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Climate change and International River Boundaries: fixed points in shifting sands

Sam Grainger^{1,2*} and Declan Conway³

The impacts of climate change will have far reaching consequences for transboundary water resources, particularly through the effects of changing frequency and intensity of extreme events, such as floods and their impacts on river channel systems. Watercourses have been used as boundaries throughout history for a variety of reasons, and as both a natural resource and political structure, they present a number of unique challenges. Despite academic studies looking broadly at the effects of changes in runoff on river ecosystems and their resources, less attention has been paid to the socio-political interactions and consequences for river functionality, in particular, as a boundary. We review the historical and legal role of International River Boundaries highlighting the paradox that exists between the stability needed for a boundary and the dynamism of fluvial landscapes in a changing climate. We draw attention to the fact that geopolitical concerns exist at other unstable border situations, such as ice-covered boundaries and lakes. We examine the knowledge gaps that exist in relation to understanding the physical impacts of climate change on terrestrial earth systems. We present an exploratory analysis of physical and political risk in Southern Africa that highlights two cases of potential risk. The paper ends with a discussion of actions to address the physical and social dimensions of this strategic issue. © 2014 The Authors. *WIREs Climate Change* published by Wiley Periodicals, Inc.

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INTRODUCTION

Climate plays an important role in the evolution of river channel systems within terrestrial earth surface systems.¹ There is general agreement that current climatic conditions are subject to human interference through our emissions of greenhouse gases, and that even immediate mitigation will not halt

continued global impacts. Warmer temperatures will allow the atmosphere to hold more moisture, affecting evaporation and humidity, and leading to higher precipitation intensities.² Observed global precipitation displays an anthropogenic climate change signal³ and increasing flood risk during autumn in England and Wales has been associated with greenhouse gas emissions,⁴ as has observed intensification of daily and five daily precipitation amounts during the second half of the last century.⁵

By the end of this century, we are likely to see substantial shifts in mean annual streamflow, water availability, and flood risk in some regions, as a result of climate change.^{6,7} Floods play a major role as drivers of channel and floodplain structures and associated riparian and in-stream ecosystems.⁸ Changes in high intensity precipitation in many regions of the world will alter flow regimes and floods, influencing

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channel development.^{9,10} Indeed, the major floods on the Indus in July 2010 appear to have altered the river's course in Pakistan, moving it closer to the Indian district of Kutch.¹¹ Limited attention has been paid, however, to the ways in which these changes in the natural system may interact with the numerous socioeconomic and political functions and structures imposed on rivers by human civilization.¹²

One of the ways human society has utilized watercourses⁴ has been through the delimitation of international boundaries. Historically, decisions to attach boundaries to rivers have been motivated by a number of national concerns. The exact location of the line along the boundary river is not always agreed upon,¹³ and therefore defining and agreeing on how the line relates to the watercourse, even when demarcated within a treaty, is often open to interpretation. Rivers are dynamic systems and the natural variability of fluvial processes has historically led to a number of riparian responses and disputes, and with continuing human modification of the environment the resilience of political structures is uncertain.¹⁴ These natural landforms serve as catalysts to connect, but also separate people, cultures, and communities.¹³

The extent and management implications of watercourse boundaries around the world have received limited attention.¹⁵ The International River Boundaries Database (IRBD) calculates that well over one third of the total length of international borders follow watercourses.¹⁶ They span the globe; from a few meters of the Zambezi River between Namibia and Zimbabwe to thousands of kilometers of the Rio Grande between Mexico and the United States.^{16,17} There is no mention of the relationship between the impact of climate change on fluvial morphology and the consequences for International River Boundaries (IRBs) in reviews by the IPCC.¹⁸ The Human Development Report in 2011 makes reference to conflict as a possible effect of environmental change but fails to acknowledge IRBs as potential sources of conflict.¹⁹ Academic studies have considered the effects of climate change-induced changes in runoff on river ecosystems and their resources,^{6,20} however, less attention has been paid to the socio-political interactions and consequences of these biophysical changes on the functionality of rivers as boundaries. Moreover, literature which deals specifically with the management of transboundary or international water resources, and the drivers of conflict and cooperation in such river basins, rarely distinguishes between the geographical configurations of watercourses, and fails to consider the implications of climate change on fluvial processes and morphology, and indirectly, corresponding boundaries.^{21–23}

