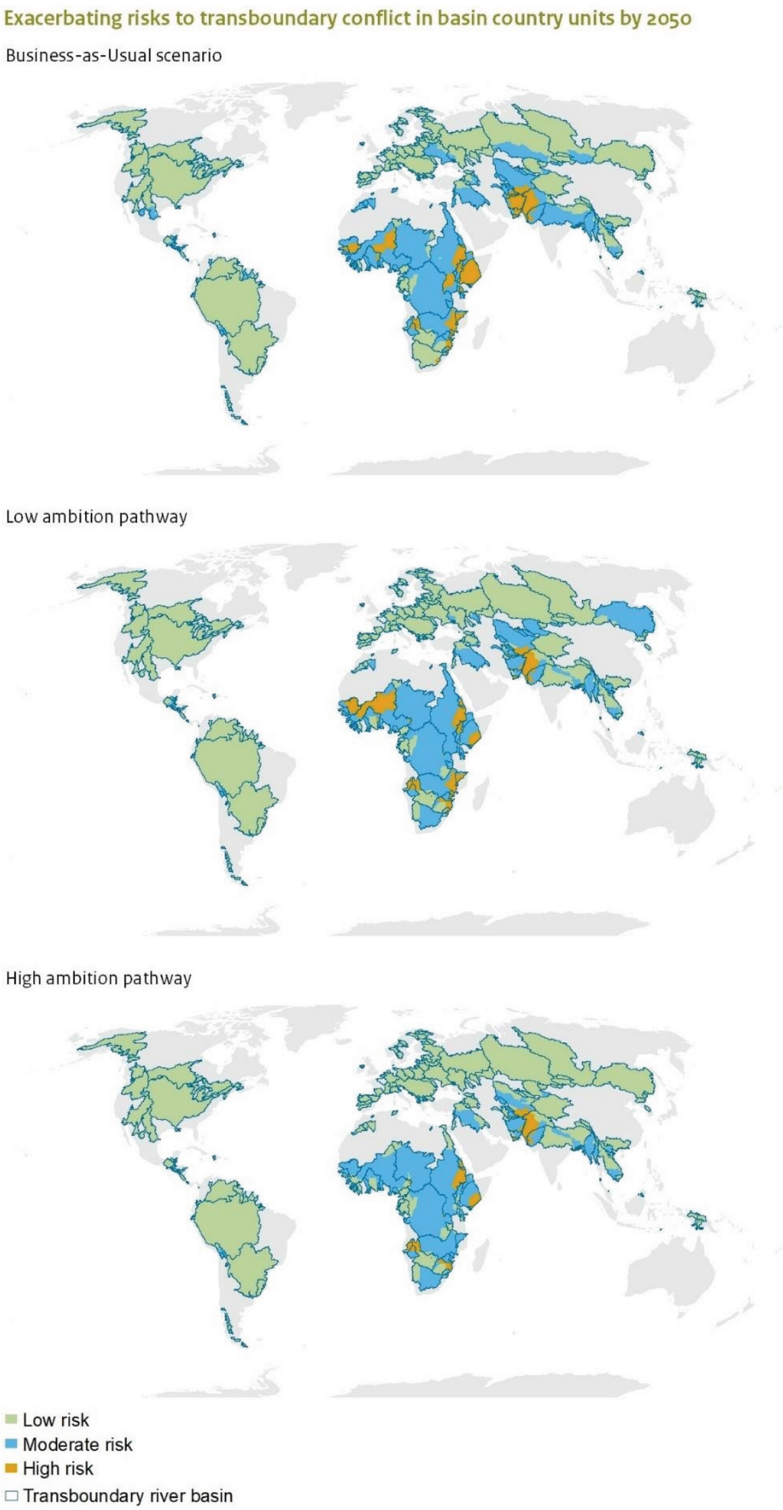

Figure 4. Projected risk score of exacerbating factors per basin-country unit (BCU) for the business-as-usual (BaU), low ambition and high ambition scenarios.

Table 4. Number of people living in basin-country units (BCUs) per risk category by 2050 (in millions).

