70264 v2

Economics of Adaptation to Climate Change

Annexes

MOZAMBIQUE

Economics of Adaptation to Climate Change

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Annex 1
Social Dimensions

The following district map identifies areas where risks from drought, flood, and cyclone are considered to be high or very high.

Figure A-1 Original universe of social vulnerability hotspots

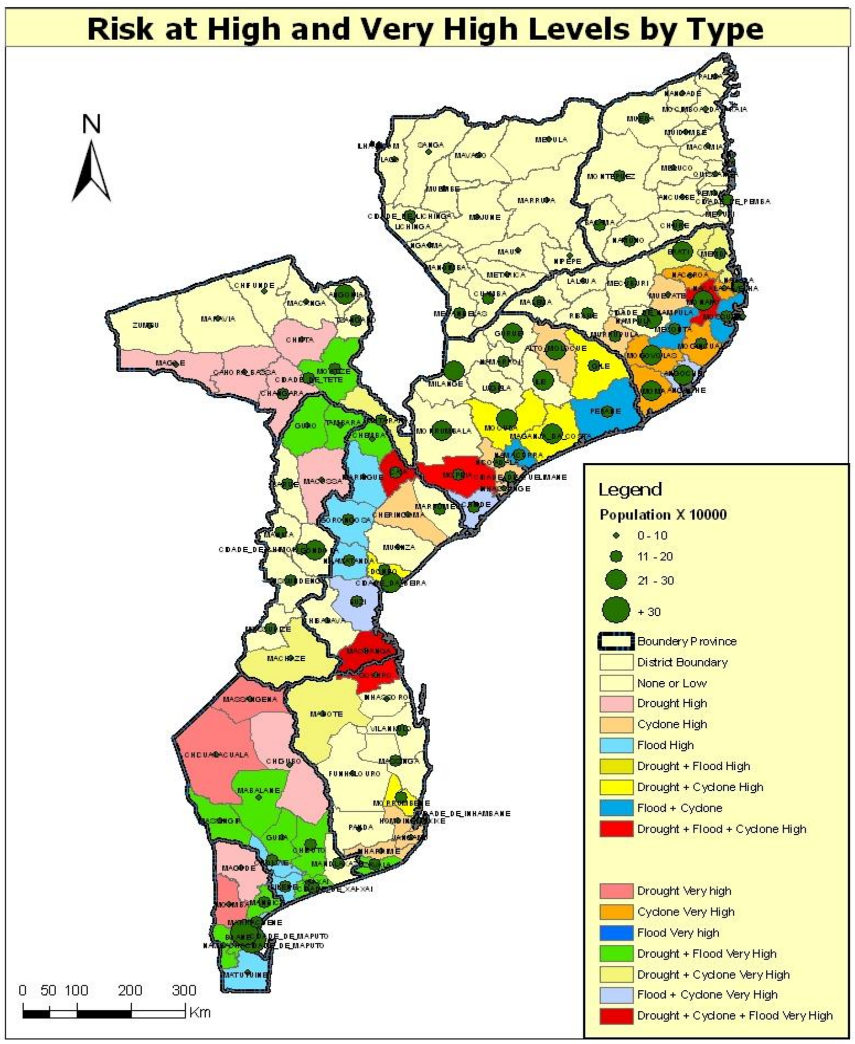
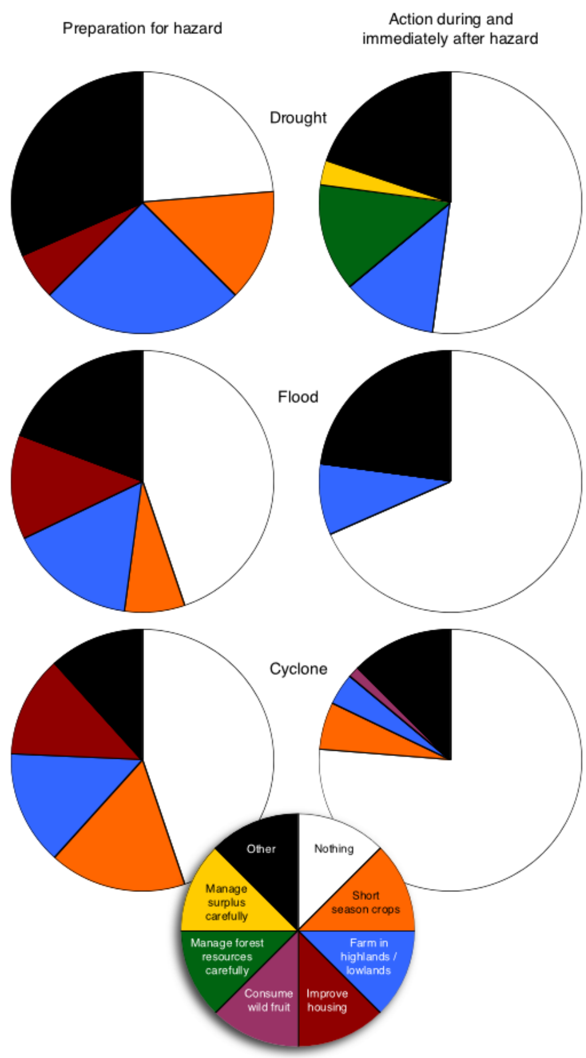


Figure A-2 Coping Mechanisms Before, During, & Immediately After Climatic Hazards



Questions Addressed in PSD Workshops

- What is the local vision of the future, in terms of development priorities, perceived climate change impacts, and feasible response strategies?
- Which areas/sectors are viewed as most vulnerable? What are the key drivers contributing to that vulnerability?
- What specific adaptation option investments and sequenced combinations of investments (pathways) are needed to respond to climate change impacts at national and sub-national levels?
    - How pro-poor are these identified options?
    - Where in the region should these be applied and who are the vulnerable groups?
    - What are the preconditions including policy elements needed to implement these effectively?
    - What are the synergies and trade-offs among these options?

Annex 2

River Basin & Hydro Power Modeling

CLIRUN-II Rainfall Runoff Model Description

CLIRUN-II is the latest model in a family of hydrologic models developed specifically for the analysis of the impact of climate change on runoff. Kaczmarek (1993) presents the theoretical development for a single-layer lumped watershed rainfall runoff model-CLIRUN. Kaczmarek (1998) presents the application of CLIRUN to the Yellow River in China.

