Water Scenarios for the Zambezi River Basin, 2000 - 2050

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Abstract

Consumptive water use in the Zambezi river basin (ZRB), one of the largest freshwater catchments in Africa and worldwide, is currently around 15-20% of total runoff. This suggests many development possibilities, particularly for irrigated agriculture and hydropower production. Development plans of the riparian countries indicate that consumptive water use might increase up to 40% of total runoff already by 2025. We have constructed a rainfall–runoff model for the ZRB that is calibrated on the best available runoff data for the basin. We then feed a wide range of water demand drivers as well as climate change predictions into the model and assess their implications for runoff at key points in the water catchment. The results show that, in the absence of effective international cooperation on water allocation issues, population and economic growth, expansion of irrigated agriculture, and water transfers, combined with climatic changes are likely to have very important transboundary impacts. In particular, such impacts involve drastically reduced runoff in the dry season and changing shares of ZRB countries in runoff and water demand. These results imply that allocation rules should be set up within the next few years before serious international conflicts over sharing the Zambezi's waters arise.

Keywords: Water demand scenarios, Zambezi River Basin, water institutions

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1 Introduction

The Zambezi river basin (ZRB), the fourth largest African freshwater catchment and the largest river system in the Southern African Development Community (SADC), is shared by eight countries (Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe). It covers an area twice the size of France (1.37 million km^2), is populated by around 30 million people and discharges an average of around 2600 m^3/s (or 82 km^3 per year) into the Indian ocean. In terms of discharge, the Zambezi is of similar size as the Nile (2830 m^3/s) or the Rhine (2200 m^3/s).

Current consumptive water use in the ZRB is estimated at around 15 - 20% of total runoff [19] [23]. The largest consumptive water users are dams (evaporation through impoundment, ca. 13 km^3 p.a.) and irrigated agriculture (ca. 1.5 km^3 p.a). This implies many development possibilities, particularly for irrigated agriculture and hydropower production. Development plans of the riparian countries in fact suggest that consumptive water use might increase up to 40% of total runoff already by 2025 [23]. Such expansion of consumptive water use could become a source of conflict among the eight riparian countries.

To start with, the average annual rainfall in the ZRB is quite high (ca. 950mm, based on CRU estimates by [21]). But it is distributed very unevenly across the basin, with the southern and western parts receiving much less rainfall than the northern and eastern parts. Moreover, the more densely populated areas are located in the medium to low rainfall areas. This asymmetry between water availability and population density is likely to become even more pronounced in future. As shown in Figure 1, Botswana, Malawi and Namibia are most likely to experience serious water stress within the next few decades. This heterogeneity implies that water demand is likely to develop unevenly across the ZRB over the next few decades.

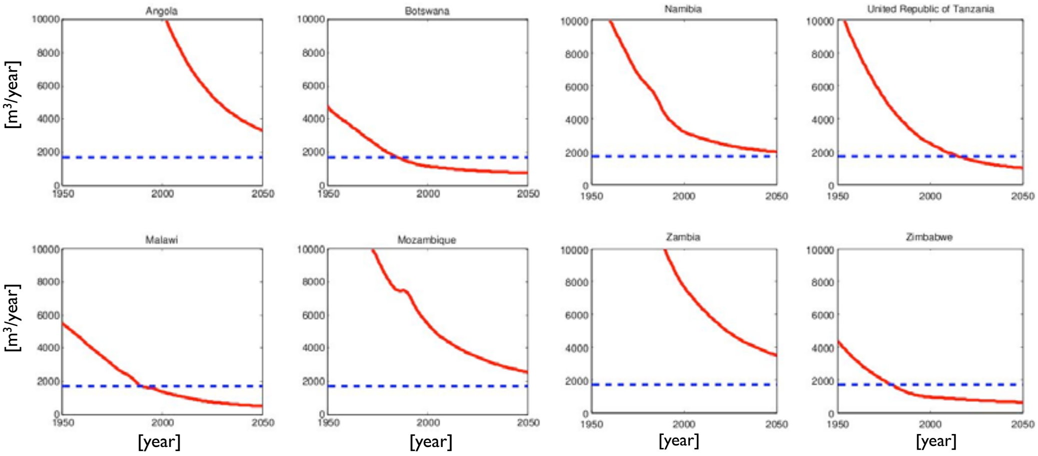

Figure 1: These graphs show projections of per capita water availability $[m^3/year]$ in the eight ZRB countries. The projections are for entire countries, not only their parts in the ZRB. In these projections, the decline in water availability is driven by population growth (we use the UN population growth projections). These projections do not take into account potential changes in runoff that may occur due to climatic changes. Also, they do not take into account factors other than population growth that may also influence water demand. The blue line marks a threshold of 1700 $m^3/year$, which is commonly regarded as a threshold for water scarcity[2].

Another source of heterogeneity and potential conflict among the ZRB countries emanates from the fact that they differ very much in terms of their investment potential and river basin shares. As shown by Figure 2, Botswana and Namibia have a higher investment potential at present that could for example be used for water abstraction projects in response to water scarcity (see also Figure 1). Zambia in turn is likely to claim that due to its very large geographic and hydrological share in the ZRB it should receive the largest allocation.

To what extent will the water development potential in the ZRB be exploited? How big is the international conflict potential over water allocation issues in the ZRB over the coming decades? Uncertainty is very high in both respects. On the one hand, the range of scenarios concerning water demand is very large. Such demand will be driven mainly by

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[2] The Falkenmark index proposes a minimuim of $1700m^3$ per capita and year for covering basic needs pertaining to food production, drinking water, hygiene, etc. According to this standard water availability in the order of $1000m^3$ per capita and year is considered severe water stress [Falkenmark 1992].

population and economic growth, agricultural policies, hydropower demand and potential water transfers within and between river basins. On the other hand, climate models predict a considerable spectrum of precipitation and temperature changes in the various parts of the ZRB, making it uncertain how much runoff will be available for anthropogenic and ecological purposes in the long term.