Scenario	Low risk	Moderate risk	High	Very high risk
BaU	1915	1596	381	539
Low	1596	815	503	171
High	3381	512	530	7

the high ambition scenario, 417 million people live in high risk BCUs. Most of these people – 316 million – live in Afghanistan and Pakistan, in the Aral Sea, Harirud, Helmand and Indus basin. But also in East Africa, 77 million people live in transboundary basins with high exacerbating risks.

Overall conflict risk in BCUs

Figure 5 presents the overall risk score per BCU combining the three risk dimensions for the BaU, low and high ambition scenarios. Overall, 4.4 billion people are projected to live in transboundary river basins by 2050. In the BaU scenario, 920 million people are projected to live in high to very high conflict risk BCUs, assuming no additional improvements in water measures and (water) governance other than the SSP2 baseline (Table 4). River basins with particular high compounding risks are the Nile, Juba–Shibeli, Lake Turkana, Congo, Zambezi (all Africa), Orinoco (South America), large parts of the Ganges–Brahmaputra, Indus and Aral Sea (all Asia). In the low ambition scenario, 674 million people live in (very) high risk BCUs. In the high ambition scenario, the number of people projected to live in high to very high risk BCUs decreases to 537 million, with solely almost 7 million people in very high-risk areas.

Aggregating BCUs to transboundary river basins

Tables 5 and 6 provide an overview of the small (population < 10 million, but > 1 million) and large (population > 10 million) basins facing the highest aggregated risk by 2050. Three African basins, the Juba–Shibeli, Lake Turkana and Congo basins, have the highest overall score based on weighting BCU scores per population. In the Juba–Shibeli, especially Somalia is projected to be highly dependent on water stemming from upstream this basin: the 6.5 million people living in this BCU face a dependency of 93%. In the Lake Turkana basin, the Ethiopian and South Sudanese BCUs are almost 50% depending on inflow from upstream. The Indus, the third most populated basin in the world by 2050, faces high aggregated risks as well. The area of Pakistan situated in the Indus is projected to have a population of 230 million people by 2050, and a dependence on this basin of 62%. The Indus will thus remain critically important to Pakistan in the future. The two smaller basins most at risk are both situated in Asia, with Myanmar as the downstream country facing local upstream dependency of over 61% in both basins.

Discussion

Understanding the projections

The results of this study present multiple, sometimes surprising insights into future developments in transboundary river basins. The potential construction of mega-

