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Impact of climate change on crops, irrigation and hydropower in the Zambezi River Basin

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Abstract

The past reliance on historical observed weather patterns for future investment in basic infrastructure planning (e.g., irrigation schemes, hydropower plants, roads, etc.) has been questioned considerably in recent years. For this reason, efforts to study the impacts of a changing future climate based on climate projections from global circulation models has been popular, where the coupled model intercomparison project models, used in the Intergovernmental Panel for Climate Change Assessment Reports, are typically used. Studies tend to focus either on climate sensitivity, ignoring specific global circulation models predictions, or an effort is made to select a set of global circulation models for use in an .../

Keywords: climate Change, Zambezi, southern Africa, investment risk, system model, water resource

JEL classification: Q54, O44, O55

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impact study. Here, we present a method for quantifying the impacts on biophysical measures (surface water supply, crop production, flooding events, and hydropower generation) of the Zambezi River Basin countries using a large pool (6,800) of climate projections, which are based on the full set of the CMIP-3 GCMs (global circulation models) and projected to 2050. This study estimates that, due primarily to increases in near-surface temperatures and reductions in precipitation, the Zambezi River Basin is will experience risks associated with drought. Surface water availability will reduce, rainfed crop yields will decrease, irrigation demand will increase, damaging floods will happen more often, and hydropower generation will decrease basinwide—although these results vary considerably both spatially and throughout the distribution of future climates. Studies like this can help decision makers develop an informed risk-based strategy for national policy decisions and help to direct further studies where local detail is considered.

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Figures appear at the end of the paper.

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1 Introduction

There has been a growing interest in a better understanding of the economic impacts of climate change on future investment in areas with a large potential for basic infrastructure growth. Due to the lack of existing development in these areas, options for planning are numerous and the present decisions are principal to future economic progress. Also, these areas tend to have a limited set of historical record, both spatially and temporally, which presents problems. Past studies have typically involved one of two approaches: (1) a climate sensitivity analysis on existing or planned infrastructure using a wide, unguided range of future climate possibilities, or (2) use of select global circulation models (GCMs) from the coupled model intercomparison project (CMIP) used in the Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Reports (AR4) applied directly to assess the impacts of climate change resulting in a limited set of future scenarios.

In this study, we present a method for quantifying the impacts on biophysical measures (surface water supply, crop production, flooding events, and hydropower generation) of the Zambezi River Basin (ZRB) countries using a large pool (6,800) of climate projections, which are based on the full set of the IPCC AR4 GCMs. The ZRB in southern Africa provides a problem area suitable for this type of study because of the hydrologic and agricultural importance for the people who live in the basin and due to previous studies concluding that the impact of climate change will be economically significant (World Bank 2010).

This study is divided into four interdependent efforts: climate scenario analysis, surface water modeling, crop modeling, and water resource modeling. This division is used in the following sections, namely materials and methods in Section 2, results and discussion in Section 3, and the conclusion in Section 4.

1.1 Spatial scale of the analysis

The majority of the basin is contained in four countries: Malawi, Mozambique, Zambia, and Zimbabwe. Regionalization, spatial resolution and aggregation are adapted separately to meet two different sub-goals of this study. The first, water resource modeling, splits the ZRB into 29 hydrologically significant sub-basins as shown in Figure 1. The second regionalizes the study area using politically and economically significant boundaries—primarily by country borders and secondarily splitting each country into regions—as shown in Figure 2.

1.2 Climatology overview

The Zambezi is a large, multi-country basin that spans portions of southern Africa characterized by great seasonal climatic swings, from rainy to dry, which are highly variable from year to year. The climate in these four countries varies from hyper-arid in western Zambia (Kalahari Dessert) to semi-humid in Malawi and northern Mozambique. This region experienced food shortages caused primarily by drought in the 1980s and 1990s, which stressed the importance of research and planning in the area of food and water security. Mean annual precipitation ranges from about 500 to over 1,200 mm/year, with an average for the basin of about 925 mm/year. The larger amounts of rainfall occur around Lake Malawi in Tanzania while the west of the basin, near Botswana and Namibia is drier (FAO 2011). The seasonality in the basin is characterized by a strong, four to six month rainy season when the

Inter-tropical convergence zone moves over the basin from the north around October and continues through the valley until around March (Beilfus and dos Santos 2001).

1.3 Biophysical background

Agriculture is essential for most these economies and accounts for a significant portion of GDP, including about 50% in Zimbabwe and 20% in Mozambique. 85% of the 5.2 million ha of cultivated land in the ZRB is contained in Malawi, Zambia, and Zimbabwe—only about 180,000 ha of which are equipped for irrigation (World Bank 2010).

Agriculturally the year is split into two productive seasons, a wet summer season and a dry winter season. The average cereal yield is about 1 tonne/ ha basinwide, while some estimate a potential irrigated yield of 5 to 8 tonnes/ha (World Bank 2010). Over 100 irrigation projects have been proposed in the basin, which would in total increase the equipped irrigated area by 366,000 ha, effectively tripling the irrigated area. Still, irrigated agriculture in the basin would remain far short of the total potential, which FAO estimates to be more than 3 million ha (Tilmant et al. 2010). Given the importance of agriculture to local economies, the need for food security, current dependence on subsistence agriculture, and the irrigation potential in the basin, investment in irrigation infrastructure will be an important issue in future planning.

Hydropower is another greatly untapped resource in the basin. Currently there is nearly 5,000 megawatt (MW) of installed hydropower generation capacity in the region, while the potential is estimated to be about 13,000 MW (World Bank 2010). Although hydropower has many advantages compared to other energy sources, there are many challenges as well: environmental sensitivity, complications related to reservoir filling, dependence on an uncertain climate, high capital costs of the infrastructure, and losses through evaporation, which are estimated by Beck and Bernauer (2011) to be as large as 10% of total potential basin flow, relative to a river with no manmade reservoirs). Given the high demands for electricity, a total of 53 projects have been proposed which would increase installed capacity by 7,300 MW for a potential production of firm power from 22,776 to 43,000 GWh/year, and increase average energy production from 30,000 to 60,000 GWh/year (World Bank 2010).

2 Material and methods

2.1 Climate scenarios

Monthly near-surface temperature and precipitation data at a half-degree by half-degree spatial scale were obtained from the Climatic Research Unit (CRU) of East Anglia (Mitchell and Jones 2005). This data is available for 1901-2002, but only the data from 1951 to 1990 was used in this study. Daily climate data, required for the crop modeling, was sourced from the Land Surface Hydrology Research Group at Princeton University (Sheffield et al. 2006) in August 2011. This data is at a scale of 1 degree by 1 degree and is corrected to match the CRU mean monthly data.

The future climate scenarios used in this study are based on GCM ensemble results from the CMIP-3 but are expanded to represent a larger range of possible outcomes following that of previous work (Schlosser et al. 2011). The MIT integrated global systems model (IGSM) (Reilly et al. 2012) developed near-surface temperature and precipitation projections to 2050 at the zonal spatial scale. A Taylor expansion technique, described by Schlosser et al. (2011), was used to expand from the zonal level of detail in the longitudinal direction. This

transformation requires the construction of climate-change pattern kernels, which vary through time as global temperature changes. The full ensemble of climate change projections is produced through the numerical hybridization of the IGSM zonal trends with pattern kernels of regional climate change from the IPCC AR4 models. This ensemble of future climate projections is called hybrid frequency distributions (HFDs). Using this framework, 6,800 climate projections are produced for each of five CO₂ emissions policy scenarios although only the ‘unconstrained CO₂ emissions’ scenario is used in this analysis. In order to reach a reasonable computation time for all subsequent modeling, the number of projections was reduced using the methods described in Arndt et al. (2012), which reduced the climate projection pool to 421 statistically significant scenarios. The changes in climate were calculated as changes in precipitation and near-surface temperature and were then applied to the historical data on a monthly basis maintaining the daily distribution of precipitation by adding the changes proportionally by daily intensities. In this study, future climate changes from 2011 to 2050 are used in the modeling efforts described in the remainder of this section. Although climate change is predicted to be more drastic after 2050, a 40-year planning horizon is apt for investment decisions.

