How will combined changes in water demand and climate affect water availability in the Zambezi river basin?∗

Lucas Beck 1, Thomas Bernauer *

ETH Zurich, Center for Comparative and International Studies and Institute for Environmental Decisions, Haldeneggstrag 4, 8092 Zurich, Switzerland

1. Introduction

Rivers and lakes embody only a tiny fraction of the water on Earth, but constitute the most accessible sources for human consumption and use (UNEP 2010). While the total global freshwater supply is constant, local supply is subject to climatic changes and uncertainties in terms of rainfall and temperature. Increasing population density, economic activity, and unsustainable water management practices have led to over-exploitation of many of the more easily accessible freshwater resources around the globe (Vörösmarty et al., 2010). Many of these water systems extend beyond the boundaries of a single country. Depending on how the count is done, around 200–400 large river basins are international. Some areas of the world already suffer from acute water scarcity, and many scientists expect worse to come as a result of climate change (Arnell, 2004; Gleick et al., 2006); climate change affects the volume and timing of river flows and also groundwater recharge (Arnell, 2004). Alcamo (2006) notes “… that many of the world’s internationally shared river basins will be in the high or very high stress categories in 2025. Indeed, 33% of the total area of international river basins will be in either of these categories. The competition for these water resources could be an ongoing source of tension between nations.”

The expected Malthean trap of diverging water supply and demand has lead to a burgeoning literature on international water problems (e.g. Yoffee et al., 2003; Wolf Aaron, 1998; Bernauer and Kalb, 2010). One part of this literature focuses on understanding the threat, for instance vulnerability in a broad sense, or damages from weather related disasters (e.g. Vörösmarty et al., 2010, 2000; Vörösmarty and Moore., 1991; Strzepek et al., 2001; Bouwer et al., 2010). The other part deals with adaptation, for instance how to design international institutions so that the available water is allocated efficiently and conflict can be avoided (e.g. Goulden et al., 2009; Fischhendler, 2004; Kistin et al., 2009; Zeitoun and Allan, 2008; Dinar et al., 2007; Drieschova et al., 2008; Wirkus and Boege, 2006).
We contribute to the first part of this literature. In contrast to the vast literature dealing with implications of climate change for human security and adaptation in international river basins, there are surprisingly few studies on how changes in water demand and in climatic conditions could affect water availability in international river basins.

Several studies have examined possible effects of climate change on global water resources or specific international water systems (e.g. Vörösmarty et al., 2000; Strzepek et al., 2001; Bouwer et al., 2010; Arnell, 2004; Ximing et al., 2006). Some studies examine the effects of population growth and other water demand factors on water availability at the country or river basin level. But they do not take into account climate change or do not examine the water distribution within basins (e.g. Alcamo, 2006; Alcamo et al., 2003; Revenge et al., 2000; Amarasinghe et al., 2005; Hoekstra, 2003; Höllermann et al., 2010; Rosegrant et al., 2000; Ringler et al., 2004). Other studies focus on the implications of climate change for international river basins, but do not take into account demand-side factors (e.g. Barnett, 2003).

Very few such studies have examined the implications of climate change and changes in water demand jointly, and most studies of this nature operate at the macro level (Vörösmarty et al., 2010; Alcamo et al., 2007). They usually combine population growth and climate change projections with macro-scale hydrological models and estimate the potential vulnerability of entire water catchments, countries, or world regions (e.g. Vörösmarty et al., 2000; Arnell, 2004). Vörösmarty et al. (2000) and Alcamo et al. (2007), for instance, find that water demand and population growth are likely to have a bigger effect on water stress than climate change.

One of the very few studies on individual international river basins that systematically examines both demand factors and climate change and provides geographically and seasonally detailed results for water distribution within the basin is by Hoff et al. (2007). They study the Jordan basin using a simple, pre-existing modeling framework, the WEAP21 (Water Evaluation and Planning) tool. Moreover, a recently published World Bank study on investment opportunities in the ZRB also takes into account changes in water demand and climatic conditions (World Bank, 2010).

In this paper we develop a new approach for analyzing, within a single modeling framework and in a geographically and temporally detailed manner, the potential implications of climate change and changes in water demand for water availability in international river systems. By implication, we also explore whether changes in demand or in supply (due to climate change) have a greater effect. To that end we combine a comprehensive set of water demand scenarios and climate change projections with a hydrological model to estimate future water availability in key parts of the Zambezi river basin (ZRB) until 2050.