While our focus is watercourses as international borders, they also form subnational borders between administrative areas such as states and provinces (e.g., United States and India), and there are other situations where political boundaries are located in dynamic environments. The potential disappearance of Small Island States due to sea level rise has been highlighted,^{24–26} however, the following examples have received much less attention and most information lies outside the peer-reviewed literature. Numerous international boundaries dissect large bodies of water including Lake Malawi (that experienced a recent dispute over oil/gas exploitation), Lakes Chad, Ontario, Superior, Titicaca, and the Caspian Sea. Ice-covered boundaries exist in the Alps, where glaciers between Switzerland and Italy have drifted in recent decades forcing both countries to redefine parts of the borders, with relatively minor consequences. At the local scale, borders may have much greater significance for communities than at state level.²⁷ Austria has recently considered the idea of a movable border, where experts from affected parties would be responsible for altering it, until the glaciers disappear completely.²⁸ Alternatively, in areas where borders are contested, melting glaciers could provoke greater controversy, for example, along disputed sections of India's borders with China and Pakistan, and the long-running dispute between Chile and Argentina over sovereignty of their boundary ice fields.²⁹ Warming in the Arctic Circle, opening up newly navigable waters and increasing access, is driving Russia, Norway, Canada, United States, and Denmark to secure and exploit shipping routes, oilfields, and mineral deposits.^{24,29} Geophysical change also has a role in maritime border disputes such as the Ganges Delta, involving India and Bangladesh, which is vulnerable to the vast flux in the seasonal flooding cycle, river and cyclone associated floods, and processes of sedimentation and erosion.³⁰ Paradoxically, boundaries located in dynamic physical environments lack the requisite stability required for these political constructs.

Here we draw attention to the potential significance of climate change for watercourses that serve as international boundaries. First, we review their history and function and then examine the relationship between climate and river channel morphology under current and future conditions. As a preliminary assessment of this issue, we present an exploratory analysis of physical and political risk in Southern Africa, a region that exemplifies the interaction of climate change, streamflow sensitivity, and complex river boundaries. Finally, we propose actions to address the physical and social dimensions of this under-recognized issue.

INTERNATIONAL RIVER BOUNDARIES

In the past, decisions to enlist watercourses as boundaries have been motivated by a plethora of national concerns including military, strategic, economic, and even practical. In the majority of cases, IRBs are historical relics constructed with little consideration for either physical or political geography. Rivers were originally adopted in boundary making as a convenient, cost-effective, and recognizable landmark to separate one empire from another and to avoid territorial confrontation.³¹ There are regions around the world where dramatic differences in the prevalence of IRBs can be observed. For example, in South and South East Asia, there is a notably low prevalence of IRBs and the deep valleys and white-water of the middle Mekong (Thailand/Laos) may be considered the only significant (majority of total boundary length) river boundary in this vast region.³² This is in stark contrast with East Asia where 98% of the China–North Korea border is aligned with the Tumen and Yalu rivers, while large sections of the Russia–China border runs along the Amur and Argun Rivers.³³

Whatever the reason was for choosing a river as a boundary, it is clear that such a dynamic physical feature is likely to present significant problems both in defining the boundary and sharing the water resource. To date river boundaries have never caused a major international military conflict, however, they carry the potential to provoke diplomatic disputes.¹⁶ Recently, the International Court of Justice (ICJ) arbitrated two cases relating to the San Juan River between Nicaragua and Costa Rica as a result of requests submitted by both nations for the indication of new provisional measures. Ultimately, the ICJ did not deem it necessary to exercise its powers on behalf of Nicaragua, but found that Nicaragua should refrain from dredging and other activities in disputed territory.^{34,35} Despite their use as territorial frontiers, it could potentially be the water resources or hydropower potential contained within these rivers that are the primary focus of any conflict of interest.³⁶ As a result, the role of IRBs in defining access to valuable natural resources influences international relations and can make allocation problematic.³⁷

Although dozens of configurations can be identified, the two pure types of international river are ‘through-border’ (successive; the watercourse flows from one country to another) and ‘border-creator’ (contiguous; the river runs along an international boundary without crossing it).³⁸ Conflict analyzes tend to focus on the former, perhaps assuming that border-creator configurations discourage resource sabotage, as aggressive actions in this case are

mutually detrimental.³⁸ However, early work on the subject discourages such dismissive approaches.³⁹ In addition, legal doctrine has sought to examine both ‘contiguous’ and ‘successive’ rivers, and at times has even argued that different rules should apply to each category.⁴⁰

To hold credibility, a boundary line must be stable, yet river boundaries are natural phenomena that undergo constant change even during average stream-flow. Such changes may be the result of natural and/or human-induced fluvial processes, leading to accretion (gradual lateral movement) or avulsion (rapid lateral movement) of a channel.³⁷ In extreme cases of the latter, sudden changes in runoff can shift the course of a river to create a completely new channel. Despite the widespread awareness of these changes, boundary treaties make little distinction between different levels of change, and as a result diplomatic responses have varied.⁴¹

State responses to the demarcation of IRBs are complex; despite the inevitable influence of such legal terms as accretion and avulsion, neighboring states have considerable discretion in resolving any border dispute. While cooperation over international watercourses seems to be partially influenced by legal rights, geographical configuration and climatic variability,^{38,42} analyzes need to appreciate that size, economic, trade, and military disparities between neighboring states also play an important part in hydro-political cooperation.³⁶ In cases of gradual accretion most countries try to maintain the original coupling of channel and boundary by conducting periodic surveys. In cases of rapid avulsion, however, some countries have chosen to maintain the original delimitation, detaching the river from its political construct. In this way, riparian neighbors have sought to ‘fix’ their fluid border in an attempt to maintain a permanent and static territorial frontier. For instance, the Rio Grande on the US–Mexico border has been subject to extensive canalisation since the 1911 Chamizal arbitration. Unfortunately, engineering a stationary boundary in this way has led to significant downstream environmental damage; particularly during dry periods.¹⁶ The emergence of GPS technology has enabled states to couple their boundary to a set of coordinates. This method, adopted by the ICJ as part of the Benin/Niger⁴³ and Botswana/Namibia⁴⁴ cases, aims to achieve geographical and legal clarity by determining a line at a fixed time period. That mentioned, even if neighboring states were to resolve existing disputes over the delimitation of an IRB section, the constant erosion and deposition of particles may still present inescapable legal and political complications in the future.