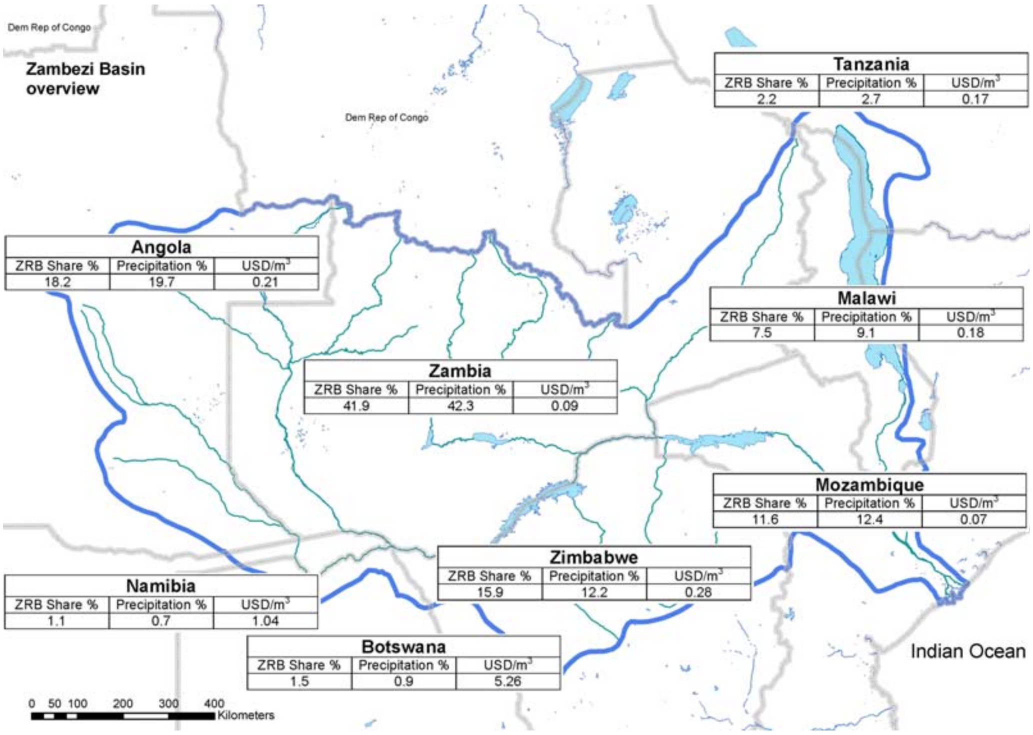

Figure 2: Zambezi River Basin, with country shares in the basin, precipitation contributions to the basin, and investment potential (GDP of the country in USD per m^3 of water available in the country, data for 2004). Based on data from [Denconsult, 1998] and [WDI, 2005]. See Appendix B.3 for details.

Several bilateral and multilateral political arrangements are in place to manage transboundary waters in Southern Africa; notably, the Zambezi River Authority (ZRA, founded in 1987), the SADC Protocol on Shared Watercourse Systems in the Southern African Development Community (SADC) Region (concluded in 2000), and the Agreement on the Establishment of the Zambezi Watercourse Commission (ZAMCOM, concluded in 2004).

The ZRA is bilateral. It involves Zambia and Zimbabwe and concentrates mainly on managing the Kariba reservoir, the second largest reservoir and hydropower production facility in the basin (185 km^3 storage capacity, 1470 MW (720 North Bank and 750 South Bank) capacity [32]). The SADC Protocol, to which all eight riparian countries are parties, includes general criteria and guidelines for managing shared water resources and resolving disputes. The ZAMCOM agreement, which was negotiated by all ZRB countries and covers the entire ZRB, is very similar to the SADC Protocol in terms of provisions on how to manage shared waters. As of October 2009, it is not yet operational because it has only been signed by seven of the eight riparian countries and has been ratified by only four of them.

The ZAMCOM agreement envisages the development of a "Strategic Plan" for the basin and a monitoring mechanism for water abstractions and intra-basin transfers. To what extent this effort should also result in specific water allocation rules and how such rules could be designed remains controversial. This problem is one of the main reasons why the ZAMCOM has not yet become effective. One fundamental prerequisite for designing an effective Strategic Plan and possibly also allocation rules is a better understanding of runoff, water availability and water demand[3] over the next few decades. To that end, our paper presents the results of a computational modeling effort that explores the effects of water demand and climate change scenarios at key locations in the ZRB.

We have constructed a rainfall–runoff model for the ZRB that is calibrated on the best available runoff data for the basin. We then feed a wide range of water demand drivers as well as climate change predictions into the model and assess their implications for runoff. The results show that, in the absence of effective international cooperation on water alloca-

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[3] Some of the water management literature distinguishes "demand" and "requirements", with the former meaning de facto consumption and the latter referring to needs or wants. We prefer to use the term demand, which in our context is equivalent to future requirements or needs.

tion issues, population and economic growth, expansion of irrigated agriculture, and water transfers, combined with climatic changes are likely to have very important transboundary impacts. In particular, such impacts involve drastically reduced runoff in the dry season and changing shares in runoff and water demand among the eight ZRB countries. This finding implies that allocation rules should be set up within the next few years before serious international conflicts over the sharing of the Zambezi's waters arise.

2 Scenarios

Consumptive and non–consumptive uses of water in the ZRB have transboundary implications in the sense that one country's use of the river affects other countries in the basin. Such effects are modest at present–, but could increase to the extent, runoff patterns change due to climate change and water demand increases in future. We examine the implications of a wide range of scenarios as shown in Table 1 (see next page).

Scenarios A, B, and C describe changes in population, urbanization, irrigated agriculture, industrial activity/mining, and water storage/hydropower production. Scenario A represents essentially a status quo scenario, whereas scenario B assumes moderate and scenario C assumes strong growth of the mentioned water demand drivers. Scenario D deals with water transfers and scenario E pertains to climatic changes. While scenarios A to D focus on water demand, scenario E relates to the supply side.

We examine the implications of these scenarios at three levels: (1) the subbasin, (2) specific locations in the basin (notably, Victoria Falls, Kariba, Kafue Gorge, Cahora Bassa, and the Zambezi Delta), and (3) the country. To facilitate the presentation and discussion of results we concentrate on three scenarios combining scenarios A to E as shown in Table 1.