Our case study area is the ZRB because it is both substantively important in terms of human security and analytically challenging in terms of demonstrating the value of our methodological approach. The ZRB is one of the largest freshwater catchments in Africa and worldwide. It has a complex hydrological and political geography. Moreover, it experiences only minor water stress today, but analysts are strongly divided over what the next few decades will bring.

The results show that our approach is feasible and can produce valuable insights. Our results indicate that current water abundance in most parts of the ZRB is unlikely to last. While climatic changes are likely to have only rather small effects on water availability, population and economic growth as well as expansion of irrigated agriculture and water transfers will have very important transboundary impacts. Such impacts involve drastically reduced runoff in the dry season at most economically or ecologically important locations. In addition, the (relative) shares of ZRB countries in the basin’s total runoff and water demand will probably change in a major way. These results indicate that effective governance mechanisms for water allocation and for dealing with flow variability should be set up within the next few years in order to manage the situation cooperatively.

2. Case study, methods and data

2.1. Case study

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 km²), is populated by around 30 million people and discharges an average of around 2600 m³/s (or 82 km³ per year) into the Indian ocean (Beilfuss, 2001; Beilfuss and Brown, 2006). In terms of discharge, the Zambezi is of similar size as the Nile (2830 m³/s) or the Rhine (2200 m³/s).

Current consumptive water use in the ZRB is estimated at around 15–20% of total runoff (MacDonald, 2007; SADC, 2008). The largest consumptive water users are dams (evaporation through impoundment, ca. 13 km³ of water) and irrigated agriculture (ca. 1.5 km³ of water). 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 (SADC, 2008). Such expansion of consumptive water use also could become a source of tensions among the eight riparian countries.

The average annual rainfall in the ZRB is quite high (ca. 950 mm, based on CRU estimates by Mitchell (2004)). 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 Fig. 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.

Another source of heterogeneity and potential tensions among the ZRB countries emerges from the fact that they differ very much in terms of their investment potential and river basin shares. As shown in Fig. 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 Fig. 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 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.

Several bilateral and multilateral political arrangements are in place to manage transboundary waters in Southern Africa; notably,
Fig. 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 dotted line marks a threshold of 1700 m$^3$/year, which is commonly regarded as a threshold for water scarcity (the Falkenmark index proposes a minimum of 1700 m$^3$ 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 1000 m$^3$ per capita and year is considered severe water stress (Falkenmark and Widstrand, 1992)).

Fig. 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 (2004). See Companion Material B.3. at Appendix for details.
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 km³ storage capacity, 1470 MW (720 MW North Bank and 750 MW South Bank) capacity; ZRA, 2009). 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 March 2011, it was 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 or could 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 over the next few decades. Our paper contributes to that effort by exploring the effects of water demand and climate change on water availability in key areas of the ZRB.

The model we develop and use to that end consists of two components: a hydrological model that mimics the natural processes, and a demand model that represents 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.

2.2. Hydrological 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 models of (Hoekstra, 2003; SADC, 2008; Denconsult, 1998), our model is based on improved data for precipitation and evaporation as well as more information on river discharge for better calibration.

The model consists of a lumped rainfall-runoff model (RRM) including surface- and base-flow, regulated dams for hydropower production, and water storage dams for consumptive water use. We assume that in times of water shortages, i.e. when total consumptive water demand is higher than available surface water, additional water will be allocated directly from the subsurface. Concerning dam/reservoir operation rules, we assume that the only objective is to prioritize water demand for power production and neglect an exact seasonal timing to coordinate with specific environmental water needs after dams.

We model each of the sub-basins (see Fig. 7) separately and aggregate the thirteen sub-basins (RRMs) to a consistent hydrological model for the entire ZRB.

For the calibration of our hydrological model we use gridded and (for our sub-basins) re-aggregated monthly precipitation data from the Climate Research Unit (CRU) resampled by Mitchell (2004). Potential evapotranspiration for the entire basin is based on seasonal measurements carried out by various water agencies and power supply companies in the ZRB (DWA, 2008; ZESCO, 2008; DNA, 2008), and data from sector studies performed in 1998 (Denconsult, 1998).