2.2 Runoff model

Runoff modelling converts the climate changes into changes in surface water availability important for the water resource modeling endeavour. Surface water runoff was modeled with the rainfall-runoff model CLIRUN-II, the latest available model in a family of hydrologic models developed specifically for the analysis of the impact of climate change on runoff, first proposed by Kaczmarek (1993). CLIRUN-II models runoff with a lumped watershed defined by climate inputs and soil characteristics averaged over the entire watershed, simulating runoff at a gauged location at the mouth of the catchment. For this analysis, a monthly time step is used to simulate the runoff from provided weather variables.

CLIRUN-II has adopted a two-layer approach following the framework of the SIXPAR hydrologic model (Gupta and Sorooshian 1983, 1985). Although CLIRUN-II can model headwater catchments or interflow catchments, interflow catchments were modeled in this study for the sake of accuracy in the calibration process. In the observed runoff data, many of the interflow basins had negative flows over long periods likely caused by the many wetlands in the ZRB. Negative flows cannot be modeled in CLIRUN-II. An extension to CLIRUN-II, ‘CLIRUN-II-WET’, was developed to better model the losses caused by the wetland areas. The model simulates wetland hydrology based on the work of Sutcliffe and Park (1987) for the White Nile Sudd wetland, Yates and Strzepek (1998) for the White Nile wetlands generally, and Kashaigili et al. (2006) for the Usangu Plains wetlands in Tanzania. The wetland area is modeled in each catchment using a reservoir-based hydrologic response, where the estimated evapotranspiration (ET) and runoff at the catchment is used to simulate the water balance including inflow, outflow, and storage.

A unique conditional calibration procedure was used to determine the coefficient values that characterize each of the 29 catchments. This parameter estimation requires observed runoff at each catchment outflow. The observed runoff was provided by Charly Cadou through personal communication.

2.3 Crop model

The purpose of the following analysis is to assess the changes in crop yields (to be used in economic models in subsequent work to assess investment opportunity) and estimate changes

in irrigation demands to feed into the water resource model. Nine crops were chosen to represent the agriculture sector across all four countries. The nine crops are maize, wheat (used to represent other cereals), cassava (used to represent root crops), horticulture, tobacco, cotton, sugarcane, and tea (used to represent other export crops). A variation of the CliCrop model (Fant et al. 2012) was used to estimate the variability of the impact on crop water requirement and rainfed crop yields caused by the range of climate projections present in the HFDs.

The CliCrop model is an attempt to balance accuracy and simplicity with an emphasis on estimating the effects of the changing climate on irrigation demand and rainfed crop yield. CliCrop is a generic crop water deficit model. The version of CliCrop used in this study uses the soil properties and precipitation amount to calculate the infiltration using a version of the USDA Curve Number method (Bureau of Reclamation 1993). The model then calculates the soil moisture in each soil layer, calculates the amount of moisture allowed to percolate into the deep soil layers, and calculates a yield coefficient at the end of the growing season.

The effects of climate on crop production are modeled by estimating water stress on crops. Water stress is related to the estimate of ET, and more specifically, the extent by which the actual ET (AET) falls short of the crop demand ET (DET). In CliCrop a yield ratio (Y) is reported as a measure of water stress. Y is calculated from a set of yield ratios (y) representing the ratio of actual yield to a theoretical maximum yield, and is based on the ratio of AET to PET. The theoretical maximum yield is the yield obtained in the complete absence of water stress. Four yield ratios are calculated, one for each of the four development stages (d): initial, crop development, mid-season, and late season (Allen et al. 1998). y is weighted using a yield response factor (K), as follows.

$$y_d = 1 - K_d \left(1 - \frac{AET_d}{DET_d} \right) \quad (1)$$

The final reported yield ratio (Y) is calculated using the multiplicative model proposed by Rao and Sarma (1988).

$$Y = \prod y_d \quad (2)$$

Here, Y represents the ratio of actual yield to the theoretical maximum yield due to water stress, and therefore is unitless. This value is reported for each year of the simulation.

Actual ET is calculated as a function of precipitation, temperature, PET, soil moisture, root depth, crop type, and atmospheric CO₂ concentration. This calculation is done each day, for each soil layer. The model uses a daily form of the modified Hargreaves equation to calculate PET (Farmer et al. 2011). Soil moisture is calculated using a bucket-type scheme similar to the method used in the soil and water assessment tool, SWAT model (Neitsch et al. 2005), details are given in Fant et al. (2012). Crop specific parameters similar to the ones used in CROPWAT (Allen et al. 1998) are used in this calculation, as well as in the calculation of the daily ET crop demand. The atmospheric CO₂ concentration affects the daily ET crop demand, which follows the methods explained in Rosenzweig and Iglesias (1998). The crop parameters are adjusted from year to year using methods developed by Allen et al (1998), adjusting crop ET demand, and Wahaj et al. (2007), adjusting crop stage durations, which estimate the local crop's reaction to deviations from 'average' climate conditions.

The rainfed yield shocks are used in economic modeling in subsequent studies and the changes in irrigation demand are used in the water resource model, discussed next.

2.4 Water resource system model

The water resource modelling in this study attempts to simulate the sequence of existing and planned reservoir activity and demand nodes along the system. The focus of this modeling effort is on three main indicators of future impact: assessing possible changes in flood risks; the operation of major hydropower plants, both existing and planned; and maintaining agricultural production, taking into account changing irrigation demands over time. Three demand types, or nodes, are modeled throughout the system, which are in competition for water dependent on the sequence (upstream/downstream). The node types are municipal and industrial (M&I) water use, hydropower generation, and irrigation withdrawal. M&I demands increase over time consistent with projections used in the World Bank Economics of Adaptation to Climate Change study (World Bank 2009). Hydropower production is calculated for existing and planned projects based on expected investment and construction schedule using the relevant scenario data from the World Bank (2010) study. And the existing and planned irrigation infrastructure changes over time are also obtained from World Bank (2010). The analysis projects perturbations, or ‘shocks,’ to hydropower production and irrigated crop yield resulting from these conflicts from 2011 to 2050 across the ZRB using the Water Evaluation and Planning (WEAP) model (Sieber and Purkey 2007), software for integrated water resources planning. WEAP provides a mathematical representation of the river basins encompassing the configuration of the main rivers and their tributaries, the hydrology of the basin in space and time, existing as well as potential major schemes, and their various demands for water.

Computations are performed on a monthly time scale for 40 years for a base-case scenario (i.e., no climate change) and the HFD climate change scenarios. Each climate change scenario is characterized by unique inflows, evaporation, and irrigation demand. Unmanaged inflows are modeled using CLIRUN-II; the output runoff projections from CLIRUN-II are used as the available runoff in WEAP.

Surface water inflows from CLIRUN-II were used as inflows to an aggregated river in each basin modeled in WEAP. Water supplies and demands are linked between upstream and downstream basins, and reservoirs, irrigation, and municipal and industrial demand locations were sequenced consistent with their actual locations. If hydropower is generated in a basin, the reservoir and turbine characteristics are calibrated to ensure that the power produced is validated with historical values. While the reservoir and aggregate demands are physically located within each basin, they are not located to represent any specific reservoir or demand site. In Section 3.4 the indicator results are discussed from this analysis.

3 Results and discussion

3.1 Future climate scenarios

Median changes in temperature are fairly uniform across the basin showing an increase between 1.5 and 2 degrees Celsius by the later half of the 2040s (see Figure 3). The coastal regions tend to show slightly less warming while the temperature in the western regions is predicted to increase about 0.2 degrees Celsius more. The distribution tails generally range from slightly less than 1 degree to about 3 degrees. Alternatively, changes in annual

precipitation vary considerably across the basin with a tendency toward a precipitation decrease (see Figure 4). In northern Malawi and north-eastern Zambia the median precipitation is predicted to be between a 3% and 8% increase. The remaining regions in the basin countries generally show a median reduction in precipitation ranging from almost no change to around 8% less. While the tails of the distribution show an alarming range of about -20% to +20% basinwide.