CLIMATE CHANGE AND RIVER CHANNEL MORPHOLOGY

Stream morphology and channel stability are primarily determined by the topography, channel material, and flow of water and sediment from the surrounding basin.⁴⁵ These, in turn, are determined by geology, geomorphology, climate and, more recently, human activity. Historical evidence and current understanding of fluvial geomorphologic processes indicate that rivers are highly responsive to changes in these processes. As discussed earlier, river channels can move gradually as occurs in meandering, or quickly in response to flood-induced erosion or sediment deposition, which can close and open channels in braided and anastomosing systems. Climate also has an impact on river basin drainage density, the total length of the streams in a drainage basin area.⁴⁶ The combined length of a basin network represents 'the signature of climate'⁴⁷ on the surrounding landscape and the surface runoff environment. Therefore, understanding the relationship between climate and drainage density is crucial to evaluate the sensitivity of hydrology and fluvial processes to climate change. As is the case with surface runoff and streamflow, the direction of drainage density response is directly related to both the sign of climatic change and the existing climatic regime.⁴⁷

Desert stream channels are extremely sensitive to changes in hydrology, displaying rapid morphological changes in response to slight climatic changes.⁴⁸ A decrease in flow may shrink the channel, and encourage bank sedimentation and vegetation growth, resulting in more stable patterns with low sinuosity⁴⁹ ('deviation of actual channel path from expected theoretical (straight) path'⁴⁶). In other cases, severe aggradation in dry regions can cause channels to broaden and the bed to fill in.⁵⁰ Over the last couple of decades, the West African Sahel has experienced a run of droughts contributing to shrinkage of Lake Chad's surface area by 95% over 35 years.⁵¹ Given that this water body straddles the borders of Nigeria, Chad, and Cameroon, any change in lake levels is likely to alter vital water resources for the respective nations, and potentially, encourage disputes over sovereignty.⁵² Extreme rainfall events in arid environments may permanently change the morphology of alluvial channels.⁵³ Detailed review of a 112-year record of a river in Arizona showed large floods caused its channel to deepen and migrate up to 1.6 km.⁵⁴ Some present day canyons, which were originally bedrock channels, were formed by the power of mega-floods thousands of years ago.⁵⁵

Water and sediment inputs are controlled not only by climatic drivers, but also human activity,

either directly through channel modification (e.g., dam construction, embankments) or indirectly through water abstraction and land use change.⁴⁹ Due to pervasive human interference, indirect responses to climate change will be highly nonlinear, typified by various feedbacks relating to different variables involving lead and lag periods of time.⁵⁶ Anthropogenic climate change impacts on river channel systems result from the direct effects of rising temperatures and CO₂ concentrations, and indirect influences through the intensification of the global hydrological cycle, leading to changes in precipitation patterns, evapotranspiration rates and soil moisture.⁵⁷ Although the detail of precipitation change remains uncertain, an intensified hydrological cycle will bring greater variability; as water vapor and the holding capacity of the atmosphere increases, storm events will be supplied with more moisture, even in places where mean precipitation is declining.⁵⁸ A recent assessment of global flood risk for the end of this century using multimodel scenarios found large increases in flood frequency in south-east Asia, peninsular India, eastern Africa, and the northern half of the Andes.⁷ At the same time, droughts will become more severe and widespread within the next 30–90 years, particularly in some of the world's most densely populated regions (Europe, the eastern United States, southeast Asia and Brazil).⁵⁹

Whether attributed to human or natural causes, changes in fluvial processes will affect channel morphology.⁴⁵ These processes are likely to involve disturbances in the balance between river sediment transport and deposition in rivers, wetlands, flood plains, and coastal areas. The extent of stream response often depends on drainage basin characteristics.^{45,46,51} For instance, river channels that flow over resistant bedrock and basins with extensive lake or glacial storage capacity tend to be more stable; whereas rivers with fine-grained alluvial beds and limited storage tend to be particularly sensitive to changes in flow regimes.⁴⁵

River channel responses to climate variability and future climatic changes are, however, highly uncertain.⁴⁹ In humid regions, an increase in streamflow could potentially widen or deepen channels as a result of increased erosional rates.⁴⁵ Furthermore, any surge in streamflow is likely to result in higher sinuosity and quickened channel migration, possibly leading to braided patterns. Moreover, if large floods increase in intensity, channel features may suddenly change resulting in chronic instability, especially if floods become more frequent.⁴⁵ Chowdhury⁶⁰ found that the Brahmaputra–Jamuna River has been widening since the early 1970s at an average rate of 130 m

per year.⁶¹ Despite uncertainty regarding the effect of future changes in streamflows and sediment, the river's future is a concern given relations between India and Bangladesh.⁶⁰