We focus on long-term mean annual water flows for two reasons. First, projected effects of climate change are rather small compared to inter-annual climate uncertainties and could be blurred by uncertainties concerning precipitation and evapotranspiration. Second, the different data sources for discharge measurements we use for calibration are, in many cases, not seasonally consistent, but match in a long-term perspective and at the basin-scale.

Changes in consumptive water demand and climatic conditions are directly included in our model. Potential new hydro-power production sites are included in terms of increased evaporation (consumptive water use) from reservoirs.5

2.3. Water demand projections

In our demand model we simulate spatially and temporally disaggregated water demand by four sectors: agriculture, hydropower production, domestic sector, and industrial sector (see Fig. 3). 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.

Our model distinguishes water demand in terms of consumptive and non-consumptive demand. Similar to the physical model, the 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 water users in certain areas (Fujita et al., 2001). We assume that water use is more intense along the main stream and at locations with greater availability, assuming that transportation and infrastructure costs increase with distance from the main water abstraction points. Moreover, we assume that water use decreases with decreasing availability. Temporal variation in demand is mainly a function of differing water demand due to climate-related seasons (Denconsult, 1998) in agriculture and varying electricity demand over the year (SAPP, 2007).

Projections for the demand variables, on which our scenarios rely (see Section 2.5), are based on the following sources of information. For agricultural demand we use projections by (Denconsult, 1998), national statistics (MacDonald, 2007), the Digital Global Map of Irrigation Areas (Siebert et al., 2006), projections by the FAO (2005), and the spatial distribution of irrigation according to a satellite derived land-cover map (Mayaux and Bartholomé, 2003).

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

---

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.

4 http://www.cru.uea.ac.uk/.

5 Technical details of the hydrological model and the demand model (see next section), long-term climatological precipitation hydrographs for the 13 sub-catchments, the calibrated parameters, and model sensitivities are shown in the Companion Material at Appendix.

6 Including seasonal variation in our simulations has no significant effect on the results.
access to ground- and surface waters. Following common assumptions (WWDR3, 2009) 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 (UN, 2006) and distribute this information spatially according to a satellite derived population density map for 2004 (Landscan, 2006). Additionally we derive an urban–rural distribution based on urbanization scenarios and urban centers defined by Denconsult (1998), and Schäppi (2007), and assume a per capita consumption of 150 l/day in urban and 27 l/day in rural areas (FAO, 2005).

For industrial water demand we use estimates by ZACPRO/ SADC (Denconsult, 1998) and projections of national growth (MacDonald, 2007). For hydropower generation and water storage projects we use estimates and information on planned projects from the Southern African Power Pool SAPP (2007) and SADC (2008). For information on water transfer projects we use Turton (2003), Turton (2005), Heyns and Piet (2002), Heyns (2006), and Namibia (2002). Fig. 3 shows existing and projected consumptive water demands of the four sectors under the scenarios described in Section 2.5. Note that for the calibration of our model we rely, for consistency reasons, on data from Denconsult (1998), whereas for the three scenarios we will also use other data sources that allow for a better design of these scenarios. These additional sources are described below. For this reason, the irrigation part of scenario (1), as shown in the figure, which relies on FAO-estimates, indicates slightly lower water consumption than under the status quo. Fig. 3 clearly suggests that the largest effect on water availability is likely to emanate from irrigated agriculture, which is the dominant consumptive water user in the ZRB in scenarios (2) and (3).

### 2.4. Climate projections

For information on climate change projections we rely on IPCC figures for monthly mean precipitation in 2050. Our model is calibrated to long-term average climatic conditions in the time-period 1900–2002. For changing climatic conditions relative to 2000 our scenarios are based on the SRES A2 scenario (IPCC, 2008), which constitutes a high emission scenario. We rely on the 16 General Circulation Models (GCM) as used in Climwiz (2009). The SRES A2 scenario expects economic development that is primarily regionally oriented and in which technological change is more fragmented and slower than in the other SRES story-lines. A regional disaggregation of this climate scenario is described in Climwiz (2009). For our assessment we use the GCM with the lowest mean precipitation (UKMO-HADCM3) and the highest mean annual precipitation (GFDL-CM2.0). We consider the GFDL-CM2.0 GCM as a moderate model because the higher temperature implying higher evaporation is largely compensated by higher basin-wide precipitation and does not indicate major changes compared to the status quo. We derive the following range of climatic changes (see Fig. 4).