Changes in the climate moisture index (CMI) are shown in Figure 5. The CMI is an indicator of aridity, which depends on average annual precipitation and average annual potential evapotranspiration (PET). If PET is greater than precipitation, the climate is considered to be dry whereas if precipitation is greater than PET, the climate is wet. When PET is greater than precipitation, $CMI = (Precip./PET) - 1$ and when precipitation is greater than PET, $CMI = 1 - (PET/P)$. A CMI of -1 is very arid and a CMI of +1 is very humid. As a ratio of two depth measurements, CMI is dimensionless. As shown in the figure, almost all of the Zambezi country regions are predicted to be drier in more than half of the climate scenarios. Only the three northernmost regions are predicted to be wetter, while the driest are predicted in the regions around the mouth of the Zambezi River in Mozambique.

3.2 Runoff modeling results

The precipitation and near-surface temperature data described above (the HFDs), along with potential ET calculated using the modified Hargreaves equation (Hargreaves and Allen 2003) was used to represent possible future climate scenario input. The percent change in mean annual runoff, aggregated to five major basins, is shown in Figure 6. In this figure the baseline mean annual runoff is shown as a proxy for the hydrologic significance of each basin. The majority of the climate scenarios predict an increase in runoff in the Shire River Basin and basically no change in the Zambezi at Cahora Bassa, while the remaining three basins are showing a very likely decrease in runoff. The Upper Zambezi, where almost half of the runoff is generated, is predicted to dry in over 68% of the climate scenarios. Based on this analysis, the flows in the ZRB as a whole are likely to decrease, suggesting adverse impacts associated with drought. These results will be used in the water resource modeling, discussed in Section 3.4.

3.3 Crop modeling results

Using the same baseline scenario (1951-1990) as the runoff analysis, the changes in climate variables were adjusted based on the future projections (HFDs) to produce a range of possible impacts on the agriculture sector. The average predicted changes in the rainfed yield for the Zambezi countries are shown in Figure 7. This study suggests a decrease in rainfed yield for all of the crops in at least 75% of the climate projections. In Figure 8, the changes in rainfed yield are shown for maize across all of the four countries. Compared to the baseline scenario, rainfed yields are predicted to be worse for Zimbabwe and Mozambique than for Malawi and Zambia, although all countries show a decrease in yield. The range of impacts for Zimbabwe is drastic, from almost -30% to +30%, which makes planning for the future difficult for the country. As shown in Figure 9, the irrigation demand is predicted to increase by the 2040s for all of the nine crops modeled in more than 75% of the climate scenarios. The distribution of the changes in irrigation demand for sugarcane is shown for the four Zambezi countries in Figure 10. There is only a slight difference across the countries where Malawi's irrigation demand is predicted to change the least and Zimbabwe the most due to much stronger drying in the southwest than the northeast of the ZRB.

3.4 Water resource modeling results

Three measures are used here to present the changes in predicted impacts to the hydrologic system: maximum monthly runoff predictions, used as an indicator for changes in flood risk; hydropower generation changes; and the changes to the unmet irrigation demand. The percent change in maximum monthly runoff is shown by country mean in Figure 11. Since the nature of the analysis restricts us to monthly changes in runoff, the indicators presented here correspond to large-scale (typically causing river inundation) flooding events rather than local flash flooding events. As shown, flooding impact is predicted to increase in Malawi for the majority of the climate scenarios with a range from -20% to +40%. In Zimbabwe, flooding is predicted to decrease significantly in most of the climate scenarios, although there is a long, thin tail reaching an alarming 150% increase. Mozambique and Zambia both show a fairly normal distribution somewhat centered on no change, but the range (-20% to +30%) does favor an increase in flooding events. Using a Gumbel distribution fitting, we can make claims on the recurrence of damaging flood events. This analysis found that the recurrence of high-damage flood events, greater than the 50-year event intensity, could increase significantly in Mozambique, as shown in Figure 12. Considering that one high-damage flood event occurs in the base scenario, Mozambique is likely to have a significant increase in high-damage flood events in the future with a likelihood of tripling the base occurrence, and a tail that suggests there will be between six and eight times more high-damage flood events.

The impacts on hydropower generation by country are presented in Figure 13. Malawi is the only country where a positive impact is predicted in the majority of scenarios. Alternatively, in Zambia, hydropower generation is predicted to decrease in most of the future climates. With runoff decreasing in Zambia in the west, upstream of the majority of the hydropower plants, these results are expected. In Zimbabwe, where hydropower is generated downstream of Zambia, hydropower production is predicted to decrease slightly in most of the scenarios, suggesting that no significant impact would be expected based on this study. In Mozambique, where there are a few large downstream hydropower plants, there is expected to be no significant change in energy production. The reservoirs behind these hydropower plants are large, with significant storage, and they are downstream of the predicted increased runoff in Malawi, in combination with the decreasing runoff in the western part of the basin, resulting in only small impacts. With these results we can see that the upstream hydropower plants located in Zambia and Malawi are much more sensitive to changes in local runoff, while the downstream plants located in Zimbabwe and Mozambique are less sensitive since they have the luxury of a large contributing area—where a combination of increasing and decreasing runoff is expected.

The impacts on irrigation availability are presented as the changes in shortage volume, where the shortage volume is defined as the volume of water delivered to the irrigation node in the WEAP model subtracted from the volume of water demanded by the particular irrigation node. In the upstream countries, Malawi and Zambia, the irrigation shortage remained insignificant in almost all of the scenarios (i.e. the amount of water delivered equaled the amount of water demanded). Due to mostly increasing predicted runoff in Malawi, and very small irrigation shortages in the base scenario, the impact of climate change on irrigated agriculture is expected to be fairly negligible. Since irrigation water is taken mostly from the river in Zambia upstream of the hydropower reservoirs, it is likely that the farmers are able to find enough water for irrigation even when there is a shortage in runoff. But, as we have seen, this choice does impact the downstream hydropower production in the country. In contrast, irrigation shortage in Zimbabwe and Mozambique is affected negatively by the predicted

decrease in runoff. The distributions are shown in Figure 14 for Zimbabwe and Mozambique, where here an increase implies a negative impact. In Zimbabwe, irrigation shortage is predicted to increase about 25% (between 5% and 50%) in most of the scenarios with a full range from a 50% decrease to a 75% increase. For Mozambique, the impacts are predicted to be less severe where, again the decrease in runoff in the west is balanced in part by the increases in runoff in the north. But the impacts are predicted to be negative in more than 98% of the scenarios with the most common around 15%.

4 Conclusions

Based on this study of the Zambezi valley system, the future climate is likely to be drier in the basin as a whole although there is a tendency toward a wetter climate in a small section in the north. Drier climate means more risk related to drought impact. We have quantified how a range of predicted climate (with a tendency toward drying) will likely reduce surface water availability basinwide, increase irrigation demand, and decrease rainfed crop yields. And finally, using a water resource system model, we have shown a range of possible impacts on economically significant outcomes, namely changes in flood probability, hydropower generation, and unmet irrigation demand. Of the four countries in the region, Malawi is the least sensitive to climate change. Based on the study, the only concern for Malawi is a slight increase in flood risk. Alternatively, Zambia is predicted to experience losses in terms of hydropower generation, caused in part by expected decreases in runoff in the west and in part by upstream irrigation projects. Also, large increases in flooding risk are not likely but possible for the country as a whole. In Zimbabwe, since hydropower plants are mostly upstream of the irrigation projects, changes in hydropower generation are not likely to be impacted although there is about an equal chance of increase as decrease. In contrast, the future irrigation investments could be at risk of water shortage. The impacts to Mozambique are likely to be fairly mild because it has the benefit of a large contributing area with varying types of impact (both increases and decreases in surface water availability), but damaging flood events will happen much more often.

As mentioned, climate changes after 2050 are generally predicted to be more drastic. Changes in the latter part of the century, not included in his study, might be useful in future planning. Also, since all of the impacts are discussed here as changes from a baseline scenario, inter-annual variability, which can be the cause of major impacts, is not considered in this analysis. Regardless, studies like the one presented here can help decision makers develop an informed risk-based strategy for national policy decisions, and help to direct further studies where local detail is considered.