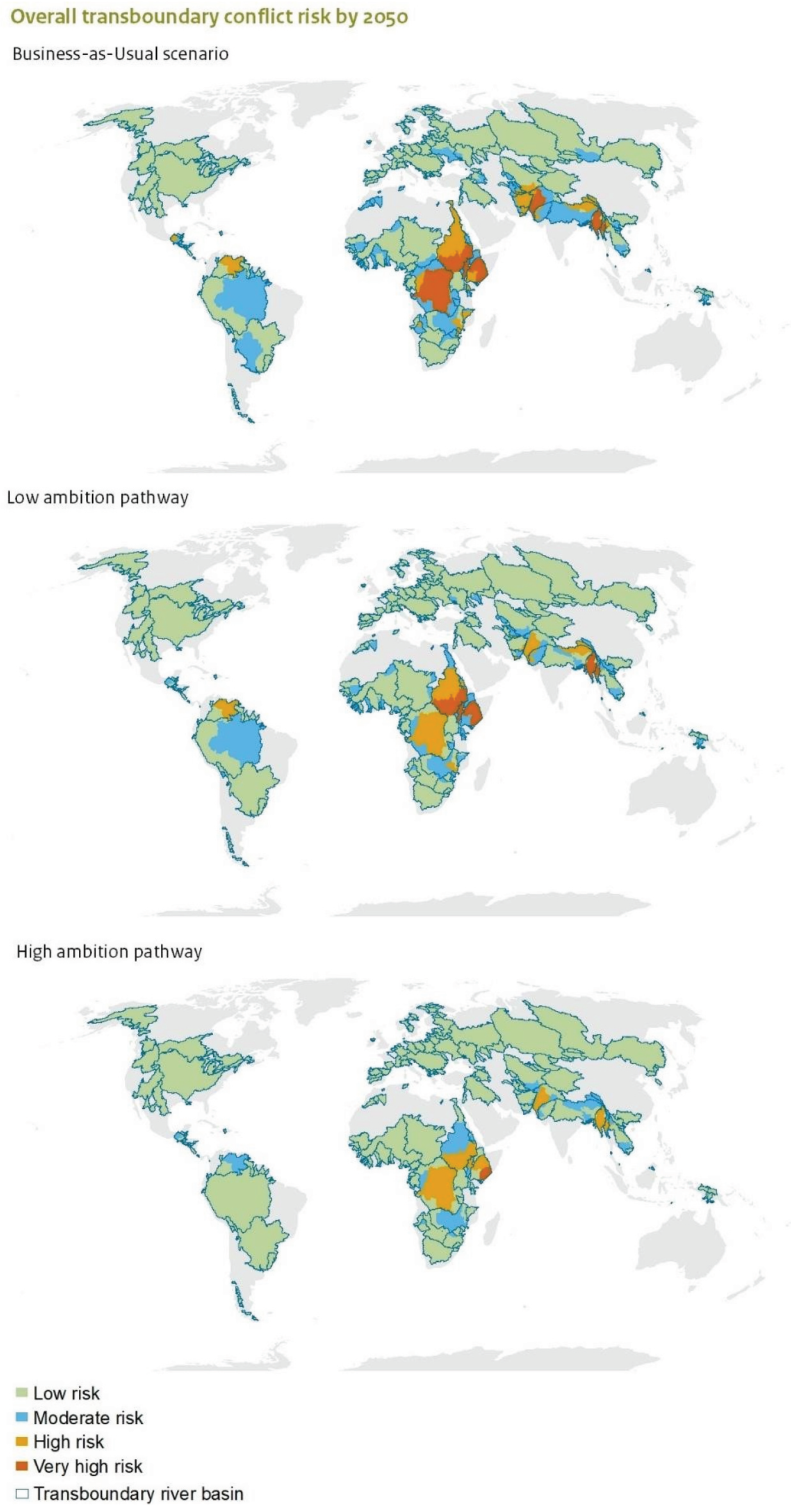

Figure 5. Projected overall conflict risk score per basin-country unit (BCU) for the business-as-usual (BaU), low ambition and high ambition scenarios.

Table 5. Overall projected risk scores of large basins most at risk in the business-as-usual (BaU) scenario.

Basin	Continent	Aggregated basin risk	Population by 2050 (millions)
Lake Turkana	Africa (Ethiopia, Kenya, South Sudan, Uganda)	25.7	25.9
Juba–Shibeli	Africa (Ethiopia, Kenya, Somalia)	23.6	45.2
Congo	Africa (Angola, Burundi, Cameroon, Central African Republic, Congo, Democratic Republic of the Congo, Malawi, Rwanda, Tanzania, Zambia)	15.4	186.1
Indus	Asia (Afghanistan, China, India, Pakistan)	15.0	315.8
Irrawaddy	Asia (China, India, Myanmar)	14.7	27.1
Nile	Africa (Burundi, Democratic Republic of the Congo, Egypt, Eritrea, Ethiopia, Rwanda, Tanzania, Sudan, South Sudan, Uganda)	9.5	425.6
Awash	Africa (Djibouti, Ethiopia, Somalia)	9.0	28.6
Helmand	Asia (Afghanistan, Iran, Pakistan)	8.8	24.0
Orinoco	South America (Colombia, Guyana, Venezuela)	7.8	15.9
Rann of Kutch	Asia (India, Pakistan)	6.9	103.0

Table 6. Overall projected risk scores of small basins most at risk in the business-as-usual (BaU) scenario.

