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Climate Change Implications for Water Resources in the Limpopo River Basin

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INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

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ABSTRACT

This paper analyzes the effects of climate change on hydrology and water resources in the Limpopo River Basin of Southern Africa, using a semidistributed hydrological model and the Water Simulation Module of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). The analysis focuses on the effects of climate change on hydrology and irrigation in parts of the four riparian countries within the basin: Botswana, Mozambique, South Africa, and Zimbabwe. Results show that water resources of the Limpopo River Basin are already stressed under today's climate conditions. Projected water management and infrastructure changes are expected to improve the situation by 2030 if current climate conditions continue into the future. However, under the four climate change scenarios studied here, water supply situations are expected to worsen considerably by 2030. Assessing hydrological impacts of climate change is crucial given that expansion of irrigated areas has been postulated as a key adaptation strategy for Sub-Saharan Africa. Such expansion will need to take into account future changes in water availability in African river basins.

Keywords: hydrology, water resources, irrigation, climate change, Limpopo River Basin

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ABBREVIATIONS AND ACRONYMS

IPCC	Intergovernmental Panel on Climate Change
WSM	water simulation model
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
WHC	water-holding capacity
AET	actual evapotranspiration
PET	potential evapotranspiration
FPUs	food-producing units
SRES	Special Report on Emissions Scenarios
CRU	Climate Research Unit
ET	evapotranspiration
C-CAM	Conformal-Cubic Atmospheric Model
IWSR	irrigation water supply reliability

1. INTRODUCTION

Climate change is expected to significantly affect water availability and use, with implications well beyond the water sector alone. In fact, many of the most serious effects of climate change on nonwater areas are mediated via water (Rogers 2008). For instance, crop growth relies on soil moisture which comes from rainfall or irrigation water. The Intergovernmental Panel on Climate Change (IPCC) identifies food systems as a key area vulnerable to climate change, along with water and three other sectors (IPCC 2007). Obviously, the importance of water to food production cannot be overstated.

Agricultural water use in the developing world is expected to face serious water scarcity from the combined effects of climate change and intensified competition for water from other sectors. This is especially true for developing countries with arid climates, lagging water infrastructure development, and rapidly increasing populations (OECD 2008). In several dry regions of the world, water scarcity has become a limiting factor for economic development. The Limpopo River Basin in Southern Africa is such a region.

The Limpopo basin is located in Southern Africa and covers an area of 416,296 square kilometers (km^2), spreading over four countries: Botswana, Mozambique, South Africa, and Zimbabwe (Figure 1). A large share of the basin lies in South Africa (45 percent), while the rest is divided roughly equally between Botswana (19 percent), Mozambique (21 percent), and Zimbabwe (15 percent). Total harvested crop area is 2.9 million hectares, and 91 percent of the area is cropped under rainfed conditions. The basin has a population of approximately 14 million, evenly divided between rural (52 percent) and urban (48 percent) areas (CPWF 2003).

Figure 1. Map of the Limpopo River Basin and the boundaries of four riparian countries

Source: Adapted from IDIS database available at http://dw.iwmi.org/idis_DP/home.aspx

The climate in the Limpopo River Basin ranges from tropical rainy along the coastal plain of Mozambique to tropical dry savannah and tropical dry desert further inland, south of Zimbabwe. Annual rainfall varies between 250 millimeters (mm) in the hot, dry western and central areas to 1,050 mm in the high-rainfall eastern escarpment areas. Rainfall is highly seasonal and unevenly distributed spatially, with about 95 percent occurring between October and April, typically concentrated in a number of isolated rain days and in isolated locations. Rainfall also varies significantly from year to year (CPWF 2003). These rainfall characteristics limit crop production because annual rainfall mainly occurs during a short summer rain season with high interannual variations. Flooding and droughts are major water-mediated impacts of climate change in the Limpopo River Basin. This paper focuses on the hydrological impacts of climate change and analyzes the potential consequences for irrigation.

2. MODEL DESCRIPTION

A recently developed semidistributed, global-scope hydrological model is linked to the existing water simulation model (WSM) of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) developed at IFPRI (Rosegrant, Cai, and Cline 2002). This paper utilizes the hydrological model and the WSM to analyze the impacts of climate change on hydrology and irrigation water supply in parts of the four riparian countries within the Limpopo River Basin.

Hydrological Model

The hydrological model is a semidistributed parsimonious model. It conducts continuous monthly simulations of soil moisture balance at 30 arc-minute grid cells. Gridded output on hydrological fluxes, namely evapotranspiration and runoff, are aggregated for subbasins and regions within the river basin and then incorporated into the WSM (Zhu, Ringler and Rosegrant 2010).

In the hydrological model, the Priestley-Taylor equation (Priestley and Taylor 1972) is used to calculate potential evapotranspiration:

$$PET = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G) \quad (1)$$

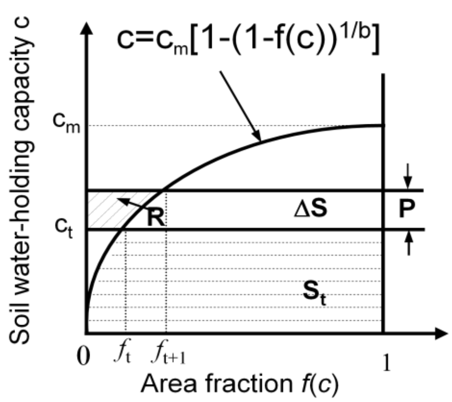
In equation (1), *PET* is potential evapotranspiration in mm a day^{-1}; the value of α is 1.26 for humid climate and 1.74 in arid locations, with relative humidity less than 60 percent in the month with peak evapotranspiration; Δ is the slope of the vapor pressure curve in *kPa °C-1*; γ is the psychometric constant in *kPa °C-1*; R_n is net radiation at the land surface in mm a day; and *G* is soil heat flux density in mm a day.