References

- Allen R, Pereira L, Raes D, (1998) Crop evapotranspiration-guidelines for computing crop water requirements-FAO irrigation and drainage, Paper 56. FAO
- Arndt C, Fant C, Robinson S, Strzepek K (2012) Informed selection of future climates. UNU-WIDER Working Paper No. 2012/60
- Beck L, Bernauer T (2010) Water Scenarios for the Zambezi River Basin, 2000-2050. ETH Zurich, Report from the Center for Comparative and International Studies, Zurich, Switzerland

- Beilfuss R, Santos Dos D (2001) Patterns of hydrological change in the Zambezi Delta, Mozambique. Program for the Sustainable Management of Cahora Bassa Dam and the Lower Zambezi Valley. http://files.gorongosa.net/filestore/348-patterns_hydrological_change_zambezi_delta.pdf
- Fant C, Gueneau A, Strzepek K, Awadalla S, Farmer W, Blanc E, Schlosser CA (2012) CliCrop: A crop water-stress and irrigation demand model for an integrated global assessment modeling approach. Joint Program on the Science and Policy of Global Change, Report 214. MIT. <http://globalchange.mit.edu/research/publications/2264>
- Farmer W, Strzepek K, Schlosser CA, Droogers P, Gao X (2011) DSpace@MIT : A method for calculating reference evapotranspiration on daily time scales. MIT Joint Program on the Science and Policy of Global Change. MIT
- FAO (2011) Food and Agriculture Organization profile of the Zambezi basin. <http://www.fao.org/docrep/w4347e/w4347e0o.htm>, accessed 10 May 2011
- Gupta V, Sorooshian S, (1983) Uniqueness and observability of conceptual rainfall-runoff model parameters: the percolation process examined. *Water Resour. Res.*, 19(1):269-276 doi:10.1029/WR019i001p00269
- Gupta V, Sorooshian S (1985) The relationship between data and the precision of parameter estimates of hydrologic models. *J Hydrol* 81:57–77
- Hargreaves G, Allen R (2003) History and evaluation of Hargreaves evapotranspiration equation. *J Irrig Drain E-Asce* 129:53–63
- Kaczmarek Z, (1993) Water balance model for climate impact analysis. *ACTA Geophysica Polonica* 41(4):1-16
- Kashaigili J, McCartney M, Mahoo H (2006) Modeling the hydrology of the Usangu Plains Wetlands for environmental management, IWMI Research Report 104. Water Management
- Mitchell T, Jones P (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int J Climatol* 25:693–712
- Neitsch S, Arnold J, Kiniry J (2005) Soil and water assessment tool theoretical documentation: version 2005. Model Description. Soil and Water Research Laboratory
- Rao N, Sarma P (1988) A simple dated water-production function for use in irrigated agriculture. *Ag Water Manage* 13:25-32
- Reilly, J, Paltsev S, Strzepek, K, Selin NE, Cai Y, Nam K-M, Monier E, Dutkiewicz S, Scott J, Webster, Sokolov A (2012) Valuing Climate impacts in integrated assessment models: The MIT IGSM. MIT Joint Program Report Series, Report 219
- US Department of the Interior, Bureau of Reclamation (1993) Drainage manual: a Water Resources Technical Publication. US Department of the Interior, Washington DC
- Rosenzweig C, Iglesias A (1998) The use of crop models for international climate change impact assessment. In: Tsuji, GY, Hoogenboom, G Thornton, PK (eds) Understanding options for agricultural production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp: 267-292
- Schlosser CA, Gao X, Strzepek K, Sokolov A, Forest CE, Awadalla S, Farmer W (2011) Quantifying the likelihood of regional climate change: a hybridized approach. MIT Joint Program on the Science and Policy of Global Change. http://globalchange.mit.edu/pubs/abstract.php?publication_id=2212

- Sheffield J, Goteti G, Wood EF (2006) Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. *J Climate* 19:3088–3111
- Sieber J, Purkey D (2007) User Guide for WEAP21. Stockholm Environment Institute
- Sokolov AP, Stone PH, Forest CE, Prinn R, Sarofim MC, Webster M, Paltsev S, Schlosser CA, Kicklighter D, Dutkiewicz S, Reilly J, Wang C, Felzer B, Melillo JM, Jacoby HD (2009) Probabilistic forecast for twenty-first-century climate based on uncertainties in emissions (without policy) and climate parameters. *J Climate* 22:5175–5204
- Sutcliffe JV, Parks, YP (1987) Hydrological modelling of the Sudd and Jonglei Canal. *Hydrolog Sci J* 32:143–159
- World Bank (2009) The cost to developing countries of adapting to climate change: new methods and estimates. The Global Report of the Economics of Adaption to Climate Change Study, World Bank, Washington, DC
<http://siteresources.worldbank.org/EXTCC/Resources/EACC-june2010.pdf>
- World Bank (2010) The Zambezi River Basin: a multi-sector investment opportunities analysis, Volume 1, Summary Report. World Bank, Washington DC.
http://siteresources.worldbank.org/INTAFRICA/Resources/Zambezi_MSIOA_-_Vol_1_-_Summary_Report.pdf
- Tilmant A, Beevers L, Muyunda B (2010) Restoring a flow regime through the coordinated operation of a multireservoir system: the case of the Zambezi River basin. *Water Resources Research* 46 W07533
- Wahaj R, Maraux F (2007) Actual crop water use in project countries: a synthesis at the regional level. World Bank, Washington DC
- Yates DN, Strzepek KM (1998) Modeling the Nile Basin under climatic change. *J Hydrologic Energy* 3:98–108

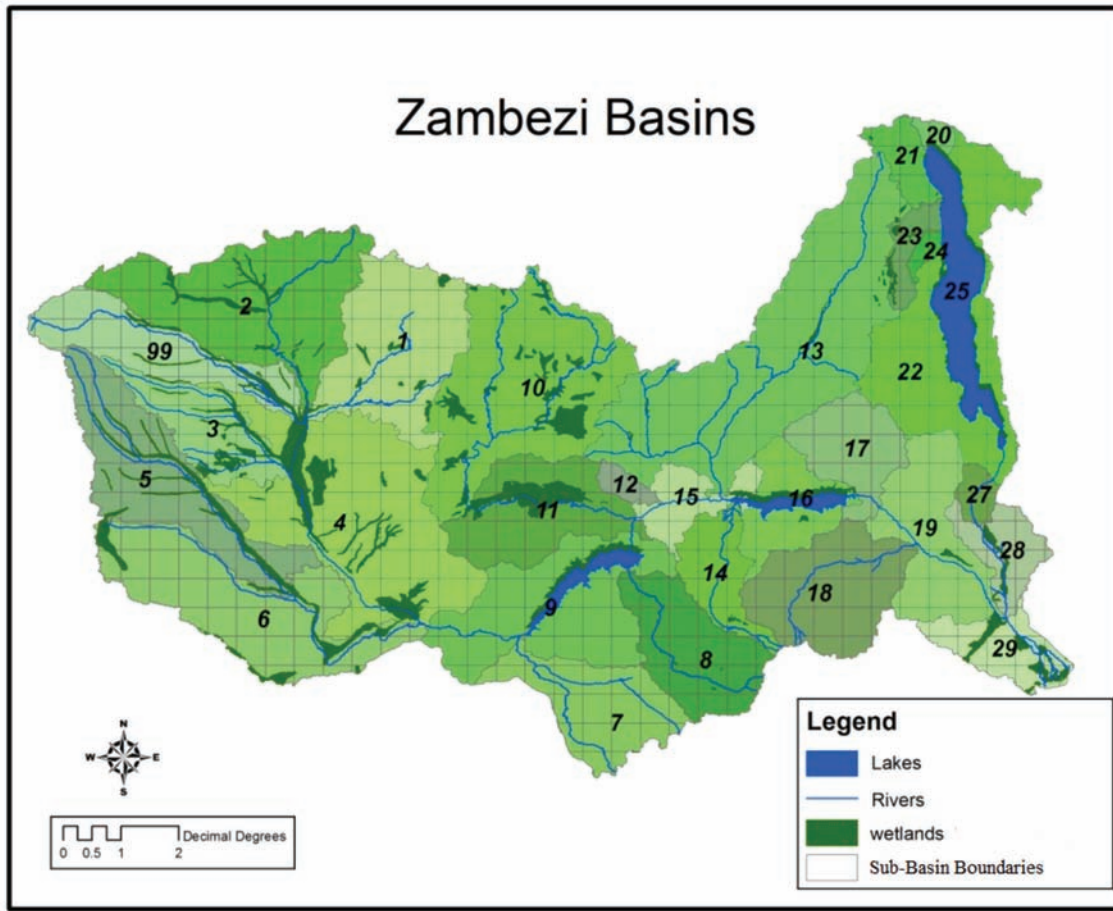


Figure 1: Sub-basin division of Zambezi River Basin with superimposed half degree grids
 Source: authors' creation.