Yates (1996) expanded on the basic CLIRUN by adding a snow-balance model and providing a suite of possible potential evapotranspiration (PET) models and packaged it in a tool: WatBal. The WatBal model has been used on a wide variety of spatial scales from small to large watersheds and globally on a 0.5 by 0.5 degree grid. (Strzepek et al., 1999; Huber-Lee, et al., 2005, Strzepek et al., 2005).

CLIRUN-II (Strzepek et al., 2008) is the latest in the "Kaczmarek School" of hydrologic models. It incorporates most of the features of WatBal and CLIRUN but was developed specifically to address extreme events at the annual level modeling low and high flows. CLIRUN and WatBal performed very well in modeling mean monthly and annual runoff, which is important for water supply studies, but were not able to accurately model the tails of runoff distribution.

CLIRUN-II has adopted a two-layer approach following the framework of the SIXPAR hydrologic model (Gupta and Sorooshian, 1983, 1985) and used a unique conditional parameter estimation procedure. A brief description of the components of the model is presented in the following section.

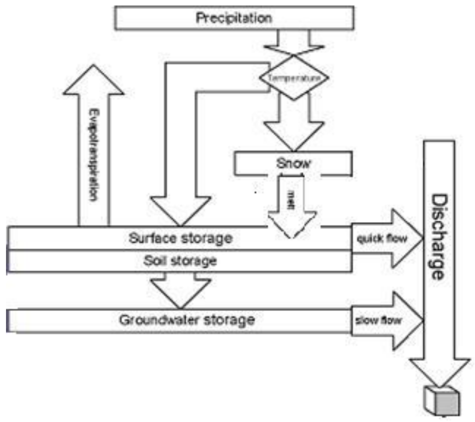
Spatial and Temporal Scale: CLIRUN II models runoff as a lumped watershed with climate inputs and soil characteristics averaged over the watershed, simulating runoff at a gauged location at the mouth of the catchment. CLIRUN can run on a daily or monthly time step. For this study, climate and runoff data were available only on a monthly basis, so monthly data were used.

Snow-Balance Model: The snow accumulation and melt model used in this study is based on concepts frequently used in monthly water balance models (McCabe, G. and D. Wolock, 1999). Inputs to the model are monthly temperature (T) and precipitation (P). The occurrence of snow is computed as a function of average watershed temperature and two parameters: Temp_snow and Temp_rain. These two parameters are calibrated for each watershed. Snowmelt is added to any monthly precipitation to form effective precipitation available for infiltration or direct runoff.

Water Balance

Figure A-3 represents the water flows of CLIRUN II. The figure shows the mass balance of water in the CLIRUN II system. Water enters via precipitation and leaves via evapotranspiration and runoff. The difference between inflow and outflow is reflected as change in storage in the soil or groundwater.

Figure A-3 CLIRUN-II Conceptual Hydrologic Model Schematic



Evapotranspiration

A suite of potential evapotranspiration models is available for use in CLIRUNII. This study used the Modified Hargreaves method. Actual evapotranspiration is a function of potential evapotranspiration and soil moisture state following the FAO method (FAO, 1996).

Soil Water Modeling

Soil water is modeled as a two-layer system: a soil layer and groundwater layer. These two components correspond to a quick and a slow runoff response to effective precipitation.

Quick Runoff

The soil layer generates runoff in two ways. First there is a direct runoff component, which is the portion of the effective precipitation (precipitation plus snowmelt) that directly enters the stream systems. The direct runoff is a function of the soil surface and modeled differently for frozen soil and non-frozen soil. The remaining effective precipitation is infiltration to the soil layer. A non-linear set of equations determines the respective volumes of water leaving the soil as runoff, percolating to the groundwater, and going into soil storage. The runoff is a linear relation of soil water storage; percolation is a non-linear relationship of both soil and groundwater storages.

Slow Runoff

The groundwater receives percolation from the soil layer and runoff is generated as a linear function of groundwater storage. The soil water processes have six parameters similar to the SIXPAR model (Gupta and Sorooshian, 1983) that are determined via the calibration of each watershed.

Modeling Dry & Wet Years

When CLIRUNII is calibrated in a classical rainfall-runoff framework the results are very good for the 25th to 75th percentile of the observed streamflows, producing an R^2 value of 0.3 to 0.7. However, for most water resource systems, the tails of the streamflow distribution are important for design and operation planning. To address this issue, a concept developed by Block and

Rajagopalan (2008) for hydrologic modeling of the Nile River know as localized polynomial was extended to calibration of rainfall runoff modeling in CLIRUNII (Strzepek, et al, 2008).

When calibrating, each observed year is categorized as to whether it falls into a dry year (0% to 25% of the distribution), a normal year (25% to 75%), or a wet year (greater than 75%). A separate set of model parameters were estimated for the three different classes of annual streamflow. This increased the R^2 value from 0.7 to 0.92.

Runoff Results

The mean of the baseline (1950 – 2000, presented in Figure A-4 and Figure A-5) was used to calculate a percent change in runoff for each basin and each of the four climate projections (Figure A-7 through Figure A-13). In this case, the percent change in runoff was calculated such that a labeled “10%” indicates a 10% increase in the baseline runoff, and “-10%” indicates a 10% decrease in the baseline runoff. These percent changes are not changes in cumulative streamflow but rather changes in the individual basin’s runoff production (affected by precipitation and temperature changes within the basin only).

The following plots show the cumulative runoff (or streamflow) for each of the major basins in Mozambique. These values are the calculated “natural flows” into the Indian Ocean (Figure A-14– Figure A-28).