Soil moisture balance is conducted at each 30-minute grid cell using a single layer water bucket. To represent subgrid variability of soil water-holding capacity (WHC), we assume WHC varies within each grid cell, following a parabolic distribution function (Zhao 1992; Wood, Lettenmaier and Zartarian 1992; Arnell 1999).

$$f(c) = 1 - \left(1 - \frac{c}{C_m}\right)^b , \quad (2)$$

where $f(c)$ is the fraction of area in a grid cell that has WHC values lower than *c*; C_m is the maximum WHC value across all points within the grid cell; and *b* is the "shape parameter" that defines the degree of spatial variability of soil moisture holding capacity.

Figure 2. Distribution of soil water-holding capacity within a 30-minute grid cell



Note: In Figure 2, P is precipitation, R is runoff and S is soil moisture content.

As illustrated in Figure 2, the maximum amount of water that can be held in the grid cell is

$$S_m = \int_0^{C_m} [1 - f(c)]\,dc = \frac{C_m}{1+b} \quad (3)$$

Assuming that, at any time *t*, each point in the grid cell is either at WHC or at a constant moisture state *c* (Zhao 1992), the mean areal water storage *S* associated with soil water- holding capacity *c* at time *t* is

$$S_t = S_m \cdot \left[1 - \left(1 - \frac{c_t}{C_m} \right)^{1+b} \right] \quad (4)$$

With precipitation P_t and actual evapotranspiration AET_t from time period *t* to *t*+1, runoff is determined by the following equations:

If $c_t + P_t - AET < C_m$,

$$R_t = P_t - AET_t - \Delta S = P_t - AET_t - S_m \cdot \left[\left(1 - \frac{c_t}{C_m} \right)^{1+b} - \left(1 - \frac{c_t + P_t - AET_t}{C_m} \right)^{1+b} \right] \quad (5)$$

Otherwise, if $c_t + P_t - AET > C_m$,

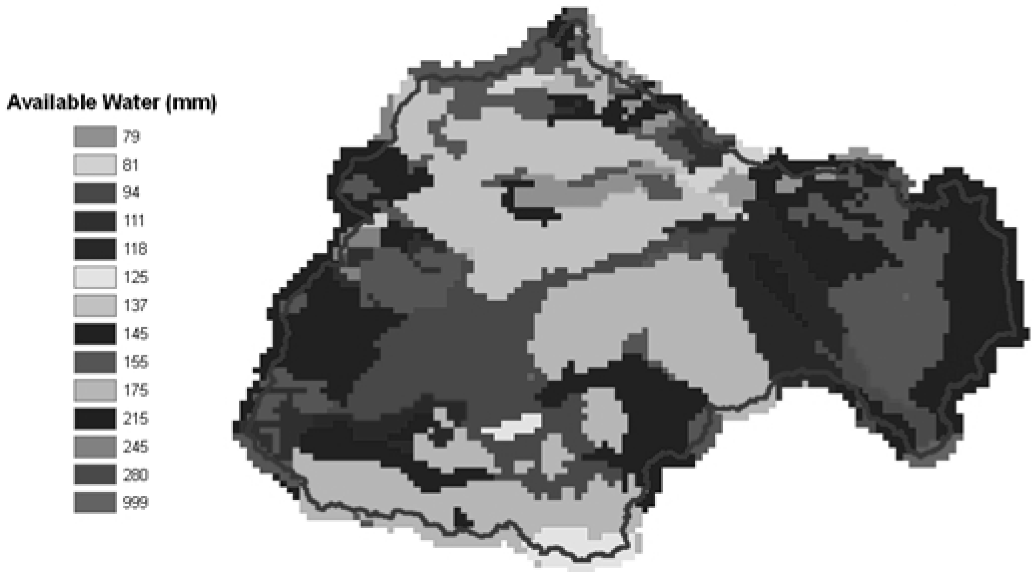
$$R_t = P_t - AET_t - (S_m - S_t) = P_t - AET_t - S_m + S_m \cdot \left[1 - \left(1 - \frac{c_t}{C_m} \right)^{1+b} \right] \quad (6)$$

The actual evapotranspiration (*AET)* is determined jointly by the potential evapotranspiration (*PET)* and the relative soil moisture state in a grid cell. A nonlinear equation is used to determine actual evapotranspiration, according to Kaczmarek (1993):

$$AET_t = PET_t \cdot \frac{5\frac{S_t}{S_m} - 2\left(\frac{S_t}{S_m} \right)^2}{3} \quad (7)$$

Field capacity serves as a practical measure of soil water-holding capacity. However, since the portion of soil moisture below wilting point does not affect soil moisture balance, we use available water capacity of soil as effective soil water-holding capacity. Available water capacity equals field capacity minus permanent wilting point. For the Limpopo study, the mean areal available water capacity values of 0.5 degree grid cells in the Limpopo River Basin is shown in Figure 3.