Scenario	Assumptions	Sources / specifics
A	minor population and urbanization growth; no expansion of irrigated agriculture compared to present; minor expansion of industry compared to present; none of the currently planned additional water storage facilities is built	Population/urbanization: low growth UN estimates for ZRB countries. Agriculture: currently irrigated land kept under irrigation at current intensity/efficiency. Industry/mining: no further growth in water demand. Storage: none of the projects mentioned in [24] and [23] is implemented
B	moderate population and urbanization growth; moderate expansion of irrigated agriculture; moderate expansion of industry; some of the currently planned storage facilities are built	Population/urbanization: medium growth UN estimates for ZRB countries. Agriculture: irrigated land increases to 1.1 Mio ha irrigated land, which amounts to 3% of the total arable land available [12]. Industry/mining: 5% growth in water demand per year. Hydropower: half of the projects mentioned in [24] and [23] are implemented.
C	strong population and urbanization growth; strong expansion of irrigated agriculture; strong expansion of industry; all of the currently planned storage facilities are built	Population/urbanization: high growth UN estimates for ZRB countries. Agriculture: irrigated land increases to 3.1 Mio ha, which amounts to 8% of the total arable land available. Industry/mining: 10% growth in water demand per year. Storage facilities: all of the projects mentioned in [24] and [23] are implemented.
D	D1: none of the currently envisaged water transfer projects is implemented D2: half of the currently envisaged water transfer projects are implemented D3: all of the currently envisaged water transfer projects are implemented	Based on information from [29], [28] and [8]
E	E1: no significant climatic changes in the ZRB countries E2: moderate decrease of precipitation in southern and western parts of the ZRB, moderate increase of potential evaporation E3: strong decrease of precipitation in southern and western parts of the ZRB, strong increase of potential evaporation	Based on SRES 1AB, WGI, Fig 10.12 [17] and [4]

Table 1: Scenarios. For more information on data sources and technical details see section on the demand model below and Appendix D

- Scenario 1: Status quo: A $\cup$ D1 $\cup$ E1
- Scenario 2: Moderate demand and supply side changes: B $\cup$ D2 $\cup$ E2
- Scenario 3: Strong demand and supply side changes: C $\cup$ D3 $\cup$ E3

Any other combination of scenarios A to E would produce outcomes (runoff predictions) that are located in between the three scenarios just listed. We discussed these scenarios with a large number of stakeholders and scientists in the ZRB during three visits to Mozambique, Zambia, and Zimbabwe in February and September/October 2008 and August 2009. These three countries contribute around 70 percent to the ZRB runoff and are by far the most important users in the basin. Based on these discussions we have come to the conclusion that the scenarios outlined in Table 1 are “realistic”. That is, they lie within the range of water demand and climatic changes that are currently thought to be possible. Examining the implications of these scenarios does, of course, not mean that one or the other scenario will in the end become reality. The main purpose of our research is to understand the magnitude of the effects on runoff that could result from these scenarios. In other words, our research intends to test the limits, that is, how sensitive the ZRB is to different types and degrees of changes in water demand and supply (climatic changes), as a whole and at specific locations that are important for the eight countries concerned.

Finally, it is important to note that our scenarios operate under the assumption that there are *no effective international water allocation rules* for the ZRB. That is, we assume that each of the eight ZRB countries unilaterally pursues its development plans without international effective coordination. We take into account, however, that water consumption by one country affects water availability in other ZRB countries, depending of course on geographic location and hydrology. We think that this approach is useful because it explores what could happen if the current institutional setting in the ZRB, where there are in fact no effective basin-wide allocation rules at present and where very little international coordination takes place, prevailed in the long term. That is, our model predicts outcomes that could happen in the absence of stronger international coordination and effective water allocation rules.

3 Supply – Demand Model

We use computational simulations to examine the transboundary implications of the scenarios described above. Our model consists of two components: a hydrological model that mimics the natural processes and a demand model that represents deterministic water demand based on actual water use and water use projections. The model includes some improved prerequisites compared to existing models, notably a better spatial resolution on the supply (precipitation, evaporation) and demand side as well as a differentiated temporal approach. With the latter we are able to examine seasonal differences and long term changes in precipitation (supply side) and also seasonal and long term changes in demand.

3.1 Hydrological (supply) model

Our hydrological model mimics the natural processes as well as the effects on the hydrological system that result from water use. Compared to the very few existing hydrological models for the entire ZRB that are in the public domain, notably the model of [16] and the model of [5], our model is based on improved data for precipitation and evaporation as well as more information on river discharge for better calibration of the model. The model consists of a lumped conceptual rainfall-runoff model (RRM) as well as regulated dams for hydropower production and water storage dams for consumptive water use modeled for each individual subbasin.

The flow of each RRM is defined as $q_{RRM} = q_s + q_b$, where q_s is the direct runoff and q_b is the base flow. River flow over time is defined as $q_{RRM}(t) = q_s(t) + q_b(t)$, where the surface runoff is defined as $q_s = (p - e)A_s \cdot r_c$ and p stands for precipitation, e for potential evaporation, A_s for catchment area and r_c is a runoff coefficient specified for each subbasin with resulting infiltration $1 - r_c$. The base flow is defined as: $q_b = q_{b_{store}} + q_{b_{over}}$[4]

$$\frac{dV_b}{dt} = A_s(p - ee_c)(1 - r_c) - q_{b_{store}} - q_{b_{over}} - q_{b_{cons}}$$

$$q_{b_{store}} = V_b s_c \qquad \forall \quad \frac{V_b}{A_s} > h_{min} \text{ else } q_{b_{store}} = 0$$

We assume that in times of water shortages, i.e. when total consumptive water demand is bigger than available surface water, additional water will be allocated directly from the subsurface.

$$e_c = e_b(\frac{V_b}{A_s} - h_{ext}) \qquad \forall \quad h_{ext} \leq \frac{V_b}{A_s}$$

,with base storage volume V_b and outflow coefficient s_c. e_c is the evaporation coefficient, and e_b a scale factor for groundwater evaporation intensity. h_{ext} is the maximum evaporation depth, h_{max} is the maximum baseflow storage level determining the threshold for additional overflow, and h_{min} is the minimum base outflow level.

$$q_{b_{over}} = A_s(p - e) \cdot s_O \qquad \forall \quad \frac{V_b}{A_s} \geq h_{max}$$

,where s_O is the overflow outflow coefficient.

For our hydrological model we use gridded and for our subbasins reaggregated monthly precipitation data from the Climate Research Unit (CRU)[5], resampled by [21], evaporation measurements carried out by various water agencies and power supply companies in the ZRB [7], [31], [6], and data from sector studies performed in 1998 [5]. For information on predicted climatic changes (scenarios E, see Figure 3) we rely on IPCC estimates for monthly mean precipitation values for 2050 (see Appendix D).