Figure A-4 Baseline Annual Runoff in Mm^3/year For All Contributing Basins

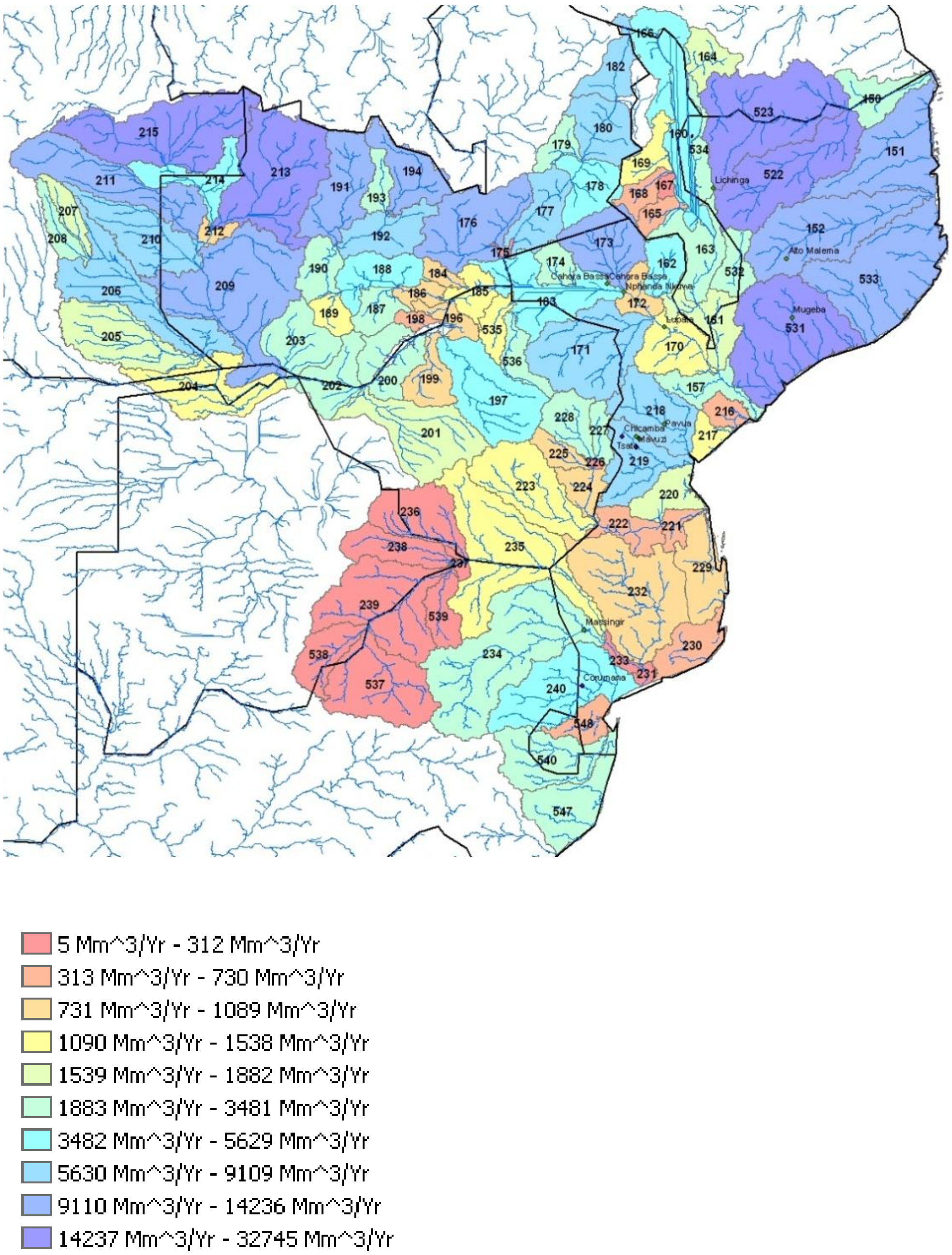


Figure A-5 Baseline Annual Flows in Mm^3/year For All Mozambique Basins

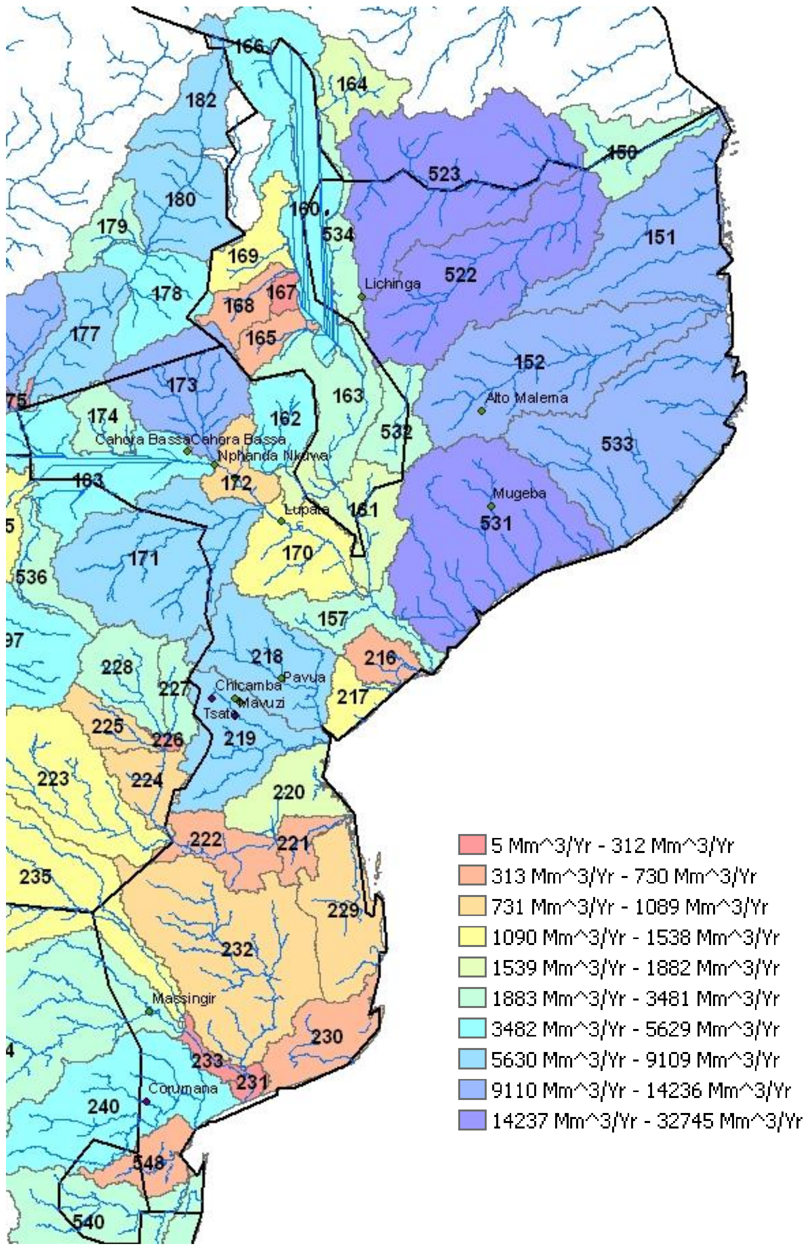


Figure A-6 Percent Change In Average Annual Runoff for the Ipsl_a2 (Mozambique Wet) Projection for All Contributing Basins