Basin	Continent	Aggregated basin risk	Population by 2050 (millions)
Kaladan	Asia (India, Myanmar)	14.1	1.0
Salween	Asia (China, Myanmar, Thailand)	13.6	7.8
Murgab	Asia (Afghanistan, Turkmenistan)	8.1	5.3
Hamun-i-Mashkel/ Rakshan	Asia (Iran, Pakistan)	8.1	1.7
Cuvelai/Etosha	Africa (Angola, Namibia)	8.0	2.6
Fenney	Asia (Bangladesh, India)	8.0	2.1
Muhuri (aka Little Feni)	Asia (Bangladesh, India)	7.6	5.0
Gash	Africa (Eritrea, Ethiopia, Sudan)	7.4	4.5
Mono	Africa (Benin, Togo)	7.4	4.6
Ruvuma	Africa (Malawi, Mozambique, Tanzania)	7.3	6.1

hydropower dams is most profound in South and Southeast Asia, which could affect already strained multilateral relations (Middleton et al., 2019; Rigi & Warner, 2020; Yangtso, 2017). Especially in parts of basins with low institutional resilience and/or broader existing geopolitical tensions, the construction of these dams is precarious. When construction and management of these new and existing dams are solely focused on national needs, multilateral relations and wider cooperation over environmental and economic issues may be harmed. Meanwhile, diplomatic relations can also be improved by the joint development of transboundary resilience and adaptation strategies, as emergent in the Hindu-Kush river basin (Molden et al., 2017).

In the Horn of Africa potential new hydropower dams are projected to be primarily constructed in Ethiopia, and some in South Sudan. The current tensions in the Nile basin over the Grand Renaissance Dam could further escalate when Ethiopia decides to develop several new mega-hydropower dams, with Egypt being highly dependent on basin-related water resources (Yihdego et al., 2016). Additionally, the impact of these new dams can exacerbate regional climate change impacts and water demands, especially when there is growth in both the population and economy. Although scholars cannot predict when this will occur, a multi-year drought in the Nile basin is inevitable, which could have severe impacts on water allocation (Wheeler et al., 2020). The prospect of a multi-year drought in parts of the Nile basin requires preparations today, especially when several new mega-dams will be built. Even if the impact of new dams in the Nile basin will be moderate, the perception of risk can affect how Egypt makes decisions over shared rivers cooperation (Subramanian et al., 2014).

Two other large basins in the Horn of Africa, the Juba–Shibeli and Lake Turkana basin, are projected to face the highest overall conflict risk levels where multiple issues such as local conflict and low human development already collide. Water availability and security risks are major issues today, which may be worsened without additional efforts towards 2050 due to relatively high population growth and climate change impacts. Even in the high ambition scenario, which implies substantial improvements in water management, overall domestic governance and institutional resilience, the Juba–Shibeli and Lake Turkana basin still face high risks. This suggests that the challenges these basins face are difficult to address, and that these risks must be explicitly included in wider regional social and economic development plans as well as diplomatic action.

In many shared river basins, no new mega-hydropower dams are projected, but risks are expected to emerge from hydroclimatic challenges, governance and socio-economic conditions and limited institutional resilience. Risks due to exacerbating factors are most profound in Africa, especially in the Sahel where large parts of the Niger and the Lake Chad basins face high exacerbating risks. Existing challenges in education, agriculture and security (Graves et al., 2019) and projected future conflict risk (Hoch et al., 2021) may restrict today's and future collaboration over water in these major basins. Although no hydropower dams > 400 MW are projected to be build, and large parts of these basins are formally covered by treaties, the risks coming from the exacerbating factors may strain domestic capacity to shape transboundary cooperation over water to deal with challenges in place. Additionally, new hydropower dams < 400 MW threshold used in this study are projected to be built in the Niger, possibly affecting transboundary relations. A limited capacity to deal with future hydroclimatic and socio-economic challenges originating in the contemporary situation may also be a risk to parts of central Asia, with especially BCUs in Afghanistan and Pakistan projected to be at high risk. Historically and contemporary tense relations between riparian states in the Aral Sea basin were and still are *inter alia* shaped by water division and use (Bernauer & Siegfried, 2012). Potential future efforts to rebuild upstream of Afghanistan may put more pressure on water availability in this basin and other basins to which Afghanistan is an upstream riparian.

Some countries are projected to face risks in several river basins, where existing tensions over shared water resources are already emergent. All five of Myanmar's BCUs are projected to be at (very) high risk (Ganges, Irrawaddy, Kaladan, Mekong and Salween), and Myanmar is a downstream country for which these rivers – especially the Irrawaddy – are crucial. Notably, Myanmar will still face high risks in these BCUs in the high ambition scenario. This suggests that also under much more favourable conditions than a BaU scenario, Myanmar will face major challenges in her transboundary basins. However, contemporary political unrest and suppression as well as dependencies on more powerful upstream countries may make much-needed additional action challenging.