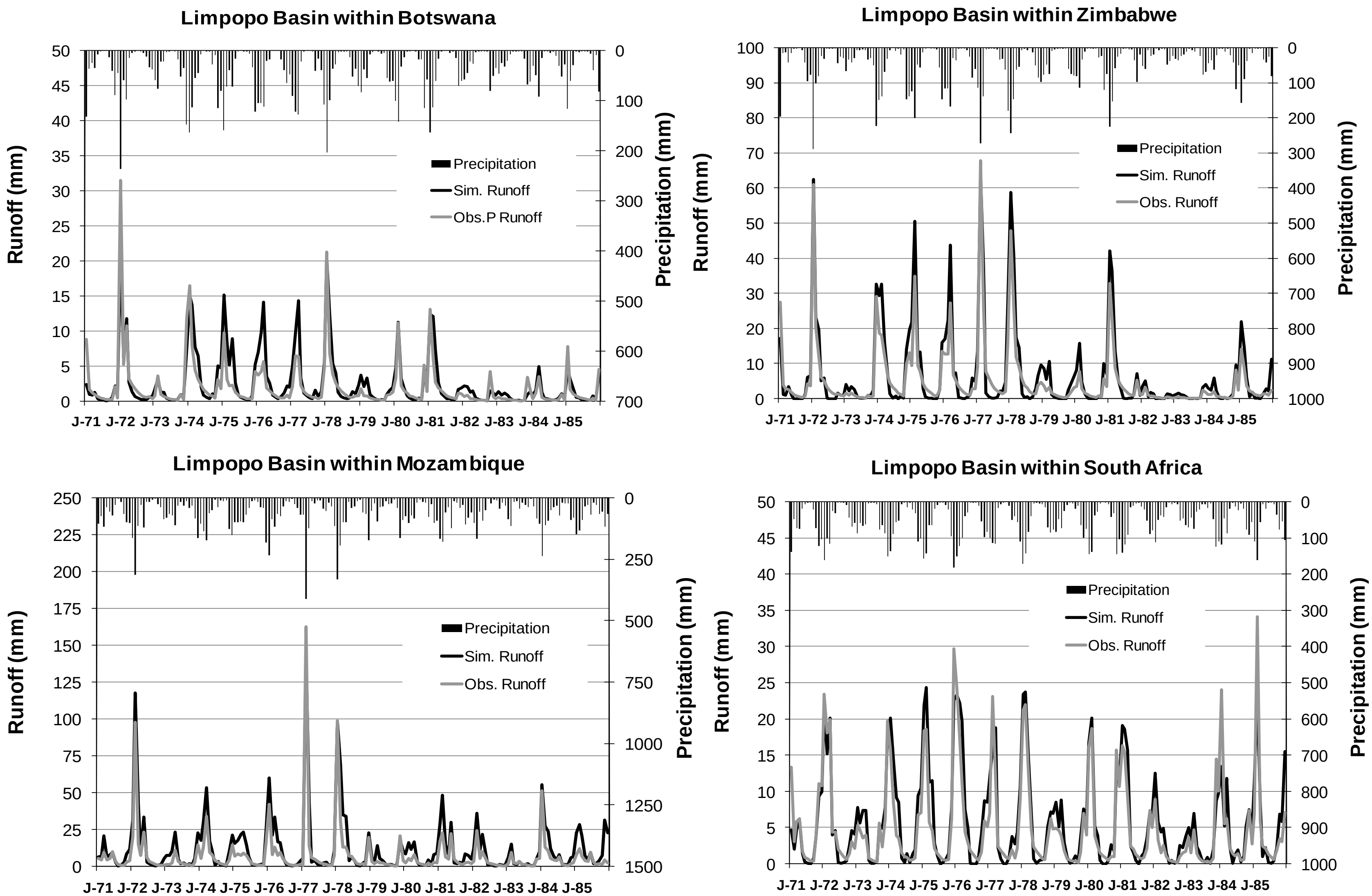
Figure 3. Available water by 30-minute grid cells within the Limpopo River Basin



Source: Authors.

Due to lack of flow observations, the simulated runoff of the WaterGAP model (Alcamo et al. 2003) is used to calibrate the shape parameter *b* in the model for grid cells in the Limpopo River Basin. We use a genetic algorithm (Goldberg 1989) to minimize the differences between the simulated runoff and "observed" runoff time series. Figure 4 shows simulated and observed runoff for the calibration period of 1971–80 and the validation period of 1981–85.

Figure 4. Runoff calibration for the Limpopo River Basin



Source: Authors

Notes: The upper bar charts show precipitation and the lower charts show simulated and observed runoff.

Water Simulation Model

The WSM of IMPACT simulates water demand, supply, and reservoir storage regulation of water at food-producing units (FPUs) (Rosegrant, Cai, and Cline 2002; Rosegrant et al. 2008). FPUs are at the scale below river basin and are the fundamental spatial unit for WSM. Long-term monthly effective precipitation, potential evapotranspiration, and internal renewable water resources are the hydrological drivers of WSM simulations, in addition to socioeconomic drivers such as population growth and economic growth that affect water demands. Climate change impacts are channelized to irrigation and crop production in the IMPACT model through changes in the hydrological drivers under climate change scenarios (such as precipitation, runoff and crop-specific potential evapotranspiration).

The Limpopo River Basin includes four FPUs, corresponding to the basin shares of the four riparian countries. Reservoir storage capacity, water diversion capacity, and basin irrigation efficiency are policy parameters that change over time to reflect investment in water infrastructure. For each FPU, the WSM simulates annually and seasonally how water supply meets demand using long-term (multi-decadal) monthly hydrology, projected water infrastructure capacities, and projected water demands of domestic, industrial, livestock and irrigation sectors, based on population and income growth, changes of irrigated areas, and improvement of water use efficiencies. The four FPUs within the Limpopo River basin are connected through upstream–downstream water transport.

3. CLIMATE CHANGE SCENARIOS

To assess the impacts of climate change on water availability and use in the Limpopo River Basin, we selected four greenhouse gas emission scenarios, namely A1FI, A2a, B1a, and B2a, from the scenario family in the IPCC Special Report on Emissions Scenarios (SRES). The scenario A family represents a future world with growth-focused policy objectives, while the B family represents eco-friendly policies. Scenario 1 represents more globally integrated development, while scenario 2 is more geopolitically divided, representing regional-oriented growth. In particular, the A1FI scenario describes a fossil-fuel intensive future, with coal, oil, and gas continuing to dominate the energy supply for the foreseeable future (IPCC 2000).

Climate projections by various general circulation models with these emission scenarios cover nearly the entire range of projected future global temperature changes (IPCC 2000). For each of the four emission scenarios, simulated mean monthly changes of precipitation and temperature from the baseline period 1961–90 to the future period of 2010-2039, were obtained from the IPCC Data Distribution Centre (http://www.ipcc-data.org/). These future precipitation and temperature data were simulated by the UK Hadley Centre global climate model, HadCM3. We choose 1961-90 as baseline period because this is the current WMO normal period and is recommended by IPCC as baseline period for climate change impact and adaptation assessment (IPCC-TGICA 2007).