The SRES A2 scenario for the ZRB anticipates a basin-wide increase in temperature of up to 2.9 °C annually and even 4.1 °C seasonally. We include changes in temperature in terms of higher evapotranspiration by scaling potential evapotranspiration proportional to projected changes in temperature. The annual mean precipitation is projected to increase slightly in almost the entire ZRB while decreases appear only seasonally. We derive two climate scenarios (additional to the status quo): (1) moderate climatic changes with slightly increased precipitation (annual basin-wide mean increase: 10.98%), as anticipated by the GFDL-CM2.0 model including temperature increase of 2.5 °C; (2) strong climatic changes with a basin-wide decrease in annual precipitation of 27.9% and increase in temperature by 2.9 °C as projected by the SRES A2 model UKMO-HADCM3. The projected climatic changes for the eight riparian countries of the ZRB are illustrated in Fig. 4.

### 2.5. 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 water use scenarios and combine them with scenarios for climatic changes as described in the previous section.
We focus on particular combinations of water demand and climate change projections and bundle them into three scenarios. These scenarios cover the entire spectrum of water demand and climate change projections described above. By implication, alternative bundling of specific projections would simply produce outcomes (runoff predictions) that are located somewhere in between those resulting from scenarios (1) to (3). Our scenarios are characterized as follows: Scenario 1: Minor changes in demand: minor population and urbanization growth according to UN estimates for the ZRB; no expansion of irrigated agriculture compared to present (currently irrigated land kept under irrigation at current intensity/efficiency); minor expansion of industry compared to present; none of the currently planned additional water storage facilities is built; none of the currently envisaged water transfer projects is implemented; no climatic changes compared to the status quo. Scenario 2: Moderate demand and supply side changes: moderate population and urbanization growth; moderate expansion of irrigated agriculture (irrigated land increases to 1.1 Mio hectares (ha) of irrigated land, which amounts to 3% of the total arable land available; FAO, 2005); moderate expansion of industry (5% growth in water demand per year); hydropower: half of the projects mentioned in SAPP (2007) and SADC (2008) are implemented; half of the currently envisaged water transfer projects are implemented (based on information from Turton, 2005, 2003; Namibia, 2002); moderate climatic changes derived from SRES A2 GCM GFDL-CM2.0. Scenario 3: Strong demand and supply side changes: strong population and urbanization growth; strong expansion of irrigated agriculture (irrigated land increases to 3.1 Mio ha, which amounts to 8% of the total arable land available); strong expansion of industry (10% growth in water demand per year); hydropower: all of the currently planned storage facilities are built; strong climatic changes as projected by the SRES A2 GCM UKMO-HADCM3.

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 (see Companion Material F at Appendix). These three countries contribute around 70% to the ZRB runoff and are by far the most important water users in the basin.

Based on these discussions we have come to the conclusion that the scenarios outlined above are “realistic”. That is, they cover 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 and estimates of their implications 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 effective international coordination. We take into account, however, that water consumption by one country affects water availability in other ZRB countries, depending on course on geographic location and hydrology. We think that this approach is realistic and 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 and where very little international coordination takes place, prevailed in the long term. That is, our model predicts outcomes that could occur in the absence of stronger international coordination and effective water allocation rules. As shown by Drieschova et al. (2008) international governance mechanisms for water allocation are particularly important in cases of strong flow variability, a condition that is clearly present in the ZRB.

We examine the implications of these scenarios at three levels: (1) the sub-basin, (2) specific locations in the basin (notably, Victoria Falls, Kariba, Kafue Gorge, Cahora Bassa, Barotse Flats, and Zambezi Delta), and (3) the country.

3. Results

We start by discussing the results for 13 sub-basins of the ZRB before focusing on key locations on the basin and the country level. We distinguish these three levels for several reasons. Sub-basins are the main components (natural accounting units) of the aquatic system that forms the ZRB. Hence it is meaningful to study the implications for those components first. Policy choices affecting water demand are made at local, national, and international levels. Moreover, policy-choices and thus water demand by local or national decision-makers have transboundary effects because the ZRB and several of its sub-basins extend across national political boundaries. This setting justifies systematic analysis of the implications for countries as a whole. 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 in 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 are important wetlands that are of local economic value but also of international importance in terms of their biodiversity.