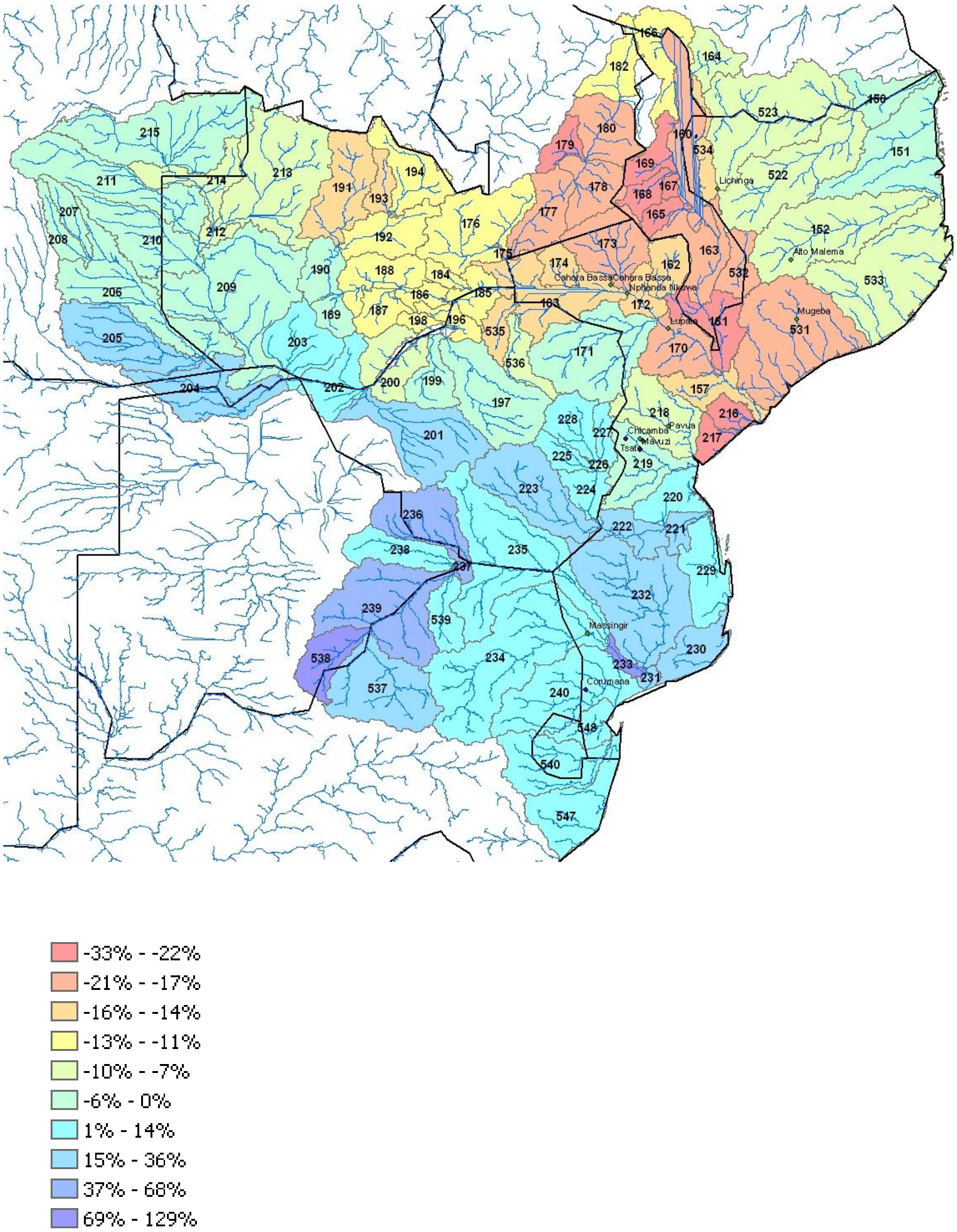


Figure A-7 Percent Change In Annual Runoff For The Ipsl_a2 (Mozambique Wet) Projection For All Mozambique Basins