The management challenge of Earth surface system response to climate change has been underestimated by policymakers and has brought calls for more monitoring and modeling of these dynamic systems.¹ Very large increases in streamflow, unless mitigated by management, are likely to alter channel patterns and reductions could shift flow regimes, from perennial through ephemeral, to episodic and even permanently dry. Thresholds in annual precipitation governing perennial runoff have been identified with the hypothesis that regions with highly variable rainfall regimes will exhibit nonlinear responses of drainage patterns, in relation to changes in precipitation.²⁰ In the context of modeling impacts of environmental change on fluvial systems two main approaches exist, each with many model types; flow models which simulate fluxes of water through a catchment, and geomorphological models which simulate change in landforms.⁶² The former include flood inundation models, which have been used widely to simulate climate change impacts on flood risk, however, these models do not capture sediment movement and geomorphological change which severely limits their application for such purposes. The coupling of flood inundation models with landscape evolution models (LEM) has been suggested to provide a more viable option.⁶² LEMs are physically based process models that simulate relevant processes for landscape formation across complete river catchments from decades to millennia. Contingency, the particulars of time and space, is known to be highly important, as timing, sequence and initial conditions strongly influence outcomes.⁶³ Palaeo-channel reconstruction has been used to infer past environmental conditions, however, there are limitations to this approach; response is often spatially and temporally variable throughout the catchment.⁶² In total, these gaps in understanding, observations, and modeling capacity mean that current projections of future runoff patterns can only be used to infer possible implications for river channel systems.

EXPLORATORY RISK ASSESSMENT: SOUTHERN AFRICA

Background

In this section, we present a preliminary approach to assessing the potential challenge climate change represents for physical and socio-political risks associated with IRBs. We chose Southern Africa as it exemplifies

a fusion of contributory factors leading to potential high risk; worsening physical and socioeconomic water scarcity^{18,64} which constrains economic growth and development,⁶⁵ transboundary and regional allocation pressures,⁶⁶ and highly variable climate and streamflows^{64,67} that will likely become drier and more variable in the future.^{6,18} Climate model experiments also indicate that Southern Africa could experience increases in daily rainfall and rainfall extremes due to changes in sea surface temperature and atmospheric circulation in the South Atlantic.⁶⁸ These challenges are exacerbated by political, institutional, and economic factors, including limited management and regulatory capacity, and highly inequitable access to reliable potable water.³¹ Moreover, what Southern Africa lacks in water resources it makes up for in IRBs and these colonial constructs have already exacerbated existing tension between neighbors and, in some cases, led to IRB-related disputes,⁶⁴ which could be worsened by changing climatic and socioeconomic pressures.¹⁴

Southern Africa is defined here as all mainland member states of the South African Development Community (SADC). This comprises the republics of Angola, Botswana, Malawi, Mozambique, Namibia, South Africa, Zambia, and Zimbabwe; the United Republic of Tanzania and the Democratic Republic of Congo; together with the kingdoms of Lesotho and Swaziland.³¹ A variety of ecosystems exist within these states and environmental systems can be highly dynamic, experiencing dramatic transformations as a result of seasonal floods and decadal fluctuations in precipitation. Water bodies notwithstanding, rivers within the 12 SADC states contribute to 19 of the 26 international boundaries in the region.⁶⁹ IRBs are distributed throughout the region and vary greatly in length and significance (Figure 1).

Much of Southern Africa has a semi-arid rainfall regime (400–1000 mm) with high multiyear rainfall variability. Regional streamflows are unevenly distributed and display high levels of variability across a range of spatial and temporal scales.^{67,70} High potential evapotranspiration results in exceptionally low conversion of rainfall to runoff (e.g., 5.1% in the Orange and Limpopo⁷¹). Extensive regions within Africa regularly experience prolonged severe droughts that are often followed by intense rainfall events.⁶⁴ For instance, continuous flows in Namibia and Botswana are particularly scarce, both relying on supplies from either small, ephemeral streams that only flow after heavy rainfall events, or perennial rivers that are sourced outside their borders.⁶⁴ The Caprivi region of Namibia has recently experienced a renewal of severe flooding after a dry period during the 1990s.⁷²