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[4] The subscript i indicating the i-th subbasin has been omitted for notational clarity.

[5] http://www.cru.uea.ac.uk/

Regulated dams for power production are included as follows

$$\frac{dV_s}{dt} = q_{in} - q_{pow} - q_{cons} - q_{ev} - q_{spill}$$

$$q_{ev} = f(V_s) = (A \cdot V_s^2 + B \cdot V_s + C)e$$

,with operation rules based on a defined maximum storage level ($V_{s_{max}}$) for each reservoir.

$$q_{spill} = 0 \qquad\qquad \forall \quad V_{s_{max}} \geq V_s + q_{in} - q_{ev} - q_{cons}$$

$$q_{spill} = V_s - V_{s_{max}} + q_{in} - q_{ev} \quad \text{and} \quad \frac{dV_s}{dt} = V_{s_{max}} - V_s \qquad\qquad \forall \quad V_{s_{max}} \leq V_s + q_{in} - q_{ev} - q_{cons}$$

where q_{cons} represents consumptive water use directly from the reservoir, q_{spill} is the water flow over the spillway, and parameters A, B and C describe the volume–surface relationship of the reservoir if no data for this relationship is available. Power production is included as $power(t) = h \cdot \rho \cdot g \cdot q_{pow} \cdot t$, with water demand for power production q_{pow} and reservoir level h.

$$q_{pow} = V_s \qquad\qquad \forall \quad q_{pow} \geq V_s$$

Concerning dam/reservoir operation rules, we assume that the only objective is to prioritize water demand for power production.

Potential new hydro-power production sites are included in terms of increased evaporation (consumptive water use) from reservoirs.

Further technical details of the hydrological model and the demand model (see next section) as well as long-term climatological precipitation hydrographs for the 13 sub – catchments and the calibrated parameters can be found in Appendix C.

3.2 Demand Model

In our demand model we simulate spatially and temporally disaggregated water demand by four sectors: agriculture, hydropower production, domestic sector, and industrial sector. Environmental water needs (ecological flows) are not explicitly included in the model as a sector that actively uses water. But we examine the availability of environmental water flows when discussing the result of our simulations.

To be able to study basin-wide and transboundary effects our model distinguishes water demand in terms of consumptive and non-consumptive demand. Similar to the physical model our demand variables are spatially and seasonally disaggregated. The distribution of water demand in space follows, where possible, spatial considerations, including distances to sources and clustering of different waterusers in certain areas [13]. We assume that water use is more intense along the main stream and at locations with more availability, assuming that transportation and infrastructure costs increase with distance from the main water abstraction points. Moreover, the amount of direct water use decreases with less availability. Temporal variation in demand is mainly a function of differing water demand due to climate-related seasons [5] for agricultural demand and varying electricity demand over the year [24].

Projections of the demand variables, on which our scenarios rely (see Table 1), are based on the following sources of information: For agricultural demand we use projections by [5], national statistics [19]), the Digital Global Map of Irrigation Areas [26], projections by FAO [11] and the spatial distribution of irrigation according to a satellite derived land-cover map [20].

For domestic water demand we implement a constant demand throughout the year, though one might argue that during the wet season less water is used by households than in the dry season[6]. We assume that domestic water demand is met through direct access to ground- and surface waters. Following common assumptions [30] we consider the distance to the sources as more important than seasonal variations. In our model, domestic water use is therefore driven by population growth and its spatial distribution. We use yearly national statistics [22] and distribute this information spatially according to a satellite derived population density map for 2004 [18]. Additionally we derive an urban-rural distribution based on urbanization scenarios and urban centers defined by [5], [25] and assume a per capita consumption of 150 l/day in urban and 27 l/day in rural areas [11].

For industrial water use we take estimates by Zacpro [5] and projections on national growth [19]. For hydropower generation and water storage projects we use estimates and information on planned projects from the Southern African Power Pool [24] and SADC [23]. For information on water transfer projects we use [28], [29], [15], [14] and [8]. Further details on sector shares and development of water demand are included in Appendix B.

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[6] Including seasonal variation in our simulations has no significant effect on the results.

4 Results

We start by discussing the results for 13 subbasins before focusing on key locations in the ZRB and the country level. We distinguish these three levels for several reasons. Subbasins are the main components (natural accounting units) of the natural system that forms the ZRB, which makes it meaningful to study the implications for those components for a start. Policy choices affecting demand are made at local, national, and international levels. Moreover, policy choices and thus demand by local or national decision-makers have transboundary effects because the ZRB and several of its subbasins extend across national boundaries. This justifies systematic analysis of the implications for countries. Finally, there are, from the perspective of policy-makers and the economy, some particularly important locations in the ZRB. Kariba, Kafue Gorge, and Cahora Bassa, for example, are crucial to the electricity supply of the riparian countries, and they generate revenue through electricity exports. Victoria Falls, another example, is a major tourist attraction in Southern Africa and thus a source of revenue as well. The Zambezi Delta, Barotse plains, and the Kafue Flats, yet other examples, are important wetlands that are of local economic value but also of international importance in terms of their biodiversity.

In essence, the first scenario (AD1E1) explores the effects of (modest) population growth and some minor industrial expansion at the national level (see Appendix D.5). The second scenario (BD2E2) examines the effects of a "middle-of-the-road" demand expansion in which the distribution of water demand across sectors remains comparable to the present distribution, combined with moderate climatic changes. In the third scenario (CD3E3), demand is driven to a major extent by the expansion of irrigated agriculture and combines with strong changes in climatic conditions. The shares of sectoral water demand under the three scenarios are shown in the Appendix D.

4.1 Subbasins

Since the hydrological model is based on 13 subbasins these hydrological units are the obvious starting point for studying the implications of our scenarios. Figure 3 shows the subbasins, and Table 4.1 the mean annual flows in each subbasin in the year 2000 and under the three scenarios in 2050.