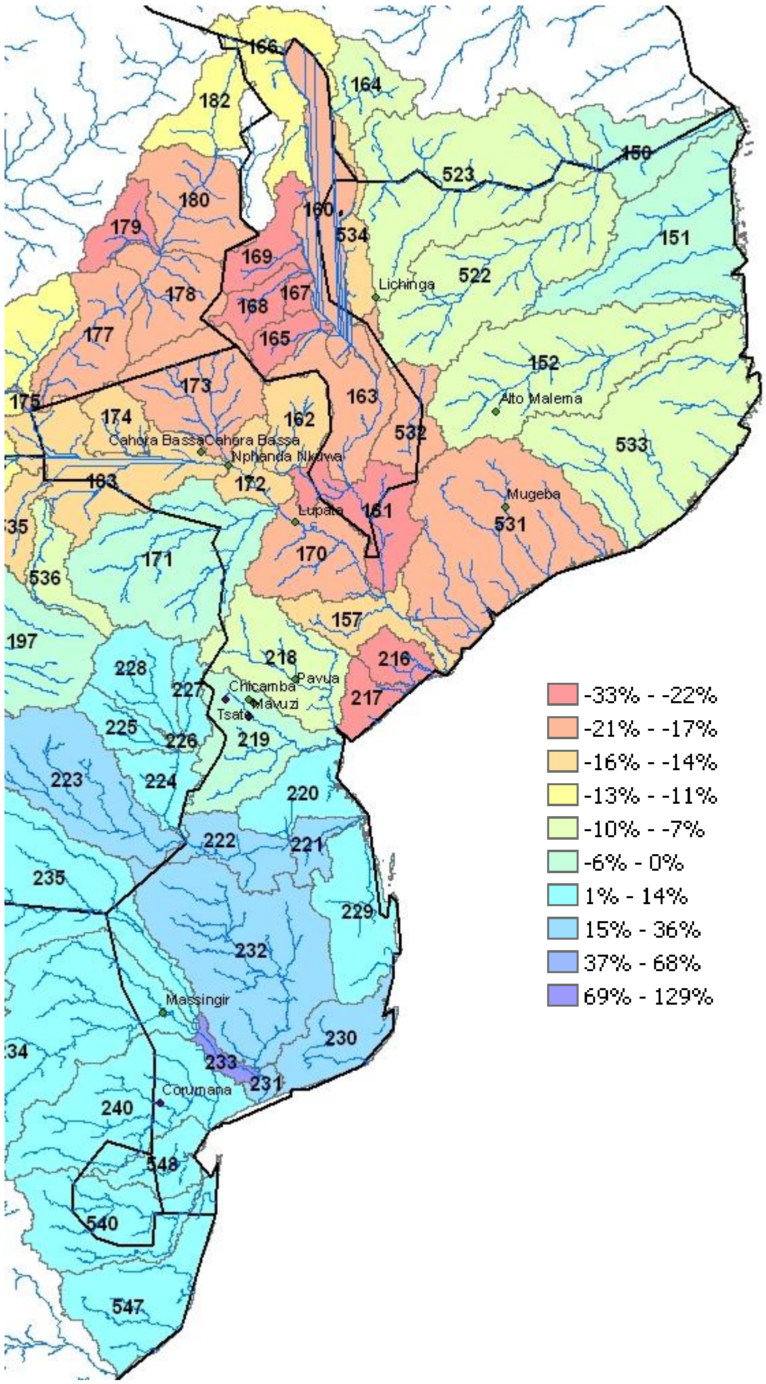


Figure A-8 Percent Change In Annual Runoff for the Ukmo1_a1b (Mozambique Dry) Projection for All Contributing Basins

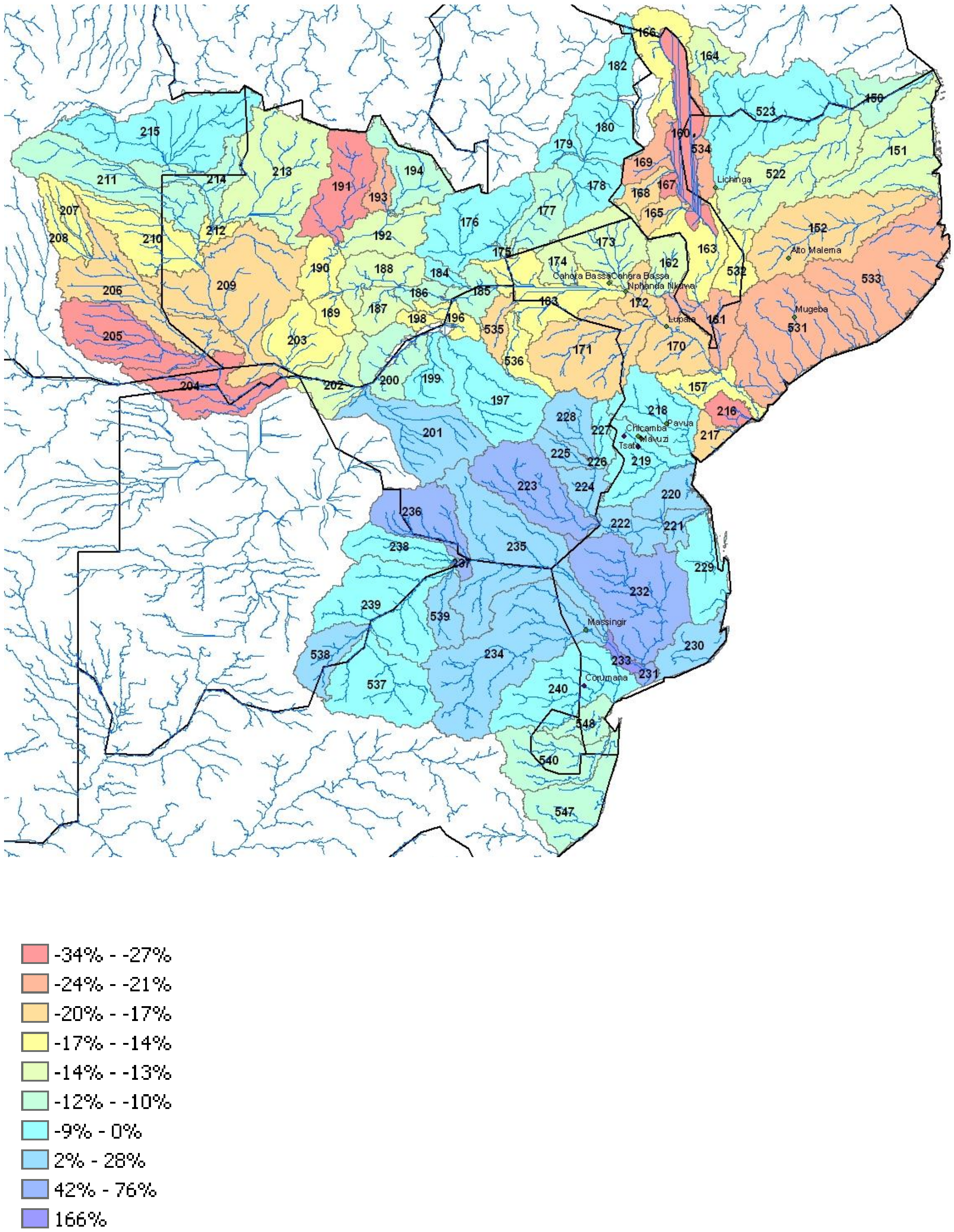


Figure A-9 Percent Change In Annual Runoff for the Ukmo1_a1b (Mozambique Dry) Projection for All Basins in Mozambique