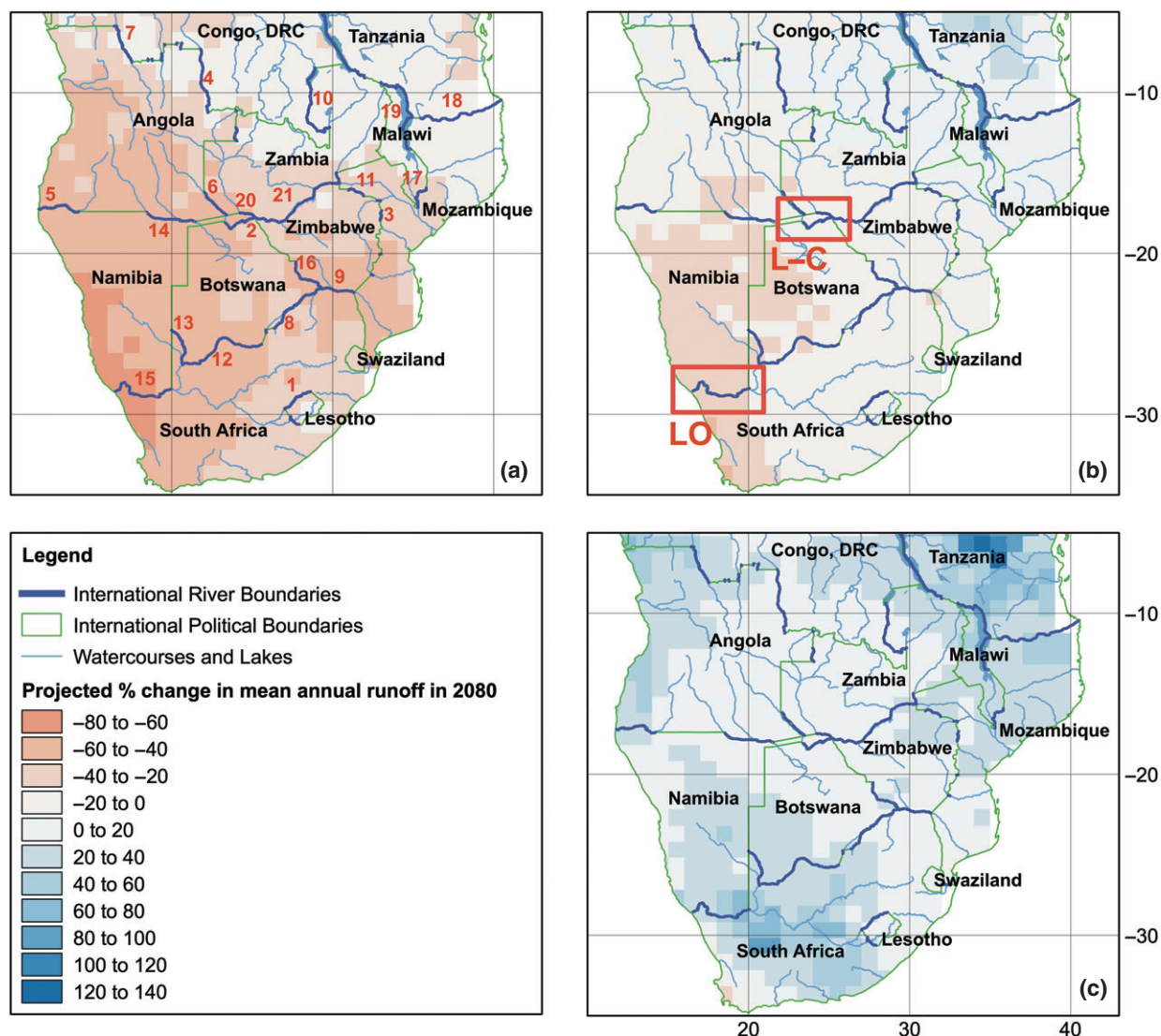


FIGURE 1 | (a–c): International River Boundaries in Southern Africa (shown in dark blue lines) (outlines derived from the IRBD; Data accessed from <https://www.dur.ac.uk/ibru/resources/irbd/>), watercourses and lakes (shown in light blue), remaining International Political Boundaries (shown in green lines) and % change in mean annual runoff (MAR) for the 2080s using a global hydrological model driven with the Coupled Model Intercomparison Project (CMIP3) multimodel scenarios (results obtained from Fung et al.⁵⁶), for a dry case (driest 10 percentile), average (median), and wet case (wettest 90 percentile) (Figure 1(a–c), respectively). Red numbers in Figure 1(a) can be cross-referenced with Table 1, and red boxes in Figure 1(b) indicate two potential hotspots of IRB risk identified during our analysis (LO = Lower Orange, L-C = Linyanti–Chobe).

In 2009, the upper Zambezi flooded parts of Zambia and Namibia, replenishing Lake Liambezi, which had almost dried out in the 1990s.⁷²

Climate change has the capacity to modify boundary environments in Southern Africa by a number of routes. It may intensify the hydrological cycle bringing greater variability to flood and drought events, creating increasingly unstable fluvial environments. It may also lengthen seasonal droughts, which could turn perennial rivers into ephemeral streams, setting it into a negative cycle of change, the results being diminished drainage capacity. It is likely to be

changes in the intensity and timing of events that cause problems, as more high intensity rainfall leads to flooding in basins with low storage capacity.⁷³ Strong interactions exist between ecological and hydrological processes in semi-arid systems. Vegetation displays marked seasonal and interannual fluctuations associated with moisture availability and patches can obstruct and retain runoff leading to positive feedbacks and patch growth.⁷⁴ The distribution of evergreen and deciduous vegetation is a potential contributory factor, along with rainfall variability, to greater streamflow variability in arid and temperate

TABLE 1 | Qualitative Risk Profile of IRBs in Southern Africa in Relation to Environmental and Political Factors Using Traffic Light Shading as Indicative Risk