The mean monthly changes of precipitation and temperature are downscaled to the 30 arc-minute grid cells within the Limpopo River Basin and imposed onto gridded 30 arc-minute monthly precipitation and temperature data of 1961–90 from the CRU TS2.1 global climate database developed by the Climate Research Unit (CRU) at the University of East Anglia (Mitchell and Jones 2005). The original 1961–90 CRU climate data forms the baseline climate condition. The baseline climate data and the constructed climate change scenario data are used by the hydrological model to simulate the responses of evapotranspiration and water availability under the baseline and the four climate change scenarios.

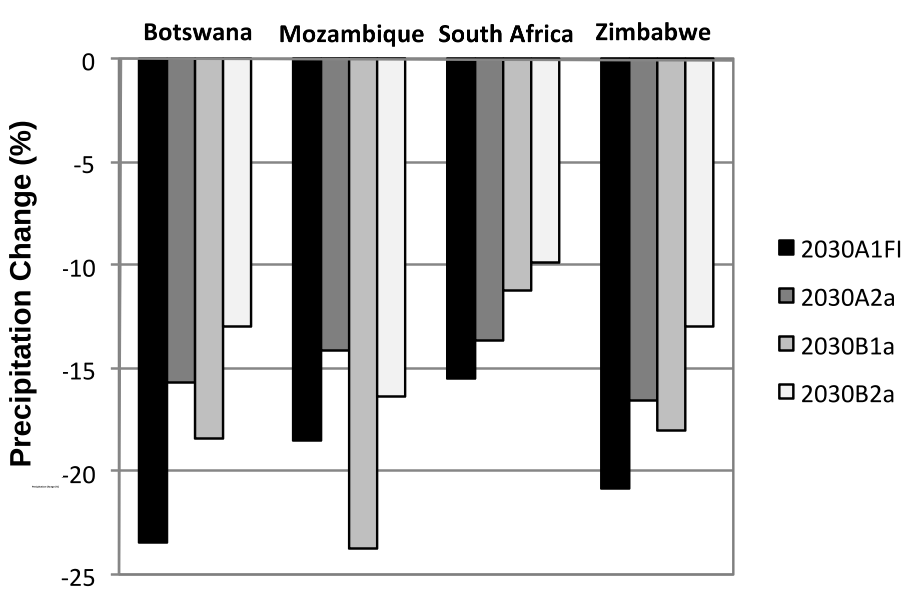
4. RESULTS AND DISCUSSION

As broadly discussed in the literature, climate change has important implications for water and agricultural systems. Altered precipitation patterns and higher temperatures affect water availability and agricultural water requirements. Changes of water availability affect water supply to various water-use sectors, including irrigation, suggesting uncertain and possibly reduced agricultural harvests. Although climate change is global, its water and agricultural impacts are local; they are expected to be most pronounced in arid and semiarid areas, such as the Limpopo River Basin.

Figures 5, 6, and 7 present changes in mean annual precipitation, potential evapotranspiration, and water availability for the four riparian countries within the Limpopo River Basin, under the four climate change scenarios for 2030, relative to the 1961–90 baseline climate. Water availability refers to total runoff, including groundwater recharge, in the FPU, also called internal renewable water. As Figure 5 shows, significant rainfall reductions are expected in all of the four riparian countries, ranging from 10 to nearly 25 percent, with changes varying significantly among different SRES scenarios. The highest percent reduction of rainfall is found for Botswana under the A1FI scenario for 2030, a 23.5 percent decrease from the historical mean, or a reduction of 85 mm per year. The lowest rainfall reduction, 9.9 percent, equivalent to 49 mm per year, is found for South Africa under the B2a scenario. Changes for other scenarios and countries fall in between these two values.

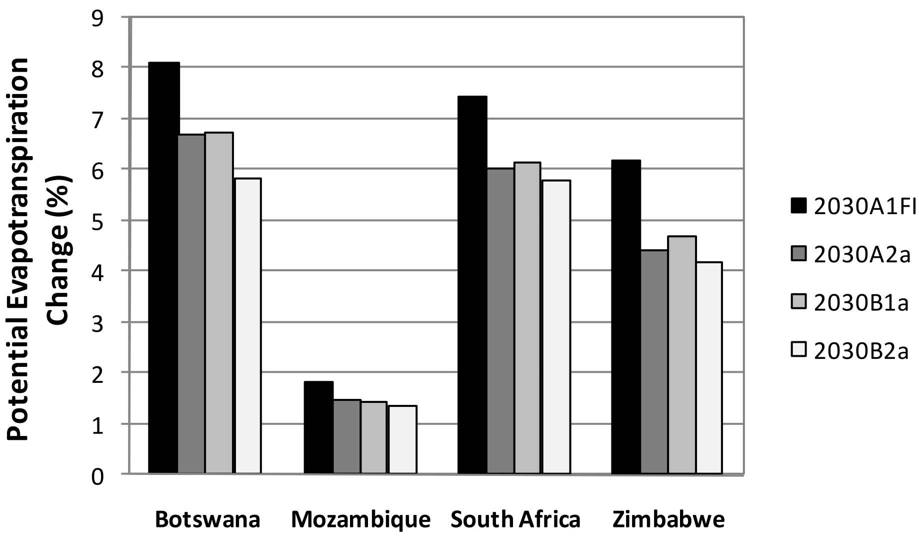
As shown in Figure 6, potential evapotranspiration (ET) is projected to increase for all scenarios and for all countries. Among the four scenarios, A1FI results in the highest increases of potential ET for all countries, primarily because the severest warming effects are brought about by the A1FI scenario and therefore raise potential ET most rapidly. On the other hand, scenario B2a is found to cause the lowest increase of potential ET for all four countries. Across the four countries, Botswana is expected to see the largest increase in potential ET, with an increase of 8.1 percent, compared with the historical mean under the A1FI scenario. Under the B2a scenario, the expected increase in potential ET is still 5.8 percent by 2030. The smallest changes are found for Mozambique, with an increase of potential ET below 2 percent for all scenarios.