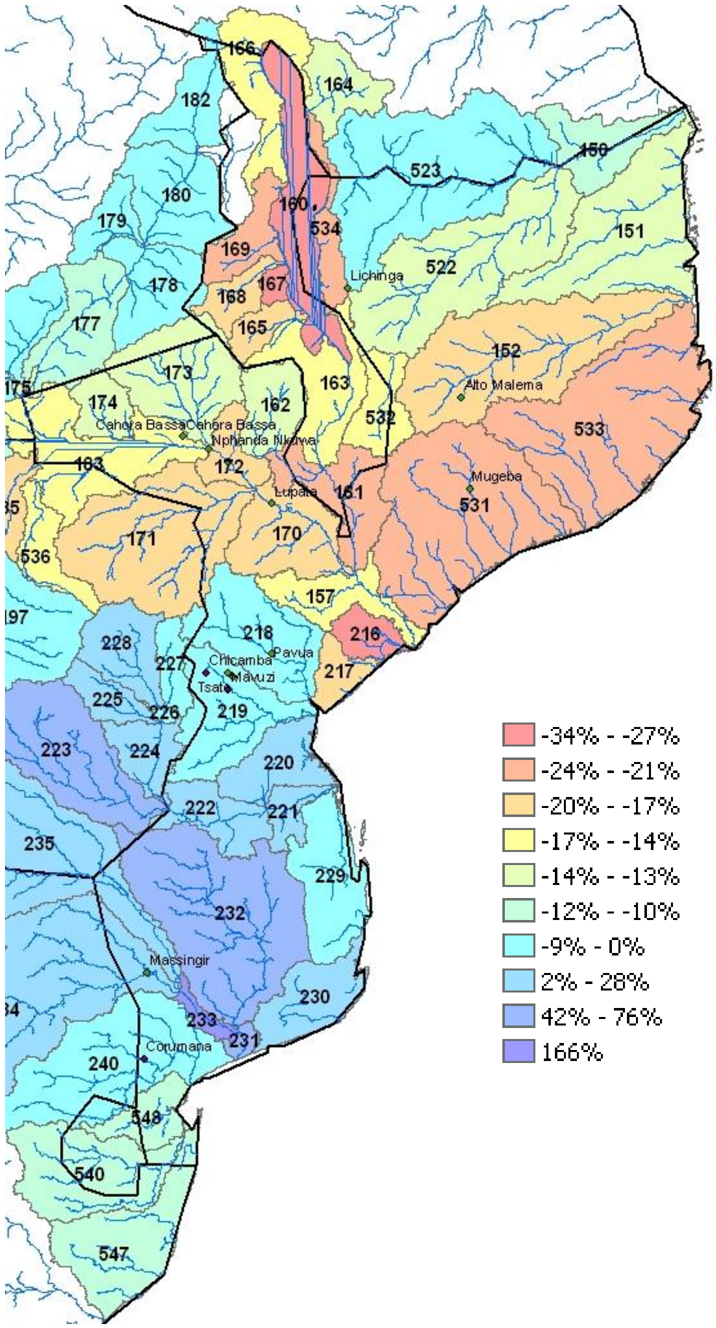


Figure A-10 Percent Change In Annual Runoff for the NCAR ccsm 3.0 a2 (Global Wet) Projection for All Contributing Basins

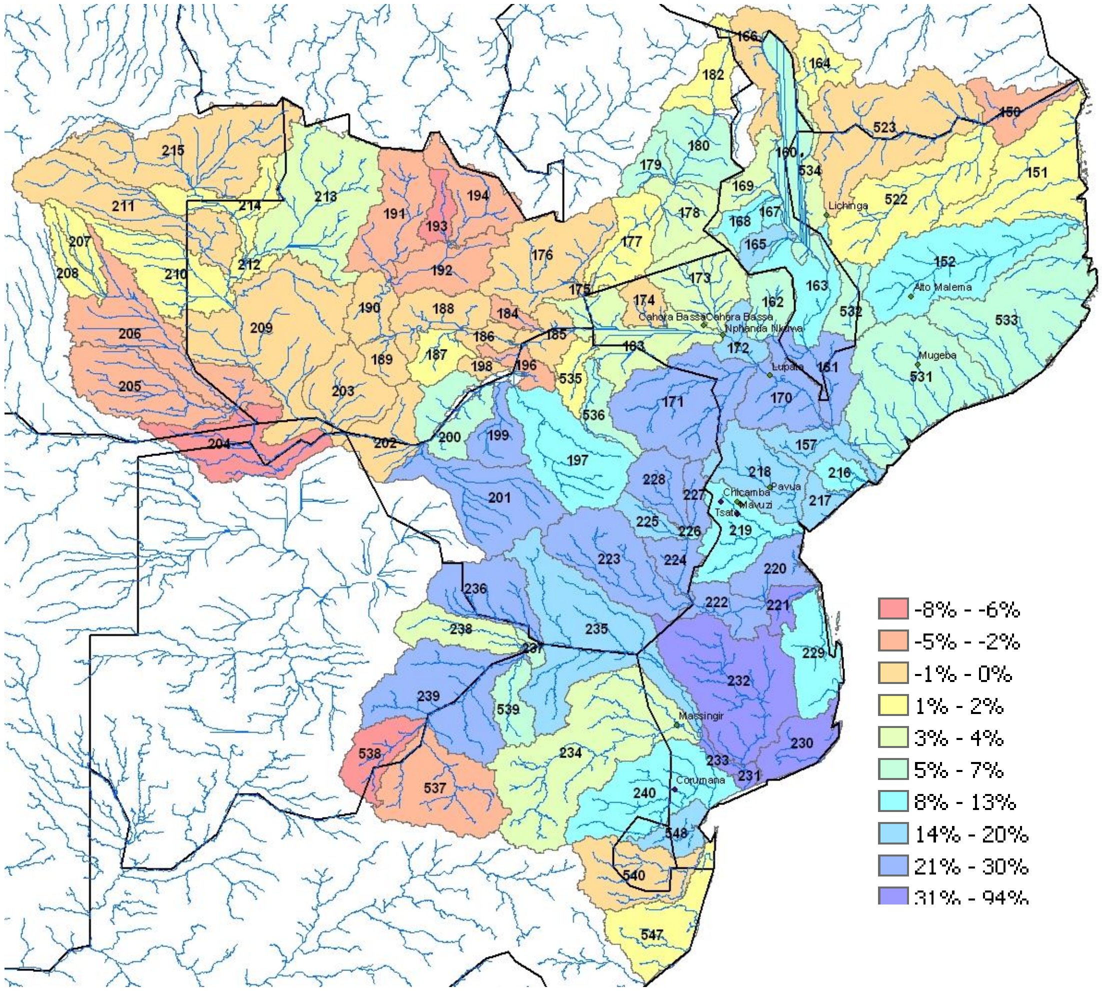


Figure A-11 Percent Change In Annual Runoff for the NCAR ccsm 3.0 a2 (Global Wet) Projection for All Mozambique Basins