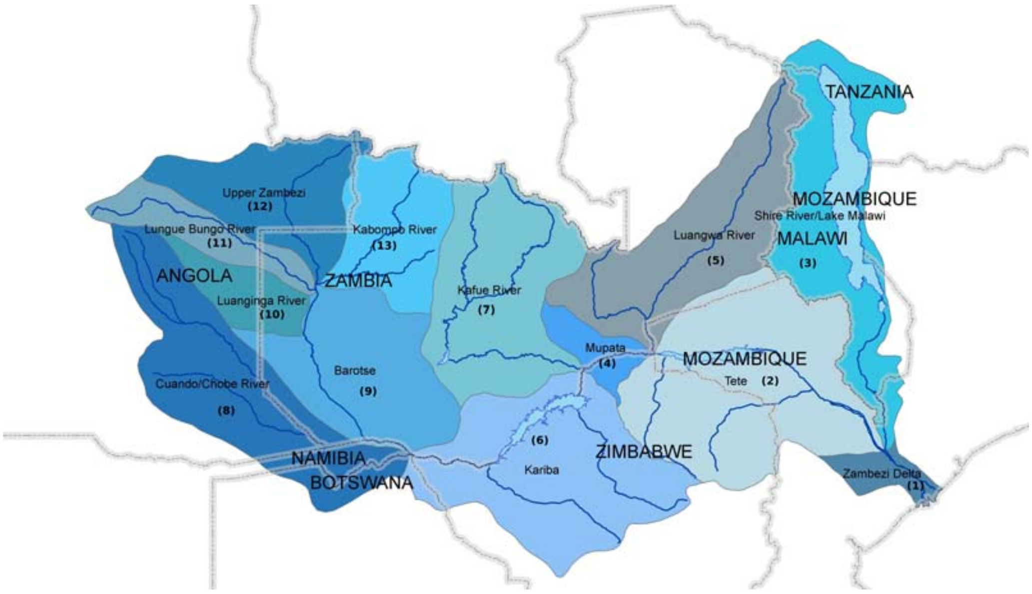

Figure 3: subbasins of the ZRB.

With the exception of the Shire subbasin, where even under the small growth scenario (AD1E1) a 20% reduction of runoff occurs primarily due to population growth, mean annual runoff declines only slightly in this scenario the main reductions besides the Shire occurring in the Zambezi Delta (5%), the Tete subbasin (3%), and the Kafue (9%) and Cuando Chobe subbasins (4%). The average flow reduction in the 13 subbasins for that scenario is 4% (and

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[8] We do not consider return or drainage flows because drainage takes place naturally during the rainy season. We assume that all water used for irrigation is consumed. We make this assumption based on interviews with managers of the Mazabuka and Marromeu sugar farms in Zambia and Mozambique, the largest irrigation sites in the ZRB. We assume in our simulations that in times of water shortages, i.e. when total consumptive water demand is bigger than available surface water, additional water will be allocated directly from the subsurface. This has the effect that in times of water shortages base flows vanish.

Subbasin	Year 2000	AD1E1	BD2E2	CD3E3
1. Delta	2597	2457	2266	1475
2. Tete	1729	1682	1530	872
3. Shire	445	354	320	210
4. Mupata	1248	1188	834	54
5. Luangwa	489	485	484	322
6. Kariba	929	898	588	20
7. Kafue	273	248	200	83
8. Cuando Chobe	32	31	0	0
9. Barotse	1007	1002	683	266
10. Luanginga	58	58	29	0
11. Lungue Bungo	263	263	220	186
12. Upper	253	252	159	13
13. Kabompo	82	82	62	23

Table 2: Mean annual flows $[m^3/s]$ in 13 subbasins, indicating total river flow at the end of each subbasin for the year 2000 and three scenarios for 2050. Note that we use the terms runoff and water availability synonomously in the remainder of the paper. This variable measures the water flow that remains after actual (year 2000) or projected water demand has been met[8]

5% at the end of the ZRB in the delta)[9], the standard deviation is 6%.

In second scenario (BD2E2), all subbasins experience rather drastic flow reductions, the average is 32%, the standard deviation is 24%. In the Cuando Chobe (100%) annual water demand would exceed river flow. Besides the Cuando Chobe, the Luanginga (49%), Upper and Kariba (37%), Barotse (32%) and Mupata (33%) subbasins are the most negatively impacted. The Zambezi Delta subbasin would lose 13% of its mean annual flow compared to the year 2000[10].

The third scenario (CD3E3) has extremely negative effects on annual flows in all subbasins. The average reduction of mean annual flow across all subbasins is 70%, the standard deviation is 26%. The worst affected subbasins are the Cuando Chobe (100%) and the Lu-

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[9] The different reduction rates on average and at the end of the river system are due to variation in climatic and water demand conditions across the subbasins.

[10] The smaller loss in the Delta (relative to losses in other subbasins) is primarily due to comparatively small losses in the Shire and Tete subbasins, which are among the largest subbasins.

anginga (100%) where demand would exceed the available water. The Kariba (98%), Mupata (96%), Upper (95%), Kafue and Barotse (70% and 74% respectively) and the Zambezi Delta (43%) would experience severe losses as well.

The negative effects under the second and third scenario are even stronger when we focus on the dry season. Table 4.1 shows that several of the subbasins could see their water flows reduced to zero even under the middle scenario. The average reductions for the 13 subbasins are 10% under the first, 70% in the second, and 93% in the third scenario. Simulation results for the implications of the three scenarios for maximum flows are shown in the Appendix E. They suggest that, on average, long term problems of water scarcity are more important than problems of flooding.

Subbasin	Year 2000	AD1E1	BD2E2	CD3E3
1. Delta	2126	1964	1561	485
2. Tete	1457	1397	1071	118
3. Shire	279	181	110	0
4. Mupata	996	873	500	0
5. Luangwa	87	82	0	0
6. Kariba	748	687	399	12
7. Kafue	159	131	63	46
8. Cuando Chobe	26	24	0	0
9. Barotse	204	198	0	0
10. Luanginga	15	14	0	0
11. Lungue Bungo	124	123	82	37
12. Upper	34	33	0	0
13. Kabompo	3	2	0	0

Table 3: Mean minimum flows $[m^3/s]$ in the dry season, projected for 2050 (October). Precipitation hydrographs for the 13 subbasins are included in Appendix C.