Figure 1. Percent changes of mean annual precipitation in 2030 relative to 1961–90 under the four climate change scenarios



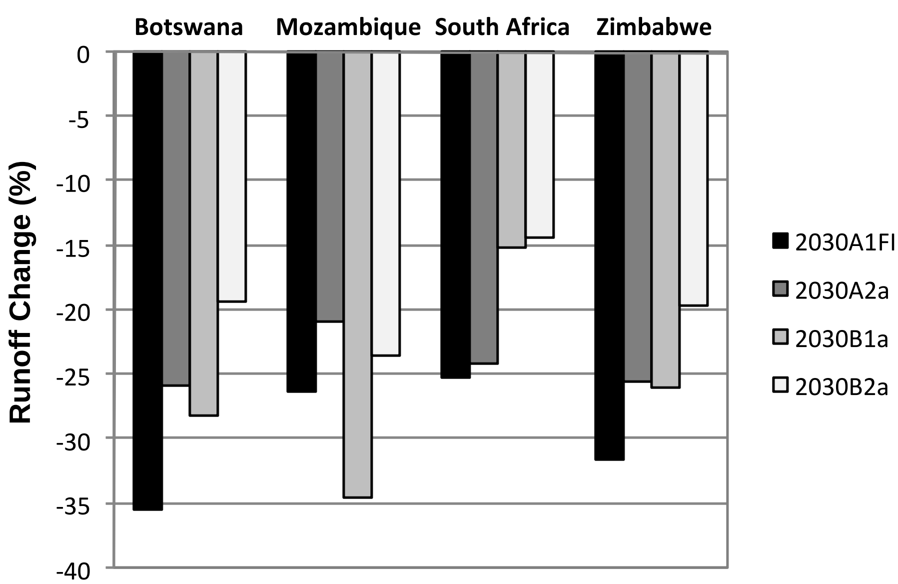
Source: Authors.

Figure 2. Percent changes of mean annual potential evapotranspiration in 2030 relative to 1961–90 under the four climate change scenarios



Source: Authors.

Figure 3. Percent changes of mean annual runoff in 2030 relative to 1961–90 under the four climate change scenarios



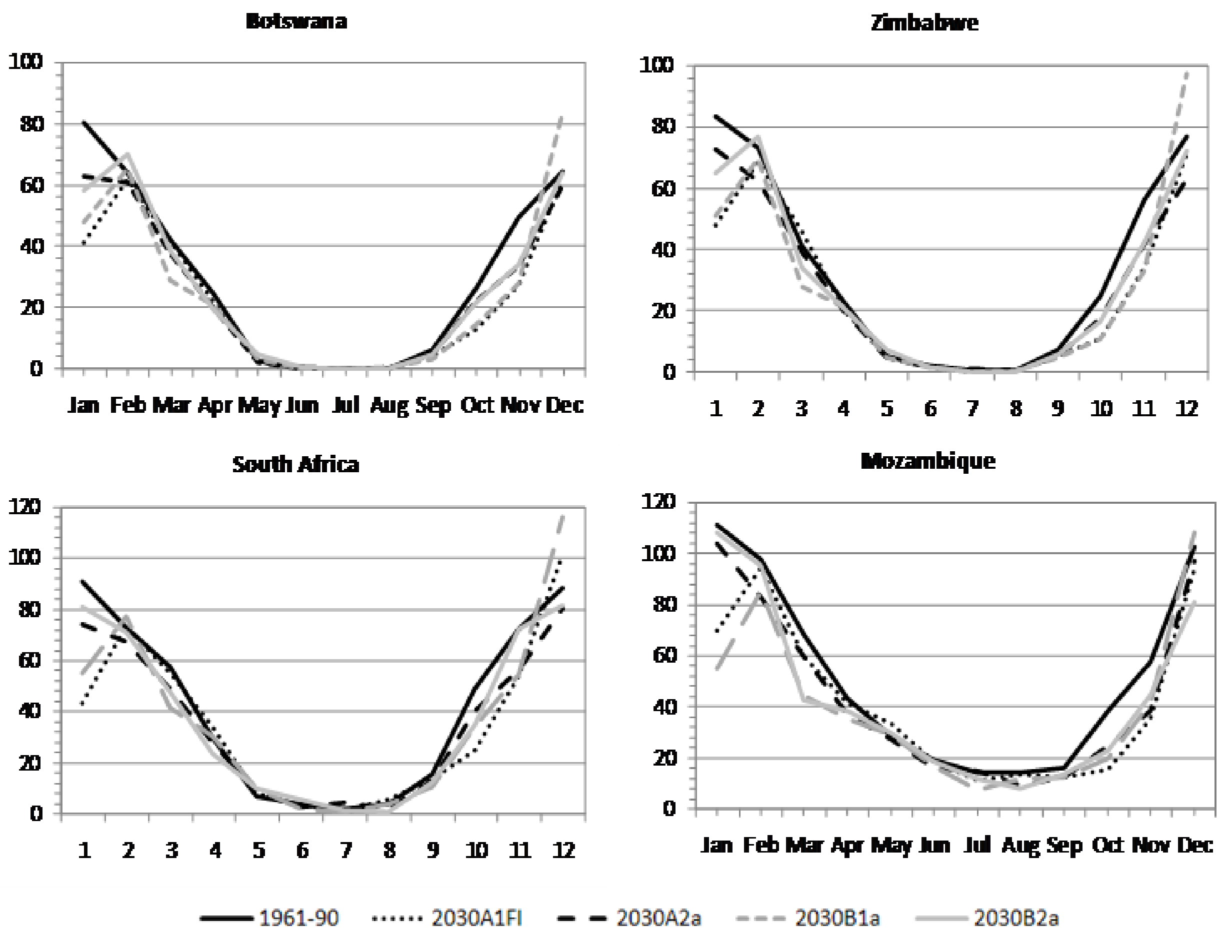
Source: Authors.

As shown in Figure 7, changes in mean annual runoff are larger than changes in precipitation. The largest declines are again found for the A1FI scenario and the smallest reductions for the B2a scenario, with the exception of Mozambique, which is projected to experience the largest water availability reduction under the B1a scenario and the smallest under the A2a scenario.