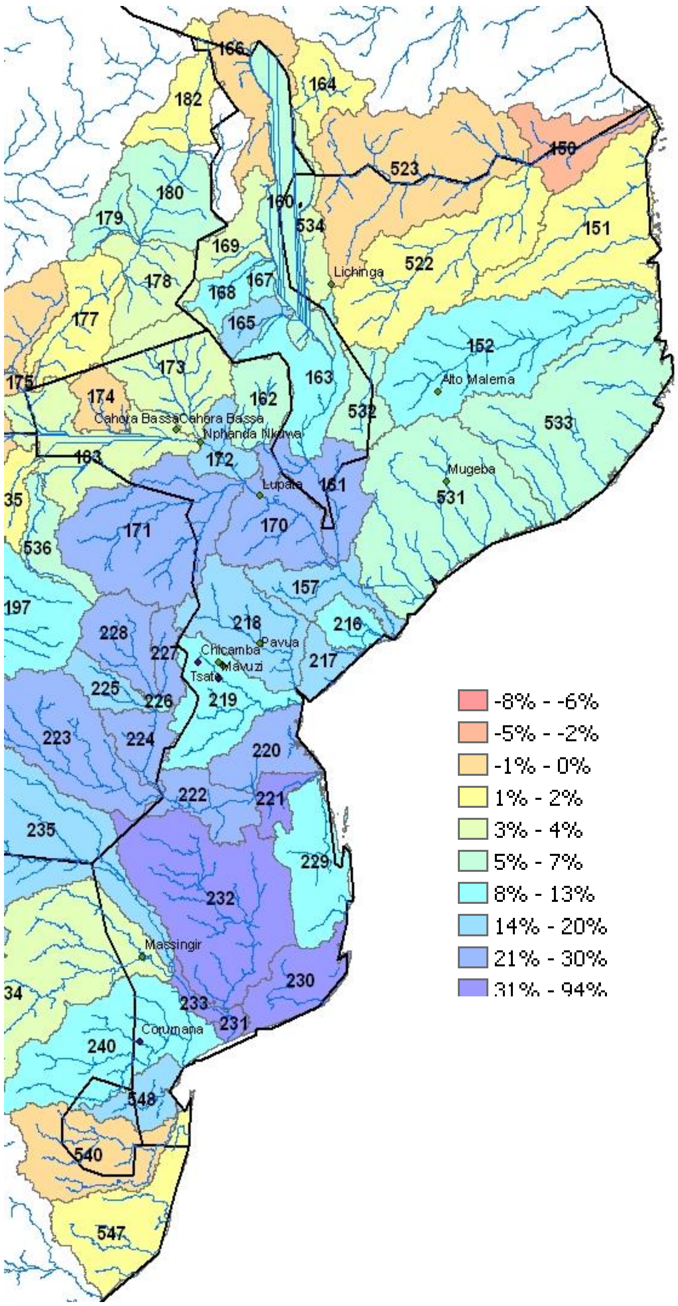


Figure A-12 Percent Change In Annual Runoff for the NCAR ccsm 3.0 a2 (Global Wet) Projection for All Contributing Basins

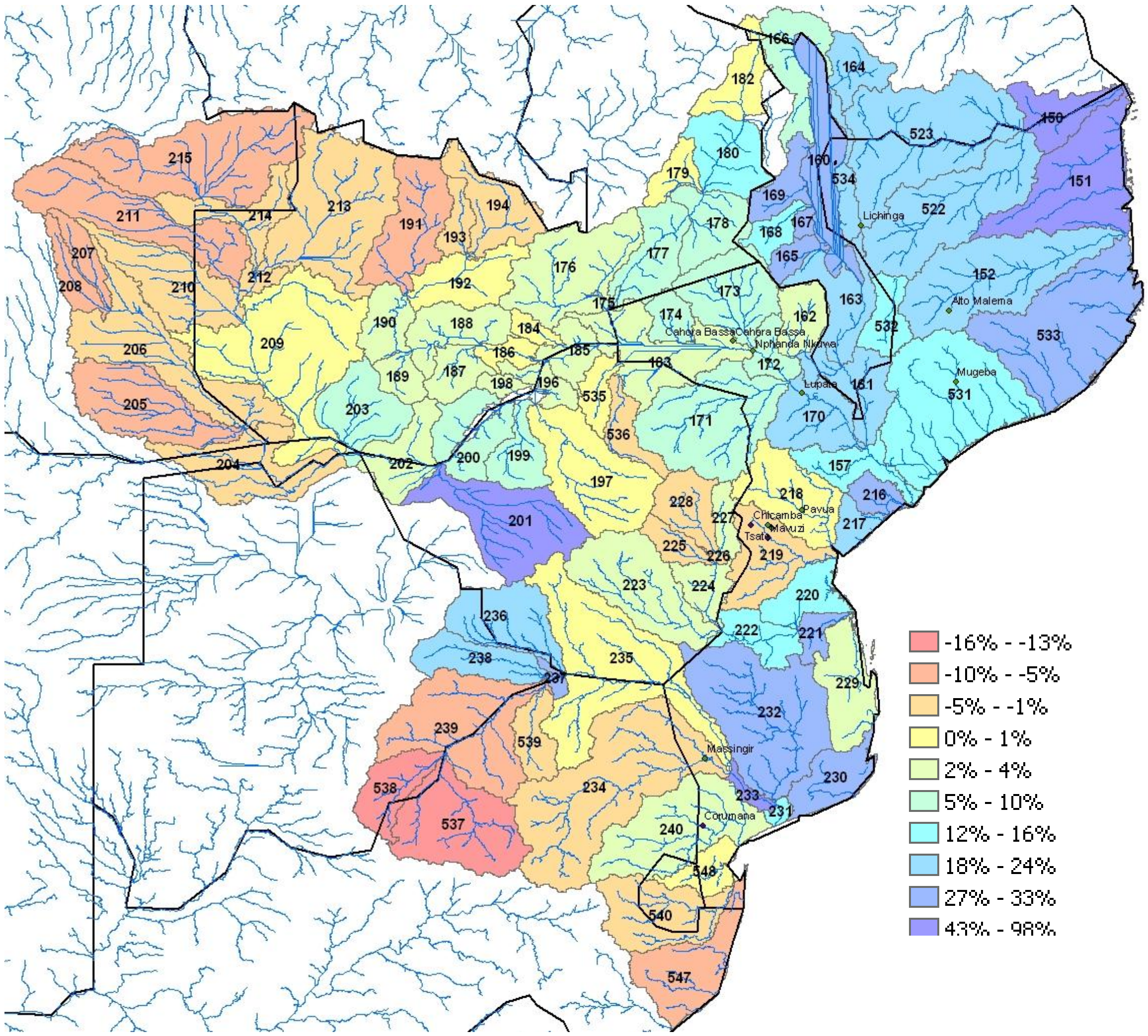


Figure A-13 Percent Change In Annual Runoff for the NCAR ccsm 3.0 a2 (Global Wet) Projection for All Mozambique Basins