4.2 Specific locations

Figure 4 shows the implications of the three scenarios for Victoria Falls, one of the major tourist attractions (and thus a source of revenue) in Southern Africa. This figure also illustrates that the effects are likely to be especially harmful in the dry season. While the first scenario has very little effect compared to the present state, even the second scenario could stop the water flow at Victoria Falls for nearly half of the year (August to January). The third scenario could leave the Falls dry for eight months of the year. According to a study by SADC, the minimum environmental flow required to maintain the character and touristic value of the Victoria Falls is $400m^3/s$ [23]. This threshold is approached during the dry season even today. Figure 5 shows the effects on electricity production at the three

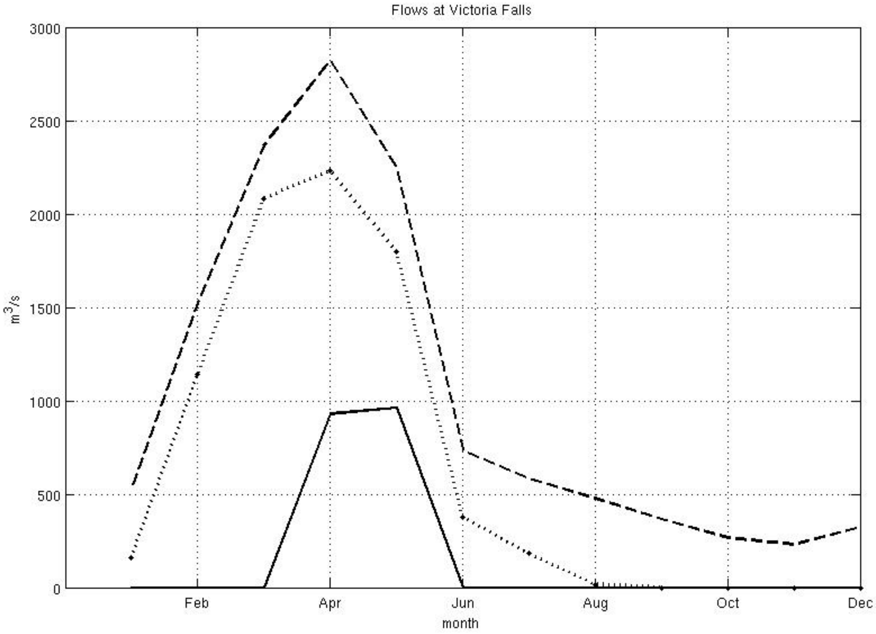

Figure 4: Mean monthly flows at Victoria Falls: Scenario AD1E1 (dashed), BD2E2 (dots), CD3E3 (solid line). The flows in scenario AD1E1 are almost the same as contemporary flows. We thus omit the latter in this figure.

largest production sites in the ZRB: Cahora Bassa, Kariba, and Kafue Gorge. Interestingly, the second scenario (BD2E2) has only a small effect on hydroelectric power production, especially at Kafue Gorge and Cahora Bassa compared to reductions at Kariba. We interpret this result in the sense that reduced river flows over the year can be compensated through a better storage of peak flows. Peak flows are currently passing mainly through the spillways of Kafue and Cahora Bassa (i.e. they are not stored and then used for power production) or are lost through evaporation in the large inundated flood-plains[11].

However, in the third scenario (CD3E3) two of the three hydropower production sites experience dramatic losses. At Cahora Bassa the loss is 65%, at Kariba it is almost total. The Kafue hydroelectric power plant could maintain its output with currently applied operation rules[12], but only in ways that violate current agricultural/fisheries and ecological objectives with respect to the Kafue Flats. The estimates for Kafue shown in Figure 5 do not take into account such objectives. We think that maximizing power production at the expense of agriculture/fisheries and ecosystems in the Kafue Flats is an unlikely scenario. This ecosystem is very important for the local economy in terms of traditional farming, fisheries, and tourism. This circumstance would probably prevent hydropower plant operators from maximizing electricity production (which is assumed in our simulation). Hence the model predictions for power production at Kafue are probably too optimistic.

As regards the most important wetlands in the ZBR, which are important from an agriculture and fisheries, biodiversity and tourism perspective, it makes more sense to examine the subbasin level, rather than specific locations. As discussed above, the Zambezi Delta could experience flow reductions in the order of 5% (first scenario) to 13% (second scenario) to 43% (third scenario). In the Kafue subbasin, these reductions could be 9%, 27% and 70% respectively. In the Barotse subbasin, reductions of 1%, 32% and 74% respectively could occur.

Figure 6 illustrates some interesting differences in flow reductions across the three main wetlands in the ZRB. In the Barotse subbasin the lack of hydraulic infrastructure for river

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[11] Data for the year 2006 ([31], [6]), for example, shows that water flows at Kafue Gorge between March and August of that year consisted on average of 650 m^3/s discharged over the spillway and 970 m^3/s of turbinated water. At Cahora Bassa the corresponding shares in the same time-period were 342 m^3/s and 1493 m^3/s. At Kariba all water can currently be turbinated, except at times of very large runoff (floods).

[12] At present, operation rules for the Kafue are defined by two dams. One dam upstream (Itezhi Tezhi) serves as the main reservoir. From there water is released to the Kafue Gorge Dam 300 km downstream where there is only a very small reservoir.

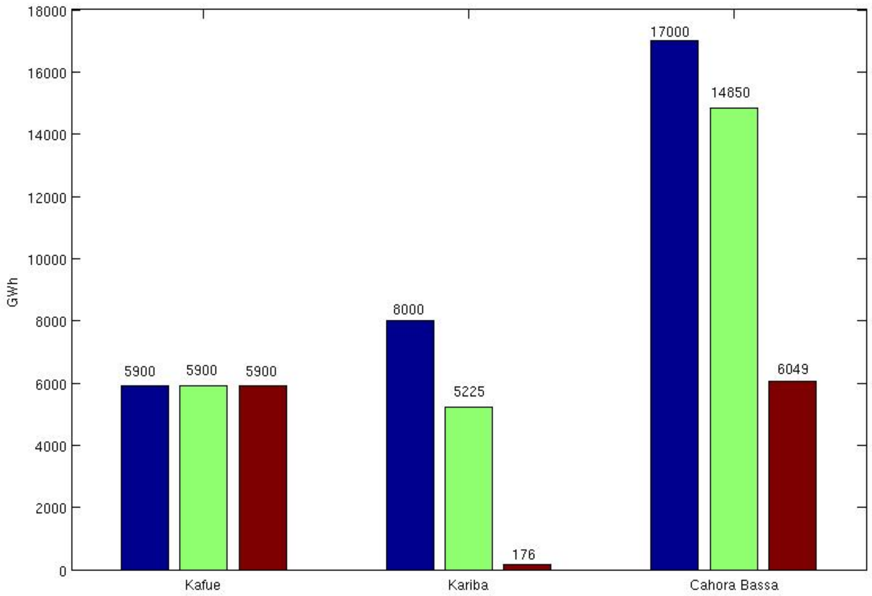

Figure 5: Hydropower Scenarios AD1E1 (blue), BD2E2 (green), and CD3E3 (red)