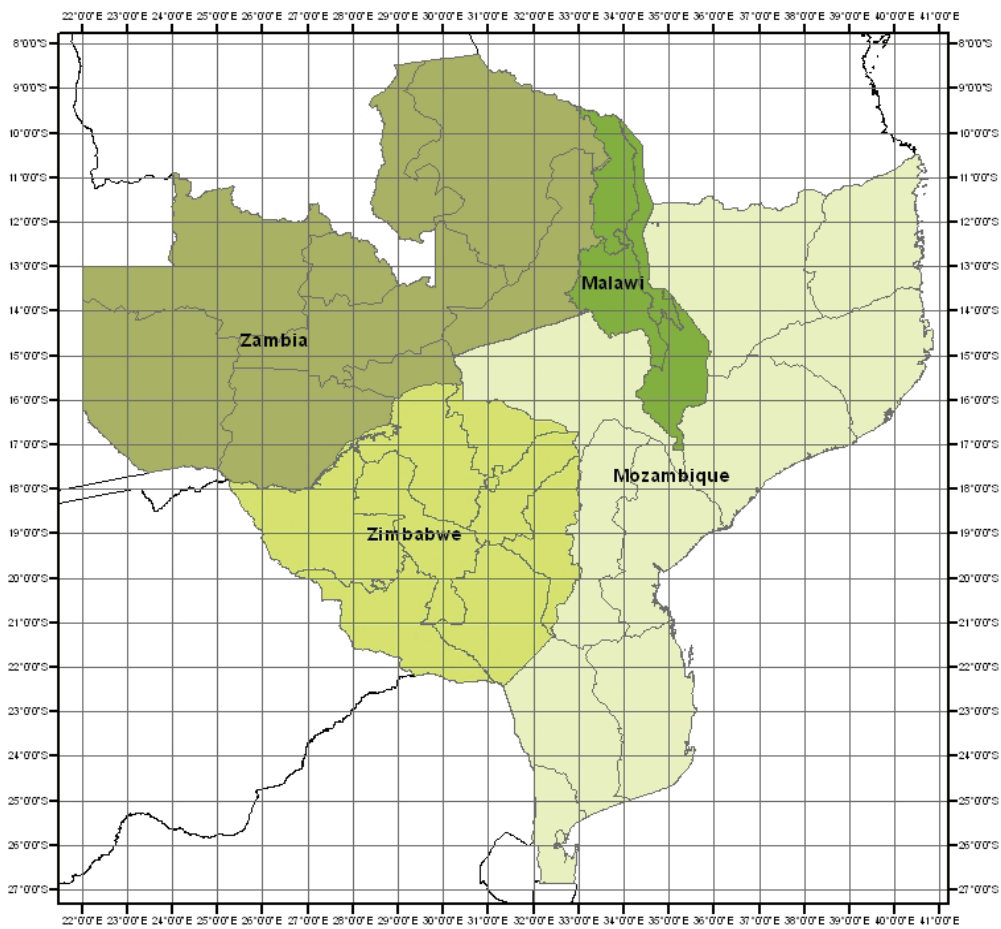


Figure 2: Political division of Zambezi river basin by country boundaries and sub-regions with a superimposed 1 degree square grid

Source: authors' creation.

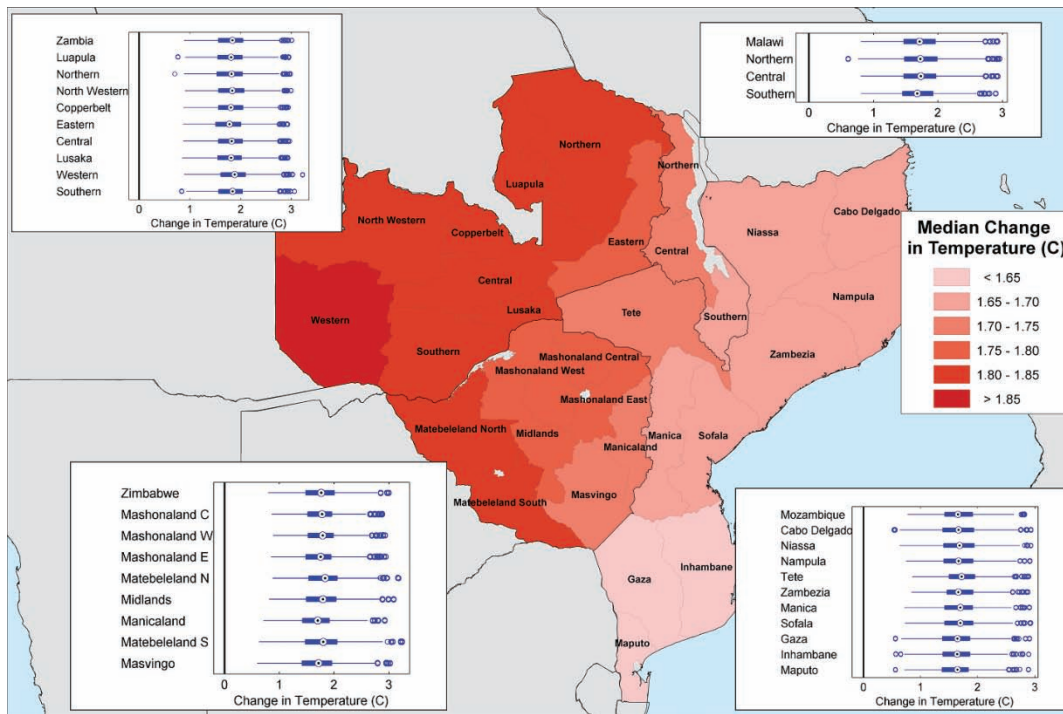


Figure 3: Climate scenario distribution of near-surface temperature (in degrees C) over the political boundaries of the four Zambezi River Basin countries averaged over the last five years simulated, 2046-2050

Source: authors' creation.