	River (Boundary)	Basin	Median Projections of MAR $>+/- 20\%$ (2080s)	Evidence of Dispute History or Existing Tensions	Sufficient Published Literature for Further Analysis?	Aggregate Risk
1	Caledon (Lesotho–South Africa)	Orange		—	—	LOW
2*	Linyanti/Chobe (Botswana–Namibia)	Zambezi			Yes	HIGH
3	Gairezi/Jora (Mozambique–Zimbabwe)	Zambezi		—	—	LOW
4	Kasai (Angola–DR Congo)	Congo		—	—	LOW
5	Kunene (Angola–Namibia)	Kunene		—	—	LOW
6	Cuando (Angola–Zambia)	Zambezi			—	POTENTIAL (climate)
7	Cuango (Angola–DR Congo)	Congo		—	—	LOW
8	Limpopo (Botswana–South Africa)	Limpopo		—	—	LOW
9	Limpopo (South Africa–Zimbabwe)	Limpopo		—	—	LOW
10	Luapula (DR Congo–Zambia)	Congo		—	—	LOW
11	Mkumvaru (Mozambique–Zimbabwe)	Zambezi		—	—	LOW
12	Molopo (Botswana–South Africa)	Orange			—	POTENTIAL (climate)
13	Nossob (Botswana–South Africa)	Orange			—	POTENTIAL (climate)
14	Okavango (Angola–Namibia)	Okavango			No	HIGH
15*	Orange (Namibia–South Africa)	Orange			Yes	HIGH
16	Ramaquabane (Botswana–Zimbabwe)	Limpopo		—	—	LOW
17	Ruo (Malawi–Mozambique)	Zambezi		—	—	LOW
18	Ruvuma (Mozambique–Tanzania)	Ruvuma		—	—	LOW
19	Songwe and L. Malawi (Malawi–Tanzania)	Zambezi		—	—	LOW
20	Zambezi (Namibia–Zambia)	Zambezi			No	HIGH
21	Zambezi (Zambia–Zimbabwe)	Zambezi			No	HIGH

Low = Green, Moderate = Yellow, and High = Red. IRBs with low future climate risk to changes in runoff are displayed in green; IRBs with high climate risk to changes in runoff but no evidence of dispute history or existing tensions are considered potentially at risk and are displayed in yellow; IRBs with high aggregate risk (both climate and political risk) are displayed in red. Risk assessment is sequential, if IRBs did not meet the first criteria [$>\pm 20\%$ mean annual runoff (MAR) change for the 2080s] they were dropped from the analysis (boxes represented with —). Basins with high aggregate risk and sufficient published literature to allow further contextual analysis are indicated with an *: two out of the five high risk basins fulfilled these criteria.

Southern Africa than is found for other continents with similar climatic zones.⁶⁷

Methodology

We present a qualitative risk profile of IRBs in Southern Africa in relation to climatic and political factors to illustrate how research on this issue could be developed. The approach infers categories of risk for specific IRB sections using insights from literature review (i.e., evidence of dispute history or existing tensions that may lead to future conflicts, derived from Ashton⁶⁴; representing political risk) and median projections of mean annual runoff (MAR, representing climatic risk). Simulated changes in MAR were obtained for the 2080s (Figure 1), derived from a

1° resolution global hydrological model driven with a multimodel ensemble of 22 global climate models from the Coupled Model Intercomparison Project (CMIP3) (results from Fung et al.⁷⁵), for a dry case (driest 10 percentile), median and wet case (wettest 90 percentile). The global hydrological model has been widely used for climate impact studies and performs well across a range of river basins, including the Orange in Southern Africa.^{75–77}

IRBs were initially assessed based on the projected severity of changes in upstream MAR, by 2080. Table 1 summarizes the sequential approach in the form of a ‘traffic light’ assessment. IRBs were discounted if median change in upstream runoff was less than $\pm 20\%$ of the baseline, with 20% defined as a threshold considered large enough to lead to channel

disruption (Schewe et al.⁶ used a threshold of 20% as an indicator for severe decrease in discharge); remaining IRBs were eliminated if there was no evidence of dispute history or existing tensions in the boundary region (assessed through detailed web searches and literature review). The final step was to exclude the border if it was not represented in the literature because for these initial purposes we wanted to consider situations where enough background existed to allow development of a narrative to contextualize the risk indicators. This final criterion was chosen to enable a more focused approach to analyzing the individual boundary contexts, and therefore, a full understanding of all of the IRBs exposed to climate risk in the region would require further study. It is possible we have excluded cases where much greater risk exists, but for which we were unable to find background information. A traffic light shading scheme was used to represent indicative risk (Low = Green, Moderate = Yellow, and High = Red). In summary, the risk assessment was sequential, if IRBs did not meet the first criteria ($>\pm 20\%$ change in upstream MAR) they were dropped from the analysis (13 out of 21), and likewise for the second criteria (no history of disputes, 3 out of 8). Boundaries and corresponding upstream basins with High Aggregate Risk and sufficient published literature were then considered for further contextual analysis (two out of the remaining five IRBs fulfilled these criteria) (Table 1).