In essence, the first scenario (1) serves to explore the effects of modest population growth and some minor industrial expansion. The second scenario (2) serves to examine the implications 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 (3), water demand is driven to a major extent by the expansion of irrigated agriculture and combines with strong changes in climatic conditions.

3.1. Subbasins

Since the hydrological model is based on 13 sub-basins these hydrological units are the obvious starting point for studying the implications of our scenarios. Fig. 5 shows the 13 sub-basins, and Table 1 shows the average annual flows in each sub-basin in the year 2000 and under the three scenarios in 2050.

With the exception of the Shire sub-basin, where even under scenario (1) 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 occur in the Zambezi Delta (5%), the Tete sub-basin (3%), and the Kafue (9%) and Cuando Chobe sub-basins (4%). The average flow reduction in the 13 sub-basins for that scenario is 4% (and 5% at the end of the ZRB in the delta), the standard deviation is 6%.

In the second scenario (2), all sub-basins experience rather drastic flow reductions, the average is 31%, the standard deviation is 23%. In the Cuando Chobe (100%), annual water demand would exceed river flow. Besides the Cuando Chobe, the Luangwa (42%), Kariba (36%), Mupata (34%), Kafue and Shire (31%) sub-basins are the most negatively impacted. The Zambezi Delta sub-basin would lose 17% of its mean annual flow compared to the year 2000.

The third scenario (3) has extremely negative effects on annual flows in all sub-basins. The average reduction of mean annual flow across all sub-basins is 77%, the standard deviation is 23%. The worst affected sub-basins are the Cuando Chobe, Kariba, Upper and Luangwa (all 100%) where demand would exceed the available water. The Mupata (98%), Kabompo (90%), Barotse and Kafue (85% and 77%, respectively) and the Zambezi Delta (47%) 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 2 shows that several of the sub-basins could see their water flows reduced to zero even under the second scenario. The average reductions for the 13 sub-basins are 10% under the first, 69% in the second, and

---

14 The shares of sectoral water demand under the three scenarios are shown in Fig. 3 and in the Companion Material D Appendix.

15 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 sub-basins.

16 The smaller loss in the Delta (relative to losses in other sub-basins) is primarily due to comparatively small losses in the Shire and Tete sub-basins, which are among the largest sub-basins.

---

Table 1

<table>
<thead>
<tr>
<th>Sub-basin</th>
<th>Year 2000</th>
<th>Scenario (1)</th>
<th>Scenario (2)</th>
<th>Scenario (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Delta</td>
<td>2597</td>
<td>2457</td>
<td>2162</td>
<td>1383</td>
</tr>
<tr>
<td>2. Tete</td>
<td>1729</td>
<td>1682</td>
<td>1464</td>
<td>834</td>
</tr>
<tr>
<td>3. Shire</td>
<td>445</td>
<td>354</td>
<td>307</td>
<td>165</td>
</tr>
<tr>
<td>4. Mupata</td>
<td>1248</td>
<td>1188</td>
<td>818</td>
<td>23</td>
</tr>
<tr>
<td>5. Luangwa</td>
<td>489</td>
<td>485</td>
<td>431</td>
<td>250</td>
</tr>
<tr>
<td>6. Kariba</td>
<td>929</td>
<td>898</td>
<td>598</td>
<td>0</td>
</tr>
<tr>
<td>8. Cuando Chobe</td>
<td>32</td>
<td>31</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9. Barotse</td>
<td>1007</td>
<td>1002</td>
<td>720</td>
<td>149</td>
</tr>
<tr>
<td>10. Luangwa</td>
<td>58</td>
<td>58</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>11. Luangue Bungo</td>
<td>263</td>
<td>263</td>
<td>235</td>
<td>152</td>
</tr>
<tr>
<td>12. Upper</td>
<td>253</td>
<td>252</td>
<td>186</td>
<td>0</td>
</tr>
<tr>
<td>13. Kabompo</td>
<td>82</td>
<td>82</td>
<td>70</td>
<td>8</td>
</tr>
</tbody>
</table>

* 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.
95% in the third scenario. They suggest that long term problems of water scarcity are more important than problems of flooding.

3.2. Specific locations

Fig. 6 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, already the second scenario could stop the water flow at Victoria Falls for nearly half of the year (August to January). The third scenario could lead 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 Victoria Falls is 400 m$^3$/s (SADC, 2008). This threshold is approached during the dry season even today.