Decreased water availability might well result in more than just reduced water supply. De Wit and Stankiewicz (2006) found that for many African river basins a reduction in precipitation may also lead to a sharp decline in drainage density in addition to a decline in runoff. This implies that many smaller rivers or their tributaries may permanently dry up due to a decline in precipitation. This particularly threatens those rural areas that lack capacity to cope with changes in runoff regimes and where the risk of loss of perennial water is high.

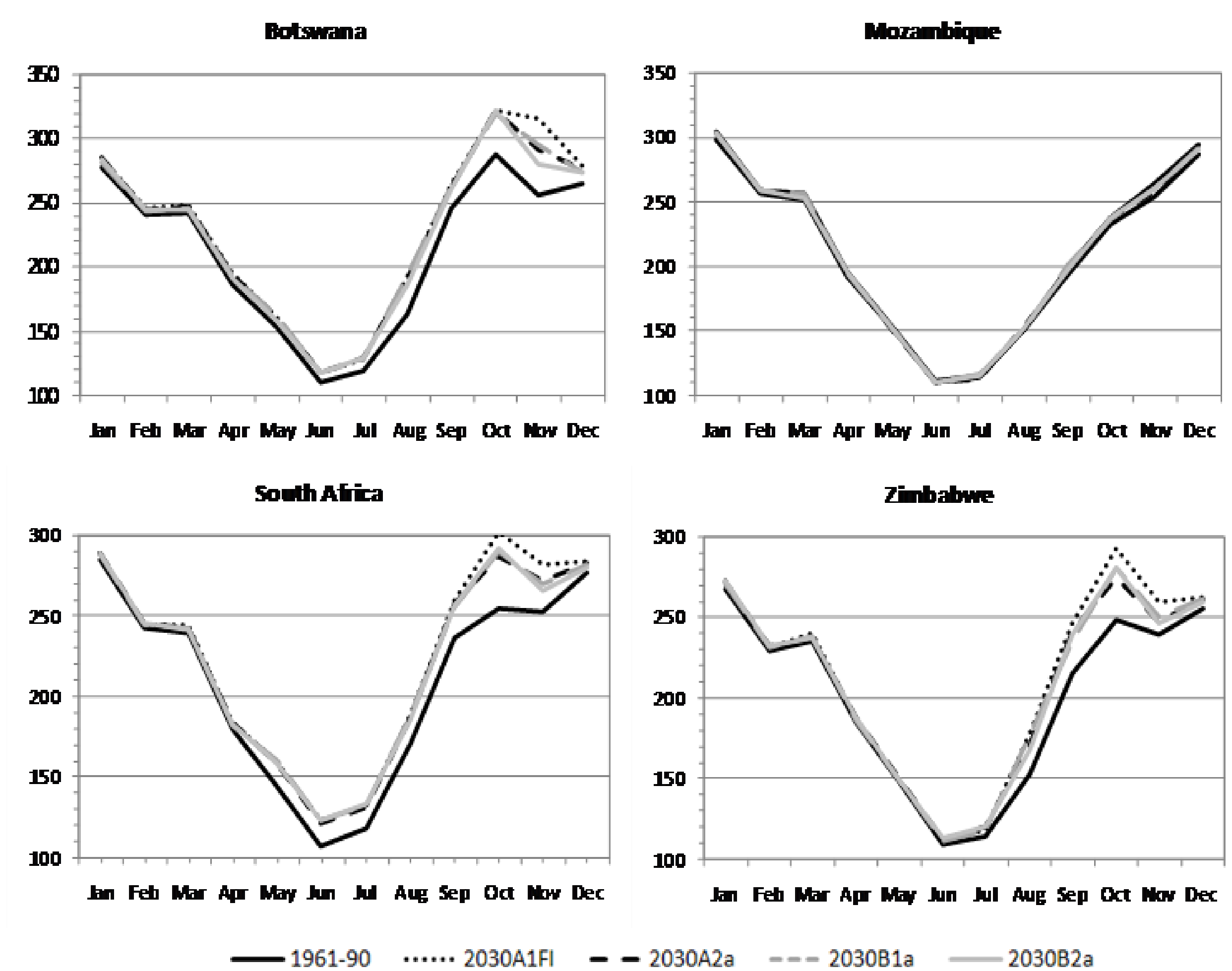
Given that annual crops depend on water supply in growing seasons, seasonal changes of hydrological variables under climate change are of particular importance for agricultural water use. Figures 8, 9, and 10 compare mean monthly precipitation, potential ET, and water availability between the 1961–90 baseline climate and the four climate change scenarios for 2030 for each of the four riparian countries of the Limpopo River Basin.

Figure 8. Mean monthly precipitation (mm) under the 1961–90 historical climate and climate change scenarios for 2030