Similarly, Ethiopia, which shares four basins (Juba, Lake Turkana, Nile and the smaller Gash basin) with mostly downstream countries, is projected to face compounding risks. Not cooperating could affect wider cooperation, potentially affecting broader political relations in the region. Likewise, for Pakistan, high to very high risks in the Indus and the Rann of Kutch basin and the smaller Dasht and Hamun-i-Mashkel/Rakshan basins may collide challenging national water management strategies. But tensions with India can also continue to play a role in cooperation and conflict over water resources, especially in the Indus.

Climate change affects the hydroclimatic conditions in the basins, though not in isolation. By 2050, the number of basins with a per capita availability of < 1000/m^3 per capita per year increases by more than 10% compared with 2015. Overall, water availability per capita decreases in 80% of the BCUs. The principal driver for the decreased availability is population growth, but climate change plays a role, too. The impacts of climate change differ widely per BCU, although overall run-off decreases by 4.8%. In 455 of the 797 BCUs, the internal runoff decreases from 2015 to 2050. Climate change decreases the amount of available water that these BCUs can rely on internally. For the external runoff, the overall change is slightly smaller, 422 of the 797 BCUs are projected to face a decrease. Water variability is projected to change in many BCUs. The overall variability of the internal and the external runoff is increasing, respectively, by 8.4% and 9.4%. For the overall runoff, the variability increases in 469 BCUs. In 278 BCUs the overall situation worsens in terms of a lower total run-off in combination with greater interannual variability, which implies less available water and lower reliability for these BCUs, where 561 million people are projected to live by 2050.

Treaties and RBOs could be of great importance to deal with climate change and infrastructural change in basins since they boost institutional capacity, thereby increasing the likelihood of long-term, stable cooperation between states (Brochmann, 2012; Dinar et al., 2019; Schmeier, 2013). Existing treaties are however not a guarantee for cooperation over climate change impacts and infrastructural change. Cooperation depends on both the intentions of the states involved and their capacity to implement treaty provisions (Karreth & Tir, 2018), which is projected to be lacking in several Asian and African basins. Strengthening the adaptative capacity of treaties and RBOs and enhancing the resilience of institutionalized cooperation are thus crucial requirements for reducing conflict risk in the future.

Usability and limitations of scenario projections

The results of this study provide a limited set of possible futures regarding conflict risk in transboundary river basins. Scenarios can be useful policy tools to reflect on and think through the potential consequences of alternative decisions in a structured manner (Henrichs et al., 2010). A related function is the creation of a mutual understanding between researchers and decision-makers about imaginable intersecting long-term risks and short-term interests. Facilitating discussion about various scenarios between policy-makers and researchers can lead to a better understanding of what information is needed to develop well-informed long-term policies (Muhonen et al., 2020). This process can also contribute to an improved balance between actors' short- and medium-term interests and long-term developments by connecting these (Jones et al., 2017).

The presented scenarios also come with several challenges. First, uncertainty regarding the future drivers of conflict in transboundary river basins. A wide combination of different factors on different spatial and temporal levels plays a role in the risk of conflict within countries and between countries, including context-specific historical and cultural settings (Bowlsby et al., 2019; Cederman & Weidmann, 2017), which are not included in this global analysis. Additionally, the existing debate about the potential increasing impacts of climate change on conflict risk increases uncertainty in these scenarios. On the one hand, because potential conflict risk within countries may rise (Mach et al., 2019; von Uexkull & Buhaug, 2021), this could reduce domestic capacity to deal with transboundary issues. On the other hand, the impact of implementing climate adaptation measures could affect transboundary relations, both positively and negatively. For example, flood adaptation control upstream can affect flood control downstream, which can damage diplomatic relations. Meanwhile, diplomatic relations can also be improved by the joint development of resilience and adaptation strategies.