Fig. 7 shows the effects on electricity production at the three largest production sites in the ZRB: Cahora Bassa, Kariba, and Kafue Gorge. Interestingly, the second scenario (2) 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.

However, in the third scenario (3) two of the three hydropower production sites experience dramatic losses. At Cahora Bassa the loss is 65%, at Kariba it is total. The Kafue hydroelectric power plant could nearly maintain its output with currently applied operation rules, but only in ways that violate current agricultural/fisheries and ecological objectives with respect to the Kafue Flats. The estimates for Kafue shown in Fig. 7 do not take into account such objectives. We think that maximizing power production entirely 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 sub-basin level, rather than specific locations. As discussed above, the Zambezi Delta could experience flow reductions in the order of 5% (scenario (1)) to 17% (scenario (2)) to 47% (scenario (3)). In the Kafue sub-basin, these reductions could be 9%, 31% and 77%, respectively. In the Barotse sub-basin, reductions of 1%, 29% and 85%, respectively could occur.

Fig. 8 indicates some striking differences in flow reductions across the three main wetlands in the ZBR. In the Barotse sub-basin the lack of hydraulic infrastructure for river regulation results in complete drying up in some months even in the second scenario. In the Kafue sub-basin peak flow is reduced but minimum flows can be kept at a higher level due to releases from the Itzhi-Tzhi 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

---

17 Results for the implications of the three scenarios for maximum flows are shown in the Companion Material E at Appendix.
18 Data for the year 2006 (ZESCO, 2008; DWA, 2008), 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).
19 At present, operation rules for the Kafue are defined by two dams. One dam upstream (Itzhi-Tzhi) serves as the main reservoir. From there water is released to the Kafue Gorge Dam 300 km downstream where there is only a small reservoir.
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. Hence it is very difficult to make reliable predictions of discharge behavior in that sub-basin. Nevertheless, compared to sub-basins with unregulated flows (e.g. Barotse sub-basin) we expect that flow reductions are more evenly distributed across the year.

From an environmental point of view especially the Kafue sub-basin faces acute water shortages. Required minimum environmental flows in the Kafue sub-basin are currently assumed to be at least 250 m$^3$/s during the low flow season (Denconsult, 1998). 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 sub-basin look rather dire despite the possibility of additional releases from the Itezhi Tezhi dam. For the Zambezi Delta a minimum flow of 250 m$^3$/s, as suggested by SADC (Denconsult, 1998), is met in all three scenarios. For the Barotse Plains, where our scenarios (2) and (3) assume large abstractions upstream, we were not able to find any proposals for minimum environmental flows in the literature.

Another important finding shown in Fig. 8 is that the effects of increasing water demand are clearly bigger than the effects of projected climatic changes. The grey shaded areas indicate how the entire range of potential climatic effects from no change compared to the status quo to the most extreme climate scenario, as described in Section 2.4, affects projected water availability.

### 3.3. 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 tensions. 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 a bispolute 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 change are important.

Table 3 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, 26% under
the second, and 71% under the third scenario. In the second scenario, the most negatively affected countries are Botswana and Namibia as well as Tanzania and Malawi. Under the third scenario, the most negatively affected countries are Zimbabwe, Zambia, Botswana, Namibia, and Angola. 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 50%, the shares of Zimbabwe and Zambia decline from 19% to 12% and 18% to 11%, respectively.

Similarly, national shares in total consumptive water demand in the ZRB are also likely to change (see Table 4). Because the first scenario (1) is driven mainly by population 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 (FAO, 2009).

Finally, we take a look at changes in water availability (runoff) and demand in combination. As shown in Fig. 9, 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). 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 the supply-demand divergence spectrum. Fig. 9 suggest that the greatest conflict potential is among Mozambique, Zambia and

Table 3
Runoff in the eight ZRB countries. For the definition of basin shares and catchment areas relevant to the individual countries see maps in the Companion Material B at Appendix.