regulation results in complete drying up in some months even in the second scenario. In the Kafue subbasin peak flow is reduced but minimum flows can be kept at a higher level due to releases from the Itezhi-Tezhi reservoir. Flows in the Zambezi Delta are generated by a combination of regulated flows from the Cahora Bassa reservoir and unregulated flows from Lake Malawi. Due to a seasonal shift of rainfall and increasing runoff resulting from climate change our model predicts a changing pattern of river flow during the wet season. Because there is virtually no reliable data on river discharge in the Delta our model relies on rough estimates (see Appendix C). Hence it is very difficult to make good predictions of discharge behavior in that subbasin. Nevertheless, compared to subbasins with unregulated flows (e.g. Barotse subbasin) we expect that flow reductions are more evenly distributed across the year.

From an environmental point of view especially the Kafue subbasin faces accute water shortages. Required minimum environmental flows in the Kafue subbasin are assumed to be at least 250m3/s during the low flow season [5]. Because water abstractions reduce flows quite considerably already at present this minimum is often not reached even today. Or it is artificially approached by dam regulation at Itezhi Tezhi. Hence the prospects for the Kafue subbasin look rather dire despite the possibility of additional releases from the Itezhi Tezhi dam. For the Zambezi Delta a minimum flow of 250m3/s, as suggested by SADC [5], is met in all the three scenarios. For the Barotse Plains, where our scenarios BD2E2 and CD3E3 assume large abstractions upstream, we are not able to find any proposals for minimum environmental flows in the literature.

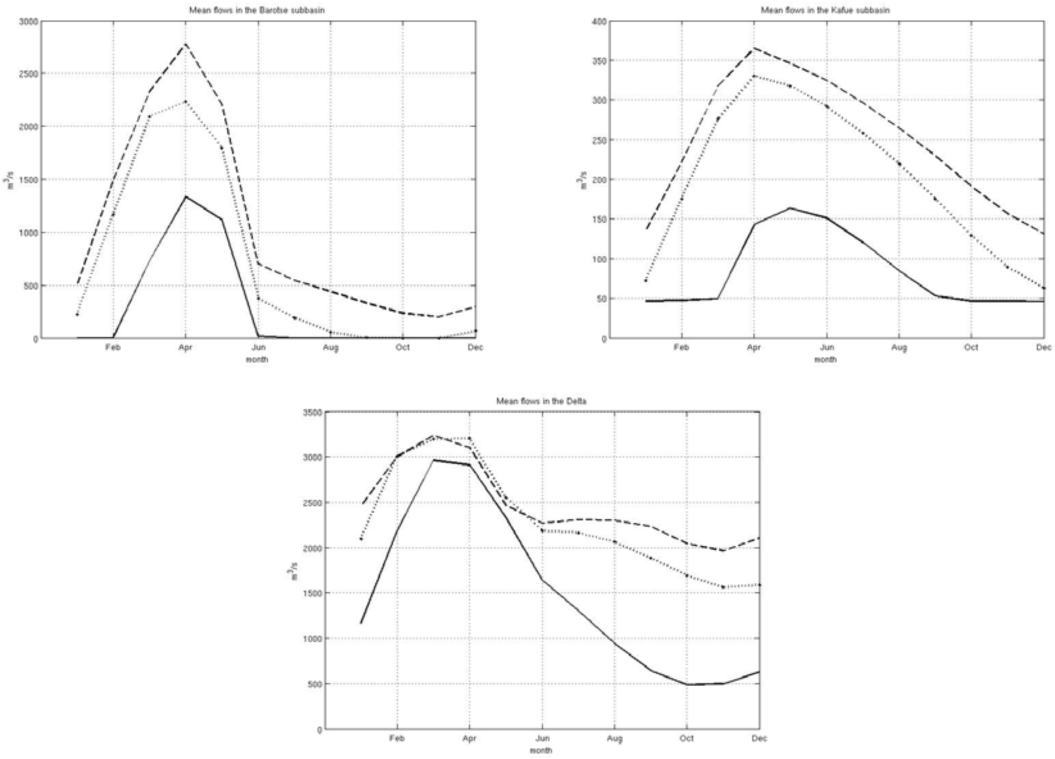

Figure 6: Mean annual flows in the Barotse Plains (before confluence with the Chobe), Kafue Flats (before confluence with the Zambezi River), and discharge into the Indian ocean at the Zambezi Delta: Scenario AD1E1 (dashed), BD2E2 (dots), CD3E3 (solid line)

4.3 Country level

The estimates presented above show that increasing water demand combined with climatic changes could lead to dramatic reductions of water flow at key points in the ZRB. Such reductions are per se highly problematic. However, in addition they are likely to also produce substantial shifts in relative water availability and water demand across countries. Such shifts could lead to international conflict. In our model and the simulation results for the three scenarios the water available to any given country in the ZRB is, to the extent that a country is contiguous to or downstream of other countries, affected by changes in water demand and climatic conditions in those countries. This dynamic process generates changes in water availability in absolute terms (runoff in a country in one of the three scenarios compared to the year 2000) and in relative terms (that is, relative to changes in runoff in other countries). We assume that from the perspective of national policy–makers both types of changes are important.

Table 4 shows the average annual runoff in the eight ZRB countries in the year 2000 and under the three scenarios. On average, runoff decreases by around 5% under the first, 25% under the second, and 66% under the third scenario. In the second scenario, the most negatively affected countries are Botswana, Namibia, Angola as well as Tanzania and Malawi. Under the third scenario, the most negatively affected countries are Zimbabwe, Zambia, Botswana and Namibia. Table 3 also shows that most national shares in total available ZRB water change across scenarios. These differences indicate that both absolute and relative changes in runoff are important. For example, while the share of ZRB water that remains available in Mozambique increases from 27% to 44%, the shares of Zimbabwe and Zambia decline from 19% to 11% and 18% to 12% respectively.