A second challenge regarding the use of scenarios is the stereotyping of potential 'hotspot regions', especially when it comes to conflict dynamics. Several studies discuss aspects of future vulnerability and fragility in Sub-Saharan Africa (Busby et al., 2014; Thornton et al., 2008), emphasizing an understanding of the region defined by weakness. These representations can affirm a one-sided representation of regions, possibly affecting *inter alia* the willingness to make long-term investments in these regions. Stigmatizing – already fragile – regions may feed alarmist scenarios of conflict and eventually contribute to the securitization of environmental risks (Verhoeven, 2014).

Last, calculating overall risk scores per BCU and river basins comes at a price. We identified the indicators and thresholds to derive at risk scores per BCU and basins based on existing literature. However, the specific decisions regarding thresholds and indicators that we made to derive at composite risk scores shape the outcome of this study (Visser et al., 2020). Arguably, some indicators could have been included or excluded, with somewhat different thresholds. The advantage of an overall risk score is that the multiple complex processes that shape conflict risk in transboundary basins can be compressed into a single number. But this also implies that the importance of the separate underlying risk factors must be weighted in the same way in all basins, which does not reflect reality. Although it is unavoidable that certain decisions have to be made to derive at composite risk indicators, the results can still be used to define which basins could and should be further analysed.

Conclusions

In this study we developed transboundary conflict risk projections towards 2050 for three distinct scenarios, the BaU, low ambition and high ambition scenarios. When analysing the different risk dimensions potentially affecting transboundary conflict risk, different patterns appear. While exacerbating risks will be especially profound in river basins of the Sahel, the Horn of Africa and parts of southern Africa as well as in Afghanistan and Pakistan, the potential to build hydropower dams is especially high in Southeast Asia, although also in South America and the Horn of Africa the construction of mega-hydropower dams is projected. Under the BaU scenario, 920 million people live in BCUs at (very) high risk. Implementing improved water management such as water saving measures, improving institutional resilience and overall governance decreases conflict risk. In the low ambition scenario, considerably less people live in (very) high risk BCUs; 673 million, while in the high ambition scenario, this number is projected to decrease to 537 million.

Large basins with specifically high conflict risk are projected to be the Juba–Shibeli, Lake Turkana, Congo and Indus.

Our findings partly overlap with Farinosi et al. (2018), who find that future demographic and climatic conditions are expected to increase the probability of experiencing water management issues in already stressed basins, such as the Nile, Indus, Colorado, Feni/Fenney, Irrawaddy, Orange and Okavango. We identify the Juba–Shibeli and Lake Turkana as the large basins most at risk, also because of the new hydropower dams that are projected to be built in these basins. Additionally, we find the Congo, Helmand, Orinoco, Rann of Kutch and Grijalva basin to be basins at high risk of conflict, whereas the Colorado, Orange and Okavango do not pop up in our study due to the absence of new mega-hydropower dams, the moderate to high institutional resilience and moderate to high governance and socio-economic conditions. However, also in our study, these basins are projected to face risks as a result of challenging hydroclimatic conditions.

Understanding potential future conflict risks in transboundary river basins is a key step towards preventing and mitigating future conflict as decision-makers gain better insights into where policy action might be the most needed and why. Including a long-term perspective in cooperation between riparians is not just nice to have. It is crucial to equitably adapt to climate change and to restore or preserve the ecological quality of rivers.

Acknowledgments

The scenario projections developed in this study are part of a larger project on water-related projections, informing the UN-Water conference in 2023. In this project, conceivable futures are developed presenting different levels of policy ambitions, in terms of water management measures and governance quality. The wider project contains projections on a wide range of water-related topics, including food production, ecological quality, hydropower development, flooding, erosion and salination, aiming to show the many different dimensions of water security. We acknowledge the contribution of our colleagues at PBL Netherlands Environmental Assessment Agency; Jan de Ruiter and Ed Beije for formatting the maps; Jan Janse and David Gernaat for providing new data on dams; and Anna de Graaf for contributing to the institutional resilience analysis.

Author contributions

SdB designed the study, developed the methodology, performed the analysis and wrote the manuscript; SuS contributed to the scientific discussion, writing of the manuscript and proofread the manuscript; RvB calculated the hydroclimatic indicators for the three scenarios and reviewed the methodology and contributed to the discussion; and MG supported the methodology development, performed the spatial analyses and reviewed the manuscript.

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