<table>
<thead>
<tr>
<th>Country</th>
<th>Year 2000</th>
<th>Scenario (1)</th>
<th>Scenario (2)</th>
<th>Scenario (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m³/s %</td>
<td>m³/s %</td>
<td>m³/s %</td>
<td>m³/s %</td>
</tr>
<tr>
<td>Angola</td>
<td>493 5</td>
<td>491 5</td>
<td>372 5</td>
<td>122 4</td>
</tr>
<tr>
<td>Botswana</td>
<td>1048 11</td>
<td>1040 11</td>
<td>725 10</td>
<td>147 5</td>
</tr>
<tr>
<td>Malawi</td>
<td>439 5</td>
<td>349 4</td>
<td>303 4</td>
<td>163 6</td>
</tr>
<tr>
<td>Mozambique</td>
<td>2561 27</td>
<td>2423 26</td>
<td>2133 30</td>
<td>1364 50</td>
</tr>
<tr>
<td>Namibia</td>
<td>1025 11</td>
<td>1018 11</td>
<td>710 10</td>
<td>147 5</td>
</tr>
<tr>
<td>Tanzania</td>
<td>439 5</td>
<td>349 4</td>
<td>303 4</td>
<td>163 6</td>
</tr>
<tr>
<td>Zambia</td>
<td>1768 18</td>
<td>1703 19</td>
<td>1278 18</td>
<td>295 11</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>1860 19</td>
<td>1784 19</td>
<td>1339 19</td>
<td>326 12</td>
</tr>
<tr>
<td>Total</td>
<td>9634 100</td>
<td>9159 100</td>
<td>7163 100</td>
<td>2726 100</td>
</tr>
</tbody>
</table>

However, because of the scale differences between the two scenarios, the changes are not significant.

Table 4
National shares in total consumptive water demand in the ZRB (domestic, industrial and agricultural water demands, evapotranspiration from reservoirs and water transfers).

<table>
<thead>
<tr>
<th>Country</th>
<th>Year 2000 (%)</th>
<th>Scenario (1) (%)</th>
<th>Scenario (2) (%)</th>
<th>Scenario (3) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angola</td>
<td>0.2</td>
<td>0.2</td>
<td>0.0</td>
<td>12.6</td>
</tr>
<tr>
<td>Botswana</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Malawi</td>
<td>5.0</td>
<td>14.2</td>
<td>11.4</td>
<td>9.8</td>
</tr>
<tr>
<td>Mozambique</td>
<td>26.7</td>
<td>24.0</td>
<td>19.0</td>
<td>17.6</td>
</tr>
<tr>
<td>Namibia</td>
<td>0.5</td>
<td>0.4</td>
<td>0.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Tanzania</td>
<td>0.4</td>
<td>1.5</td>
<td>4.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Zambia</td>
<td>33.5</td>
<td>30.0</td>
<td>39.1</td>
<td>42.3</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>33.4</td>
<td>29.5</td>
<td>16.0</td>
<td>11.5</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Fig. 9. Changes in availability (runoff) and demand under scenarios two (2) and three (3). Note the scale differences between the two scenarios.
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.

4. Discussion

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 (2) the consequences could be quite dramatic, both in terms of local effects on wetlands, hydroelectric power production, agriculture, and tourism, as well as international political effects associated with large shifts in relative national river basins affected by water scarcity and flow variability (Drieschova et al., 2008) we think that the current institutional setting in the ZRB 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.

The (cautiously) good news emerging from our results is that changes in water demand are likely to have a much bigger effect on water availability in the ZRB than chaotic changes, even under pessimistic climate change scenarios, such as the SRES A2 scenario used for our projections. This finding implies that policy-makers are not primarily facing an up-hill battle against nature and large greenhouse gas emitters in other parts of the world that are causing climatic changes. Rather, the largest part of the prospective problem is likely to be “home-made”: policy-makers should thus be able to solve the problem by putting into place an effective international water allocation system that maximizes efficiency in consumptive and non-consumptive water use as the eight ZRB countries develop further.

Further research could couple our supply-demand model with an optimization modeling effort (for a suggestion of this kind see Tilmant et al., 2010). 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.

Finally, we think that the analytical approach developed in this paper, which enabled us to study the implications of changes in water demand and climate for water availability within a coherent modeling framework, can be very useful also for the analysis of other complex international freshwater systems that face similar challenges. Examples include the Nile, the Niger and Senegal rivers, and the rivers of the Aral Sea basin.

Appendix: Companion Material

Companion material for this article can be found in the online version, at doi:10.1016/j.gloenvcha.2011.04.001.

References


Denconseil, 1998. Sector Studies under ZACPAN. Zambezi River Authority, Danida, SADC.


Dirección Nacional de Aguas (DNA), Mozambique, 2008. Personal communication and data through SADC, Maputo.