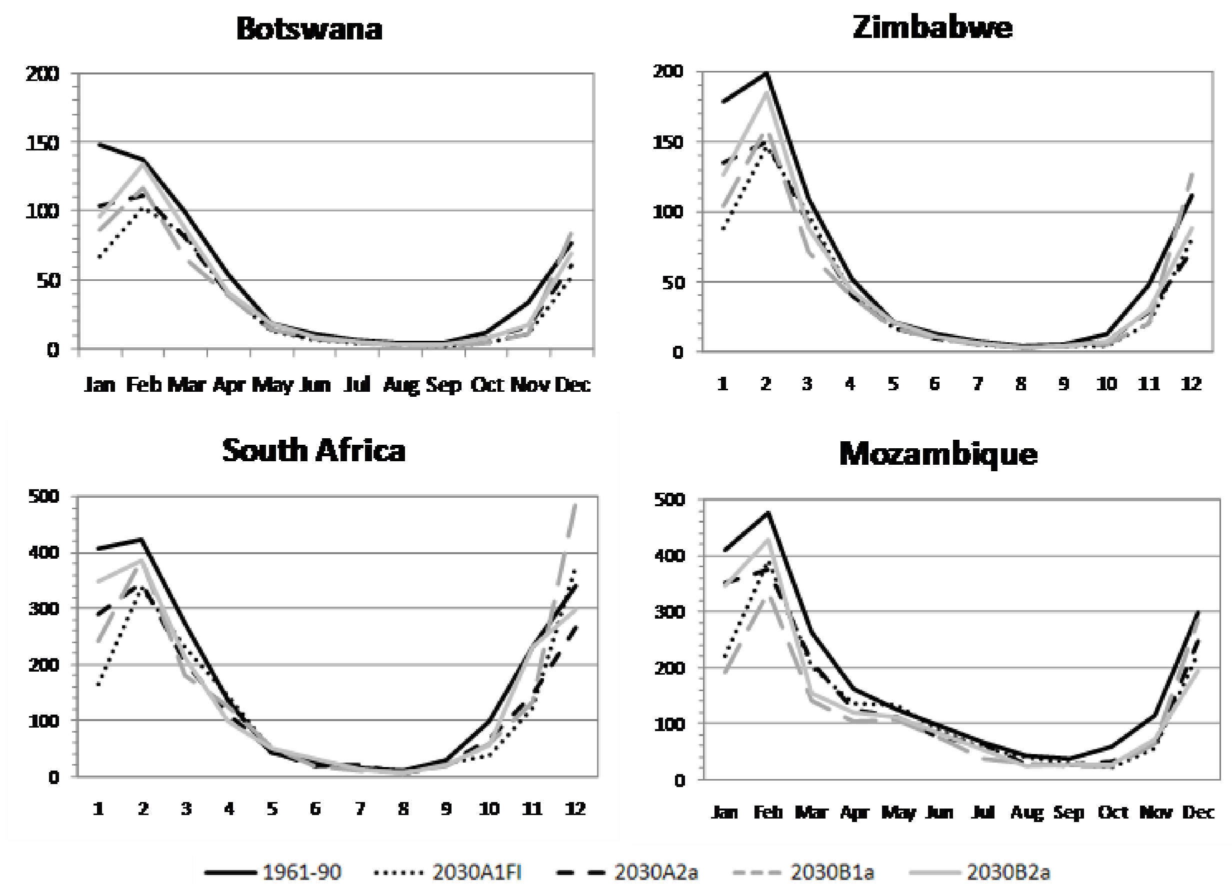
Source: Authors.

Figure 9. Mean monthly potential evapotranspiration (mm) under the 1961–90 historical climate and climate change scenarios for 2030



Source: Authors.

Figure 10. Mean monthly runoff (10^6 m^3) under the 1961–90 historical climate and climate change scenarios for 2030



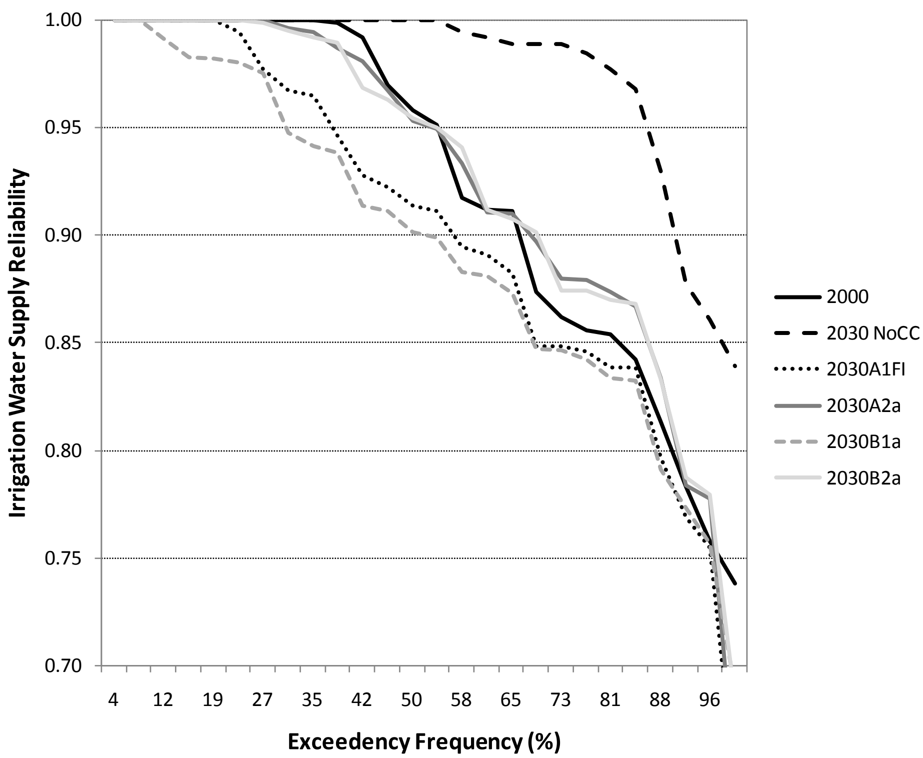
Source: Authors.

Figure 8 presents a decline in rainfall during the rainy season combined with very little change in the dry season when there is virtually no rain. The largest reduction in rainfall amount is seen in January for the A1FI and A1a scenarios, ranging from 35 to 48 mm and 32 to 56 mm, respectively. The other two scenarios show smaller rainfall declines. Interestingly, scenario B1a consistently shows a rainfall increase in December for the four countries, ranging from 6 to 21 mm. These monthly rainfall changes do not indicate a major change in the rainfall pattern over the Limpopo River Basin by 2030. However, incorporation of these changes in water resources and agricultural planning is important as even small changes in long-term rainfall patterns will require changes in crop varieties, planting dates, and cropping patterns. Moreover, reservoir storage will change under changes in monthly precipitation patterns, as a result of which irrigation scheduling will need to be adjusted.

In Figure 9, we find that potential ET is consistently higher in 2030 relative to the 1961–90 baseline, with the largest increases occurring in September through November. Unlike the other three countries, Mozambique shows only slight changes in potential ET. The water availability changes in Figure 10 show patterns similar to changes in rainfall, with the largest changes occurring in January. Of all the scenarios, scenario A1FI leads to the largest decline in water availability for most rainy months for all countries. Scenario B1a leads to increased water availability in December for all countries except Zimbabwe. Based on a downscaled Regional Climate Model called the Conformal-Cubic Atmospheric Model (C-CAM), Midgley et al. (2007) find that streamflows are projected to shift between one and two months earlier over much of Limpopo. They also find considerable changes and uncertainty in the transitional area between summer and winter rainfall regions, presenting major challenges to water resource planners. We find similar results for streamflows for the B1a scenario and considerable variation in precipitation for January and February.