Results

Climate model results suggest the region will become warmer and most project drier conditions.⁷⁵ Figure 1 shows simulated changes in runoff for the 2080s. The dry case (Figure 1a) suggests a decline in runoff (compared with the 1961–1990 period) of over 20% across most of the region by 2080. Furthermore, a predominant northeast to southwest gradient of change in runoff occurs, from a 0–20% reduction in the Rovuma Basin to as much as 80% along the Lower Orange River. The median case shows a decrease in runoff across most of the region by 2080 (Figure 1b). Reductions of over 20% extend northeast as far as the Okavango Basin, while increases in runoff spread west across the Congo Basin and as far south as the Lower Zambezi. Lastly, the wet case projects increasing runoff across most of the region by 2080 (Figure 1c). The Rift valley, and middle course of the Orange Basin are projected to experience the most pronounced wetting (60–140% increase in places), while decreases in runoff still appear along the South Mozambique Coast (–0–20%) and Western Cape (–20–40%). Analysis of scenarios from the recent CMIP-5 climate model experiments presented in the IPCC's Fifth Assessment

Report show broadly similar patterns of change in precipitation.⁷⁸ An ensemble of global hydrological models driven by five scenarios from the CMIP-5 process shows for the multimodel mean reductions in annual discharge from 0% to 50% across much of Southern Africa, excluding Southwest Botswana.⁶ The range in results due to differences between climate model scenarios (see supporting information in Figure S2 of Ref 6) appears broadly consistent with results shown here in Figure 1. In addition, they find global hydrological model differences also contribute significantly to the spread in relative discharge changes in much of Southern Africa.⁶ These results indicate that without adaptation certain boundary regions within Southern Africa could experience marked changes in river channel systems as a consequence of changes in surface runoff. The changes in Figure 1 should be seen as indicative, as they represent gridded runoff, not accumulated streamflow, derived from just one global hydrological model.

Two IRB sections met our risk assessment criteria: the lower section of the Orange Basin (Namibia–South Africa) and flowing into the Zambezi Basin, the Linyanti–Chobe section of the Cuando tributary (the southern edge of the Caprivi Strip between Namibia and Botswana). They display traits of both biophysical and socio-political risk factors, but unlike other IRBs had been covered in the literature. The characteristics of these two potential hotspots of IRB risk are explained in Figure 2. The Lower Orange is clearly vulnerable to climate change given its geographical configuration, extreme climatic regime,⁷⁹ looming basin closure, and disputed delineation,⁸⁰ although, due to heavy upstream regulation, management responses will strongly determine future outcomes.³¹ Along the Linyanti–Chobe section of boundary, channel morphology is extremely dynamic; flow direction and the shape and position of channels can change suddenly, especially after extreme flood events.^{72,81} Given there is a history of conflict over channel islands,⁴⁴ basin states may start to view the role of this IRB differently. The importance of key factors such as perceptions of water stress and historical and political context will characterize the risk at specific IRBs. For instance, the uncoupling (i.e., when two countries continue to perceive a boundary as fixed despite shifts in channel morphology) of the Linyanti–Chobe River (as occurred in 1999 after an ICJ judgement⁴⁴) demonstrates preference toward land stability over unreliable channels. In the future, states may undertake hard engineering measures to secure access to increasingly scarce water resources, and simultaneously 'fix' their boundary. This is of concern, given the high potential for knock-on



Lower Orange IRB	Biophysical characteristics and risk factors	Socio-political characteristics and risk factors
	<p>a, Negligible surface runoff in the boundary section of the basin, high evaporation rates.</p> <p>b, Bedrock to alluvial transition upstream of the IRB suggests this section of river is particularly vulnerable to changes in upstream runoff (e.g., through increased braiding).</p> <p>High seasonal and inter-annual variability in streamflow.⁷⁹</p> <p>Geographically vulnerable due to reliance on upstream rainfall/runoff.</p> <p>Ensemble model projections suggest a decrease in MAR by the 2080s.</p>	<p>c, Constitutes 58% (560 km) of the border between South Africa and Namibia.</p> <p>Border demarcation disputed since Independence.⁸⁰</p> <p>Namibia is more concerned about channel change due to limited national water resources.</p> <p>The most regulated basin in SADC region.³¹</p> <p>Approaching basin closure (demand = supply).</p> <p>Increased demand for water resources could lead to local management disputes.</p> <p>Stable relationship between countries as South Africa has greater regional power.⁹⁰</p>
	<p>d, Zambezi main channel floods often stretch across the Caprivi Strip to the Linyanti-Chobe IRB during the wet season. Creates a flood plain 1,670–1,870 km².⁸¹</p> <p>e, Extremely dynamic channel morphology.</p> <p>Part of the Cuando sub-basin, one of the driest within the Zambezi basin.</p> <p>High evaporation in the dry season creates channel landforms.</p> <p>Climate change has the potential to even further reduce annual flow of the Linyanti-Chobe.</p> <p>A drop in annual rainfall in the central Angola headwaters could have implications for the runoff regimes and channel system further downstream.</p> <p>Increased intensity of flood events could connect the Zambezi with the Okavango system, transforming the fluvial environment.</p>	<p>f, Forms the border between Namibia and Botswana.</p> <p>g, The Cuando sub-basin remains largely unregulated.⁸¹</p> <p>h, Namibia–Zambia–Botswana tripoint downstream at the confluence has been an arena for conflict in the past.</p> <p>History of conflict over islands along the channel.</p> <p>Both countries have ratified boundary coordinates, but there is no mention of the need for future reappraisals.¹⁷</p> <p>Namibia has long-standing ambitions to divert freshwater from the Okavango to the capital, Windhoek³¹ with morphological implications for the Linyanti–Chobe IRB.</p> <p>South Africa in cooperation with Botswana is keen to divert water resources south.</p>