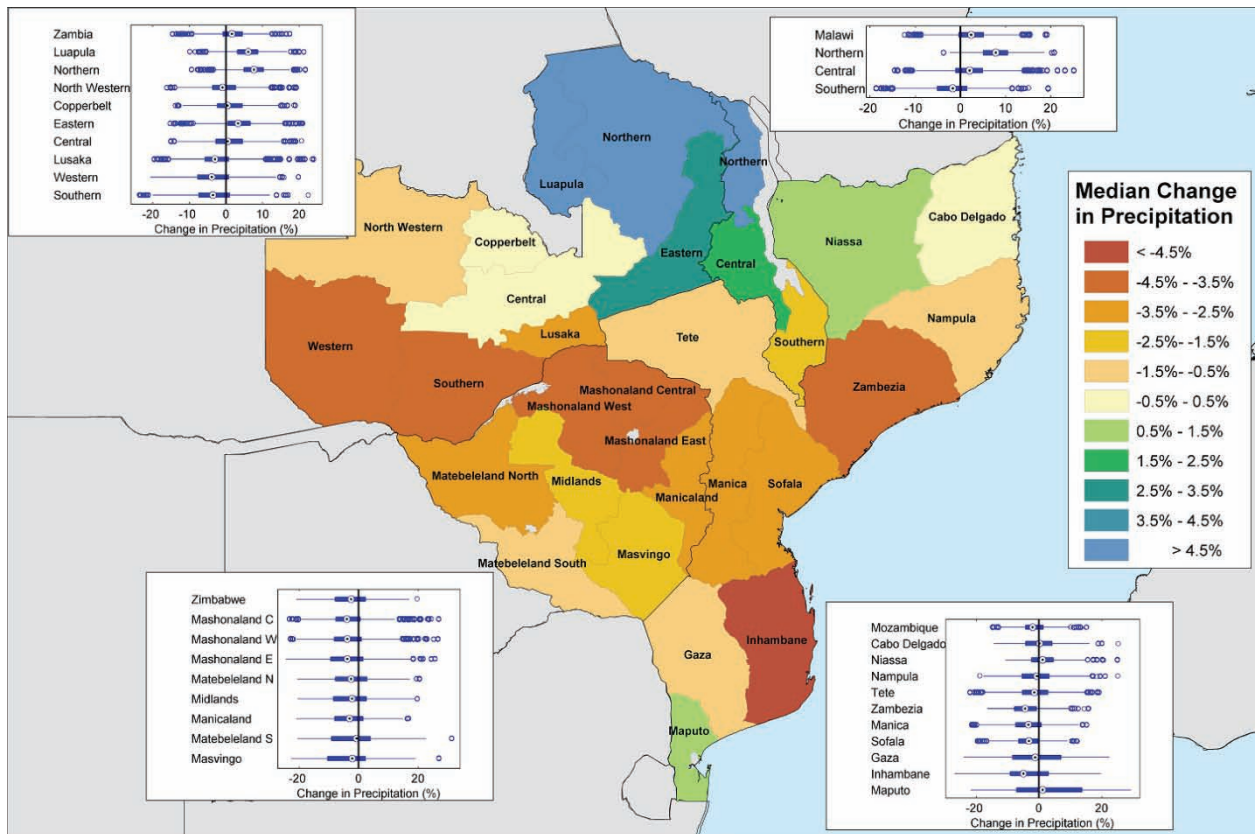


Figure 4: Climate scenario distribution of % changes in precipitation over the political boundaries of the four Zambezi River Basin countries averaged over the last five years simulated, 2046-2050
 Source: authors' creation.

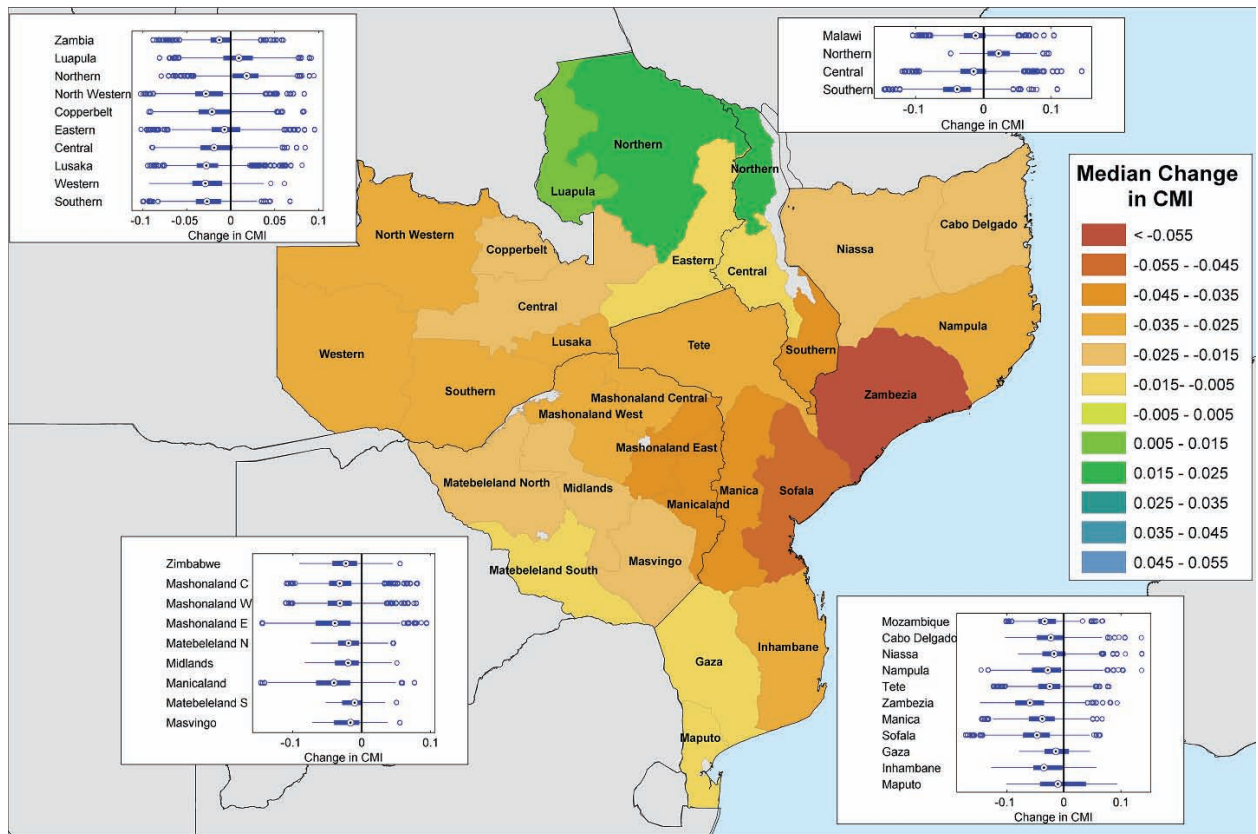


Figure 5: Climate scenario distribution of changes in climate moisture index over the political boundaries of the four Zambezi River Basin countries averaged over the last five years simulated, 2046-2050

Source: authors' creation.

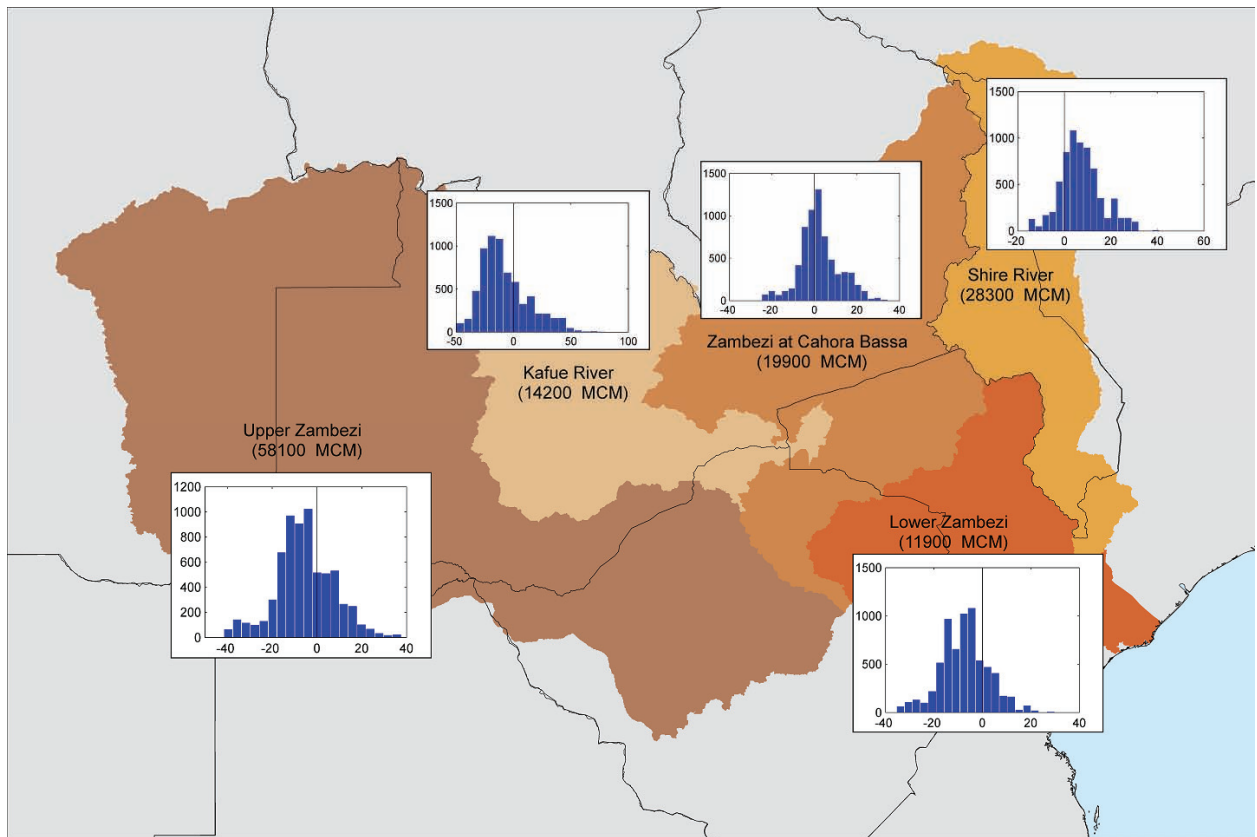


Figure 6: Climate scenario distribution results of the predicted % change in runoff for the five major sub-basins of the Zambezi Valley averaged over the last five years simulated, 2046-2050

Source: authors' creation.