Based on the hydrological simulations for the four climate change scenarios, the WSM of IMPACT calculates irrigation water supply reliability for each scenario. Figure 11 provides the exceedence probability for irrigation water supply reliability (IWSR) in the Limpopo River Basin under the 1961–90 baseline climate and the four climate change scenarios for 2030. IWSR is defined as the ratio of irrigation water supply to irrigation water requirement, on an annual basis. The exceedency frequency x of a given IWSR value means that the chance of IWSR being higher than the given IWSR value is not greater than *x*.

Figure 11. Exceedence probability of irrigation water supply reliability in Limpopo River Basin under historical (1961–90) climate and climate change scenarios for 2030



Source: Authors.

Results show that the water resources of the Limpopo River Basin are already stressed under 1961–90 climate conditions. For instance, there was less than a 50 percent chance that the IWSR indicator would be higher than 0.95 under irrigation demand in 2000, which is the baseline year in the IMPACT model. Projected improvements in basin irrigation efficiency and increases in irrigation infrastructure capacity (storage, withdrawal, and conveyance) are expected to improve the irrigation situation in the basin by 2030 under historic climate conditions (1961–90). However, under alternative climate change scenarios, conditions are expected to worsen significantly compared to the situation in 2030 without climate change.

5. CONCLUSIONS

The impacts of climate change on the hydrological and water resource systems of the Limpopo River Basin were analyzed with a semidistributed hydrological model and the water simulation module of IMPACT, using four HadCM3 model projections for four SRES emission scenarios compared to the 1961–90 baseline climate. Significant reductions of annual rainfall and water availability by 2030 are found for all four climate change scenarios and for all countries. The A1FI scenario is found to lead to the largest decline in rainfall and water availability. Changes in river hydrology can reduce irrigation water supply and reliability, adding an additional constraint for future irrigation development in the basin. Even small, permanent changes in precipitation patterns need to be incorporated in water resource and agricultural planning as they will require changes in crop varieties, planting dates, and cropping patterns; placing new requirements on both agricultural research and development and extension services. Moreover, reservoir storage will change under changes in monthly precipitation patterns, as a result of which irrigation scheduling will also need to be adjusted.

Improvement in water infrastructure and management can potentially mitigate the adverse effects of climate change, although the mitigation effects may not compensate for the effects caused by climate change. Assessing hydrological impacts of climate change is crucial given that expansion of irrigated areas has been postulated as one key adaptation strategy for Sub-Saharan Africa. Such expansion will need to take into account changes in availability of water resources in African river basins.

REFERENCES

Alcamo, J., P. Doll, T. Henrichs, F. Kaspar, B. Lehner, T. Rosch, and S. Siebert. 2003. Development and testing of the WaterGAP2 global model of water use and availability. *Hydrological Science Journal* 48 (3): 317–337.

Arnell, N.W. 1999. A simple water balance model for the simulation of streamflow over a large geographic domain. *Journal of Hydrology* 217: 314–335.

CPWF (Challenge Program on Water and Food). 2003. *Limpopo Basin Profile: Strategic research for enhancing agricultural water productivity*. Colombo, Sri Lanka.

De Wit, M., and J. Stankiewicz. 2006. Changes in surface water supply across Africa with predicted climate change. *Science* 301: 1917–1921.

Goldberg, D. E. 1989. *Genetic algorithms in search, optimization, and machine learning*. Boston: Kluwer Academic Publishers.

Mitchell, T. D., and P. D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology* 25: 693–712.

IPCC (Intergovernmental Panel on Climate Change). 2000. Emissions scenarios 2000, Special report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

IPCC-TGCIA (IPCC Task Group on Scenarios for Climate Impact Assessment). 2007. General guidelines on the use of scenario data for climate impact and adaptation assessment. Version 2. Available at: http://www.ipcc-data.org/guidelines/TGICA_guidance_sdciaa_v2_final.pdf

Kaczmarek, Z. 1993. Water balance model for climate impact assessment. *Acta Geophysica Polonica* 61 (4): 423–437.

Midgley, G. F., R. A. Chapman, P. Mukheibir, M. Tadross, B. Hewitson, S. Wand, R. E. Schulze, T. Lumsden, M. Horan, M. Warburton, B. Kgope, B. Mantlana, A. Knowles, A. Abayomi, G. Ziervogel, R. Cullis, and A. Theron, 2007. *Assessing impacts, vulnerability and adaptation in key South African sectors: A background study for the Long Term Mitigation Scenarios assessment*. Energy Research Centre, Cape Town.

OECD (Organization for Economic Cooperation and Development). 2008. *OECD environmental outlook to 2030*. Paris.

Priestley, C.H.B. and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. *Monthly Weather Review* 100: 81-92.

Rogers, P. 2008. Coping with global warming and climate change. *Journal of Water Resources Planning and Management* 134 (3): 203–204.

Rosegrant, M.W., S. Msangi, C. Ringler, T.B. Sulser, T. Zhu, and S. A. Cline. 2008. *International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description*. Washington, D.C.: International Food Policy Research Institute.

Rosegrant, M., X. Cai, and S. A. Cline. 2002. *World water and food for 2025: Dealing with scarcity*. Washington, D.C.: International Food Policy Research Institute.

Wood, E. F., D. P. Lettenmaier, and V. G. Zartarian. 1992. A land-surface hydrology parametrization with subgrid variability for general circulation models. *Journal of Geophysical Research* 97 (D3): 2717–2728.

Zhao, R. J., 1992. The Xinanjiang model applied in China. *Journal of Hydrology* 135: 371–381.

Zhu, T., C. Ringler, and M. W. Rosegrant. 2010. *Development and validation of a global hydrology model for climate change impact assessment.* International Food Policy Research Institute, Washington, D.C. Photocopy.

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