FIGURE 2 | The main characteristics of two potential hotspots of IRB risk in Southern Africa (letters in white refer to text description).

environmental and social effects downstream. In an ideal world, IRB confrontation would only be fully mitigated by reconciliation and continual dialog between governments and local communities.

IMPLICATIONS AND CONCLUSIONS

This review and exploratory analysis aims to highlight an issue of potential concern, across physical and socio-political domains, which has received very little attention. Future climate change is unlikely to be a major issue in all instances of IRBs or other dynamic physical border settings; many river channels are stable, naturally or through management, the environmental response to changes in climate may be relatively manageable or countries may already have agreements to deal effectively with shifts in boundary conditions when they occur. However, this will not always be the case and it would therefore be prudent to consider the coincidence of potential risk factors in order to identify hotspot situations where further analysis could be beneficial. Below we outline several areas of further action required to assess fully the scale and significance of the problem.

We stress the need to address recognized gaps in understanding of monitoring, modeling, and managing the impacts of climate change on river channel response and other Earth surface systems.⁴⁹ A key challenge is that fluvial systems exhibit chaotic and nonlinear behavior, such that some studies question whether it is even possible to determine a response to external forcings within the same network.⁸² They suggest the true value of models is not in precise predictions but rather what is likely to happen, or what direction a system might take after an external forcing. Given the extent of IRBs globally, establishing criteria for defining channel stability ratings and identifying river channel systems that demonstrate natural sensitivity could help infer hotspots of boundary physical vulnerability.

From the standpoint of international law, because each change in river morphology possesses its own particular character, establishing a set of legal principles that distinguish between levels of change has proven to be a major challenge.³³ Globally, territorial and boundary issues have not been high on the list of priorities for transboundary water institutions⁸³ and most boundary treaties fail to include a contingency for when the watercourse begins to shift away from a set of coordinates. In these instances, treaties should include regular appraisals of the coordinates to ensure accuracy and lessen ambiguity. Boundary treaties should also be updated to integrate with water treaties and include periodic surveys and contingencies

for future channel change, while simultaneously delegating responsibility to those states directly involved. Conflict resolution mechanisms have been recognized as vital components of water treaties,^{84,85} and four main types have been identified in the literature. These span from informal soft law (e.g., negotiation and mediation) to more formal measures (e.g., arbitration and adjudication),⁸⁶ however many treaties are without such facilities.⁸⁷ Where diplomatic incidents have arisen, Article 33 of the UN Charter obliges all states to settle their disputes in a peaceful manner. The 1997 United Nations Convention on the Law of the Non-Navigational Uses of International Watercourses also represents an important conflict prevention mechanism through its framework of principles and rules on international rivers.

Transboundary databases of treaties and water events held by the Program in Water Conflict Management and Transformation (e.g., Yoffe et al.⁸⁸) and drawing from other river basin vulnerability assessments,⁸⁹ could provide a useful basis for characterizing the socio-political aspects of risk. Coupled with a comprehensive assessment of physical risks for IRBs and other unstable boundaries this would form a benchmarking exercise to identify hotspot sites deserving further study. We have presented an exploratory example of such an assessment for Southern Africa, a hotspot region that exemplifies the challenges arising from water insecurity. This identified the Lower Orange (Namibia–South Africa) and Linyanti–Chobe (Namibia–Botswana) sections as situations where aggregate risk (projected change in MAR and history of disputes or tension) is high and therefore deserving more detailed analysis.

As a resource, river water serves domestic, industrial and recreational users, and supplies communities with fish and the potential to produce energy. On the other hand, these naturally variable systems represent a constant threat from flooding and erosion. Watercourses serve as essential arteries, linking states and transporting communities, commodities and cultures across borders. River channels also constitute boundaries between neighboring states. Climate change is expected to intensify the hydrological cycle bringing greater variability to flood and drought events. Geomorphological studies suggest that changes in fluvial processes, brought on by changes in flow and sediment, could reshape river channel systems. Climate change could therefore exacerbate underlying weaknesses and in some cases dramatically alter political and social landscapes at boundaries located along watercourses and other unstable features, such as ice cover and lakes; the very boundaries designed to mitigate conflict now have the potential to provoke it.

NOTES

^a Although we make reference to other surface systems (lakes, glaciers, small island states) the term

‘watercourse’ in this case, is used as a general term for ‘river’, and while the 1997 UN definition includes groundwater, our analysis is restricted to surface water.

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