Similarly, national shares in total consumptive water demand in the ZRB are also likely to change (see Table 5). Because the first Scenario (AD1E1) is driven mainly by population

Country	Year 2000		AD1E1		BD2E2		CD3E3	
	$[m^3/s]$	[%]	$[m^3/s]$	[%]	$[m^3/s]$	[%]	$[m^3/s]$	[%]
Angola	493	5	491	5	335	5	161	5
Botswana	1048	11	1040	11	688	9	263	8
Malawi	439	5	349	4	316	4	208	6
Mozambique	2596	27	2423	26	2235	31	1455	44
Namibia	1025	11	1018	11	674	9	262	8
Tanzania	439	5	349	4	316	4	208	6
Zambia	1768	18	1703	19	1347	18	399	12
Zimbabwe	1860	19	1784	19	1379	19	371	11
Total	9669	100	9159	100	7290	100	3326	100

Table 4: Runoff in the eight ZRB countries. For the definition of basin shares and catchment areas relevant to the individual countries see maps in the Appendix B.2.

growth, which is particularly high in Malawi, the latter's share in total ZRB water consumption grows most strongly (from 5% to 14%) though Zambia remains the biggest water user in the system. Because of massive growth of irrigated agriculture Zambia's water consumption share grows from 30% to 39% to 42% (from 2000 to scenario three). The biggest drop occurs in Zimbabwe, whose share declines from 33% to 29% to 11%. This massive shift in consumptive shares occurs mainly because Zambia has much more land that is suitable for irrigated agriculture than Zimbabwe. Finally, we take a look at changes in water availability (runoff) and demand in combination. As shown in Figure 7, the eight ZRB countries cluster at five places in the second and third scenario. Angola, Malawi and Tanzania are likely to experience small decreases in runoff and small increases in demand (relative to the other countries).

COUNTRY	Year 2000	AD1E1	BD2E2	CD3E3
Angola	0.2	0.2	9	12.6
Botswana	0.3	0.3	0.2	1.4
Malawi	5	14.2	11.4	9.8
Mozambique	26.7	24	19	17.6
Namibia	0.5	0.4	0.6	1.9
Tanzania	0.4	1.5	4.8	3
Zambia	33.5	30	39.1	42.3
Zimbabwe	33.4	29.5	16	11.5
Total	100	100	100	100

Table 5: National shares in total consumptive water demand in the ZRB (domestic, industrial and agriculture water demands, and evapotranspiration from reservoirs)

Botswana and Namibia are likely to see moderate to large decreases in water availability, but only a small increase in demand. Zimbabwe is likely to encounter a large decrease in water availability, but only a small growth in demand. Mozambique and particularly Zambia are likely to experience the biggest supply-demand divergence, with Zambia located at the extreme end of supply-demand divergence spectrum. Figure 7 suggest, therefore, that the greatest conflict potential is among Mozambique, Zambia and Zimbabwe: all three countries are likely to experience a large decrease in water availability, but their projected demand growth differs by a very large amount. It appears quite likely that (downstream) Mozambique and (contiguous) Zimbabwe will challenge Zambia at some not too distant point in time if the latter expands its water consumption as assumed in scenarios two and three.

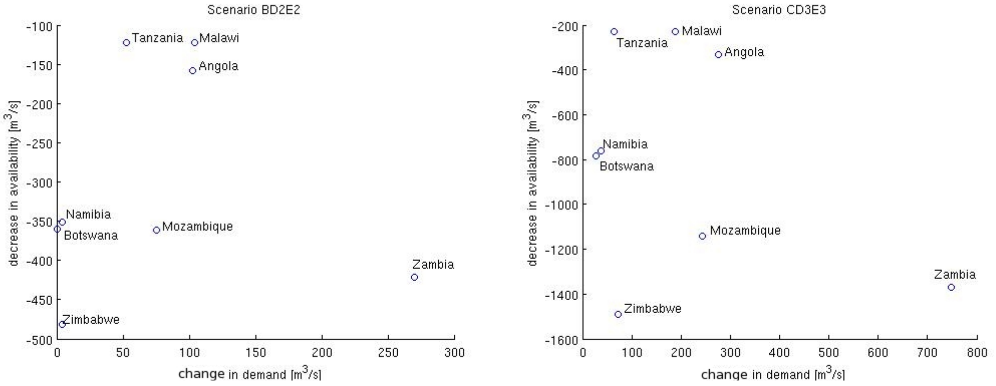

Figure 7: Changes in availability (runoff) and demand under scenarios two (BD2E2) and three (CD3E3)

5 Conclusion

The results reported in this paper are obtained under the assumption that the eight ZRB countries continue to pursue their water policies in a unilateral fashion, that is, in the absence of effective international cooperation on water allocation issues, as they have done so far. These results suggest that even under the "middle-of-the-road" scenario the consequences could be quite dramatic, both in terms of local effects on hydroelectric power production, wetlands, and tourism, as well as regional political effects associated with large shifts in relative shares in total ZRB runoff and water demand in the eight countries. Moreover, our model predictions are for "average years", implying that the implications of our water demand and climate change scenarios could even be much worse in drier than average years and locations.

Current international institutions governing the Zambezi's waters are very weak, and it remains uncertain whether the ZAMCOM agreement, the only international agreement for the entire ZRB, will enter into force. Even if ZAMCOM becomes operational the constraints it would impose on the water policies of the individual ZRB countries are very modest. We think that this institutional setting is probably not going to be able to weather changes in ZRB runoff in the order predicted by our model. A better system for allocating the Zambezi's water resources is urgently needed before distributional conflicts arise. Our results suggest that the most likely such conflict is going to occur between Mozambique, Zambia, and Zimbabwe, with Mozambique and Zimbabwe challenging Zambia if the latter expands its consumptive water use along the lines assumed in the second and third scenario.

Further research could couple our supply-demand model with an optimization modeling effort (for a suggestion of this kind see [27]). This approach could generate valuable insights into how international management of the ZRB's water resources could be improved. In particular, it could help in identifying potential national and international solutions (e.g. water allocation strategies and rules, international water transfers, compensation arrangements) that improve on or avoid the negative consequences of and conflicts associated with unfettered unilateral expansion of water demand, as illuminated in this paper.

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