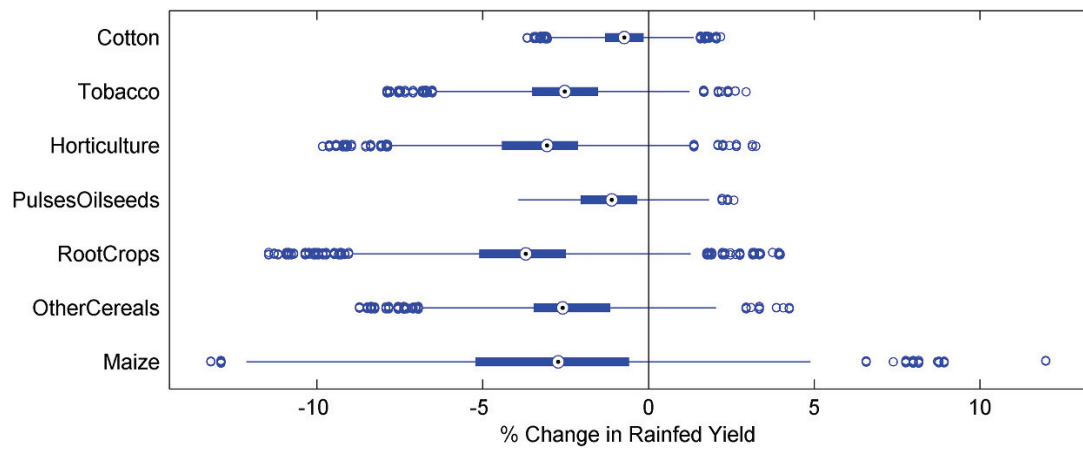


Figure 7: Climate scenario distribution of the four-country mean % change in the rainfed yield of all Crops for the Zambezi countries averaged over the last five years simulated, 2046-2050

Source: authors' creation.

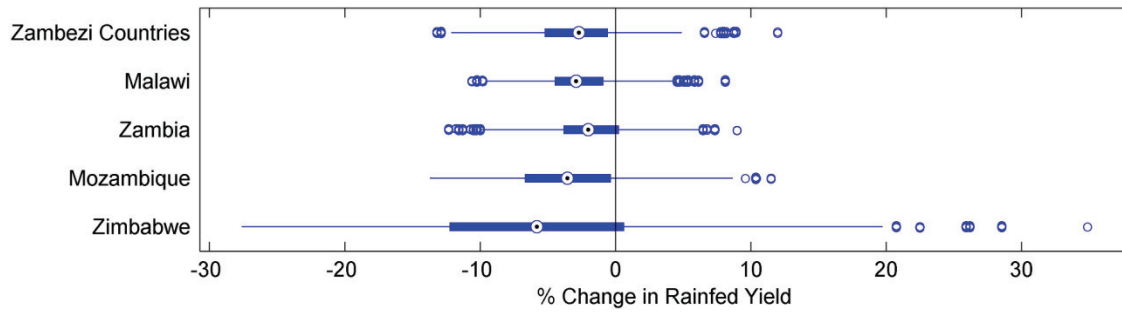


Figure 8: Climate scenario distribution of the country mean % change in the rainfed yield of crops for the Zambezi countries averaged over the last five years simulated, 2046-2050

Source: authors' creation.

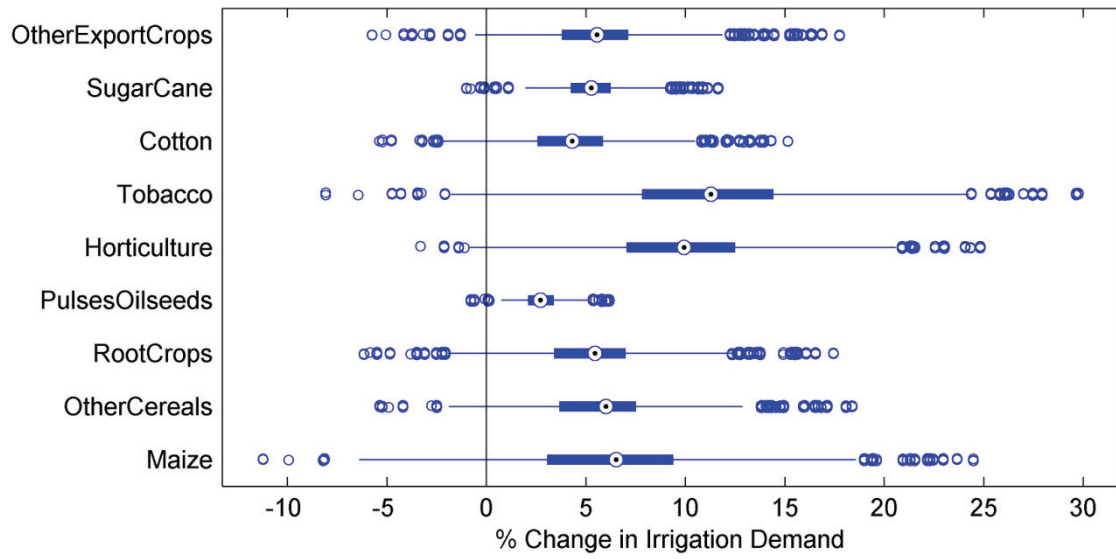


Figure 9: Climate scenario distribution of the four-country mean % change in the irrigation demand of all crops for the Zambezi countries averaged over the last five years simulated, 2046-2050

Source: authors' creation.

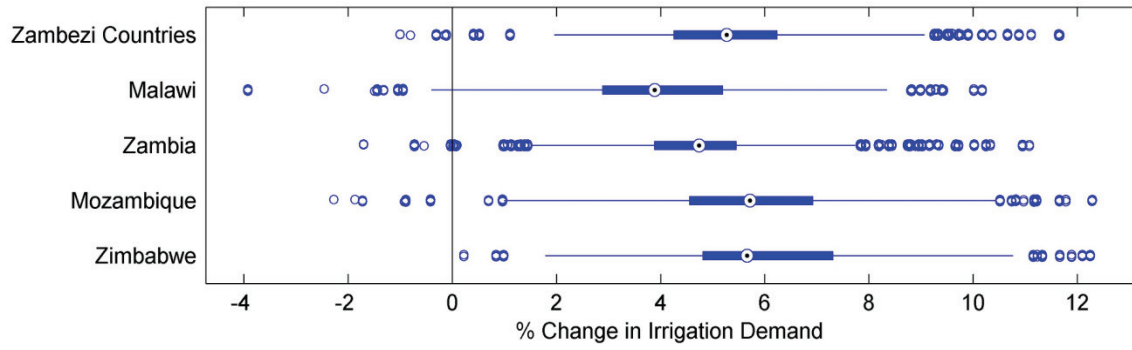


Figure 10: Climate scenario distribution of the country mean % change in the irrigation demand of crops for the Zambezi countries averaged over the last five years simulated, 2046-2050

Source: authors' creation.

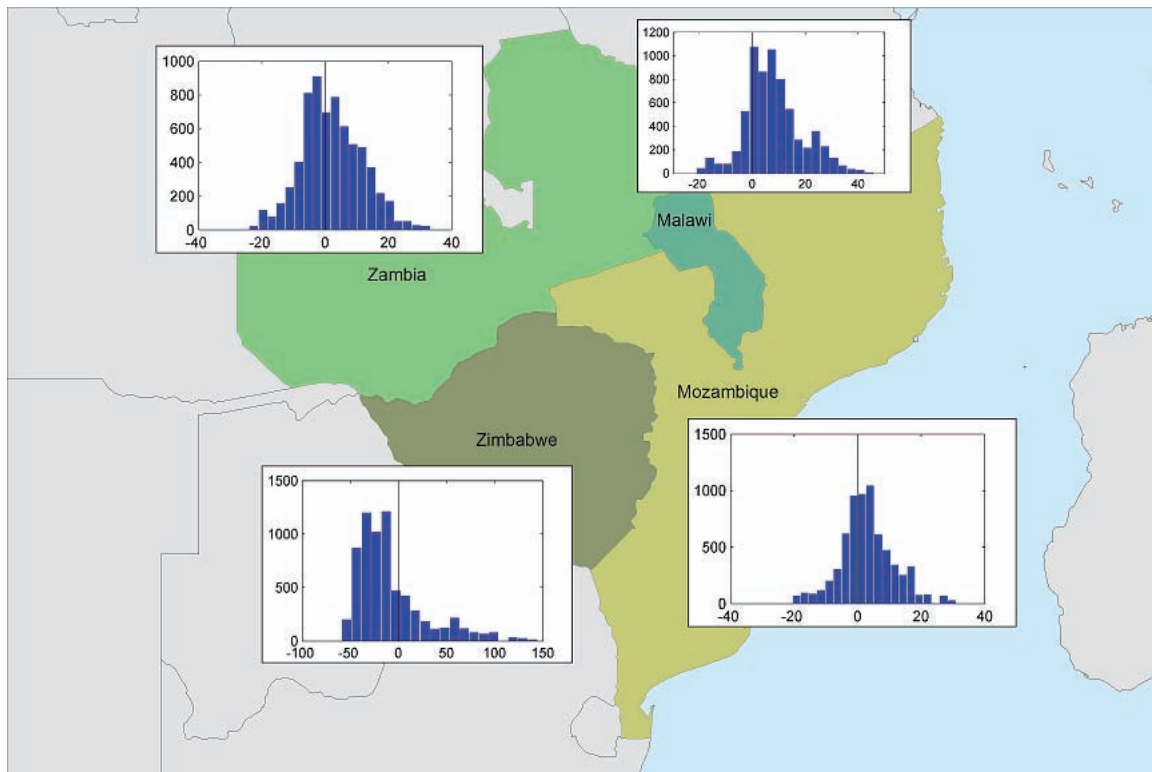


Figure 11: Climate scenario distribution of the % change in maximum monthly runoff (used as an indicator for changes in flood events) is shown by country mean over the last five years simulated, 2046-2050

Source: authors' creation.

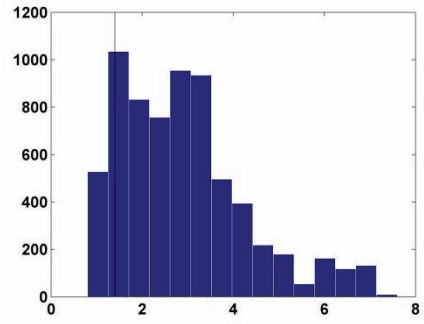


Figure 12: Distribution of flooding events over the 50-year return period intensity in Mozambique normalized by regions. The black line represents the base scenario

Source: authors' creation.

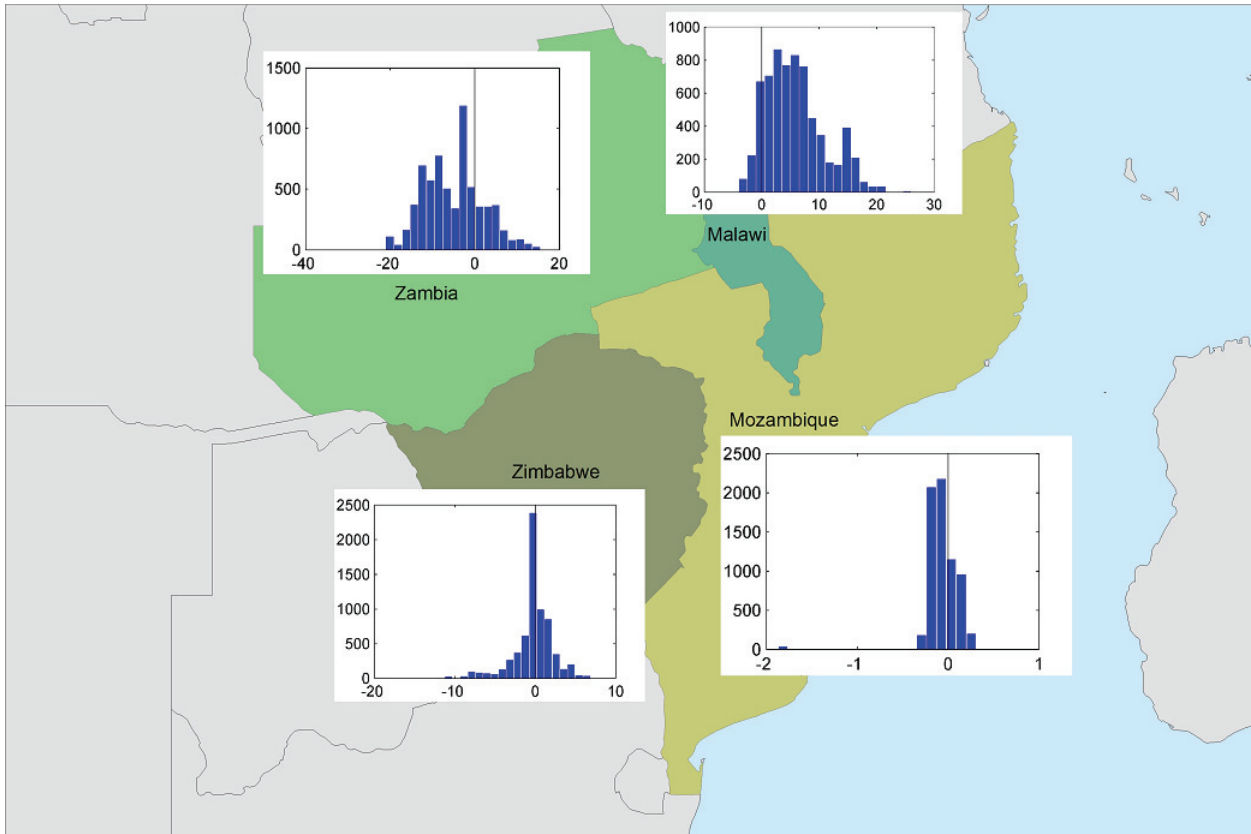


Figure 13: Climate scenario distribution of the % change in hydropower generation is shown by country mean over the last five years simulated, 2046-2050

Source: authors' creation.

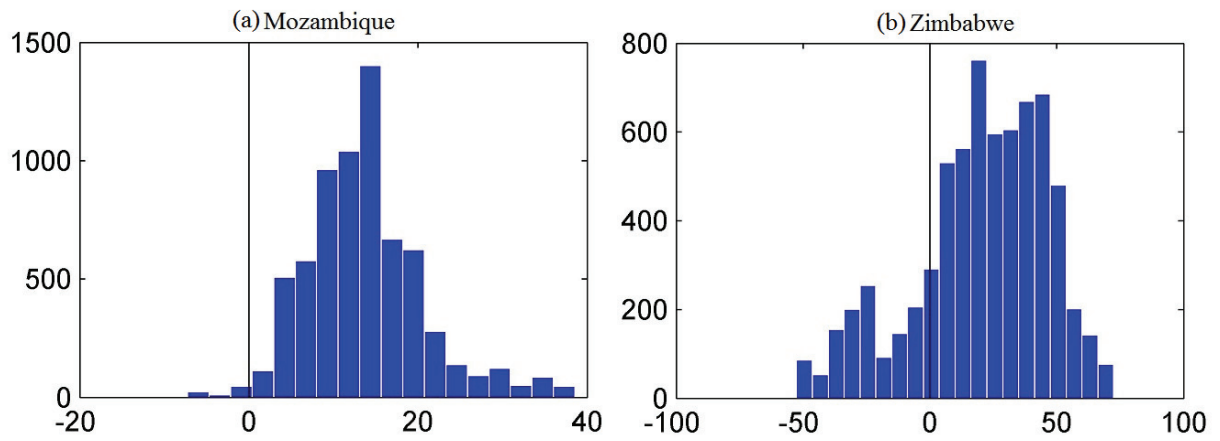


Figure 14: Climate projection distribution of the % change in irrigation shortage in Mozambique (left) and Zimbabwe (right)

Source: authors' creation.