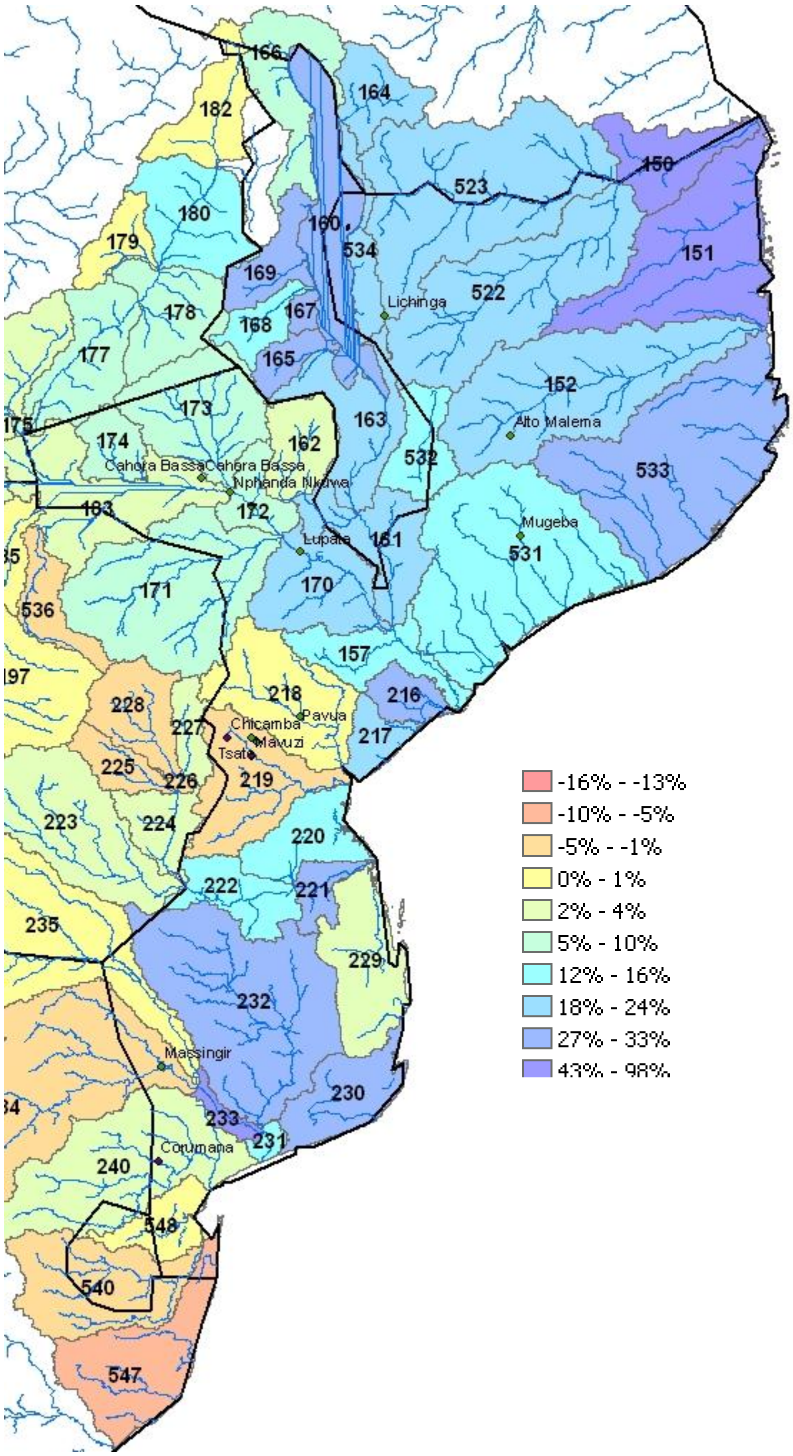


Figure A-14 Historic Runoff Into The Indian Ocean For The Incomati River Basin

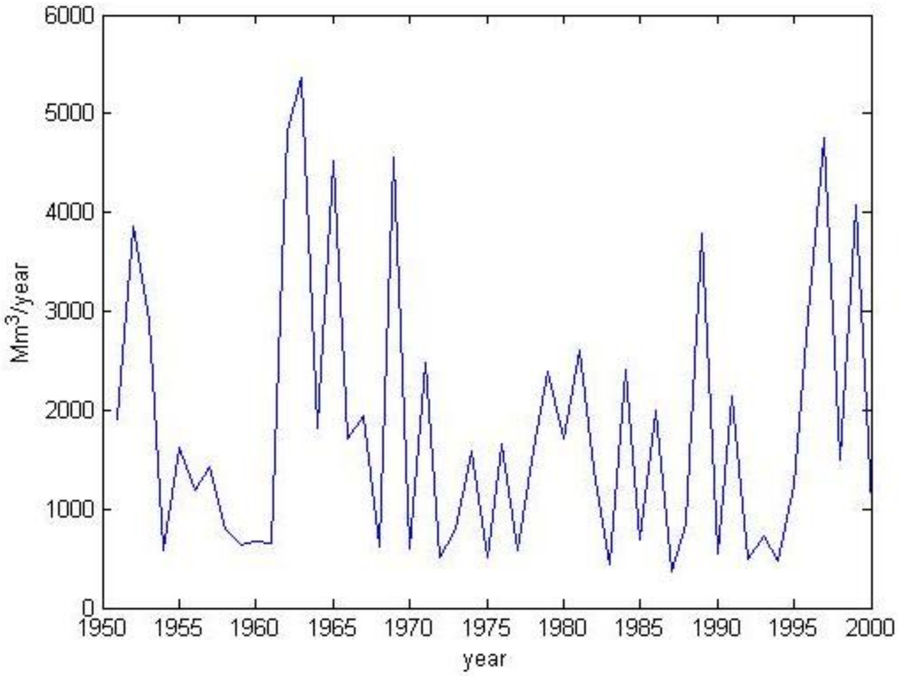


Figure A-15 Future Runoff Into The Indian Ocean For The Incomati River Basin

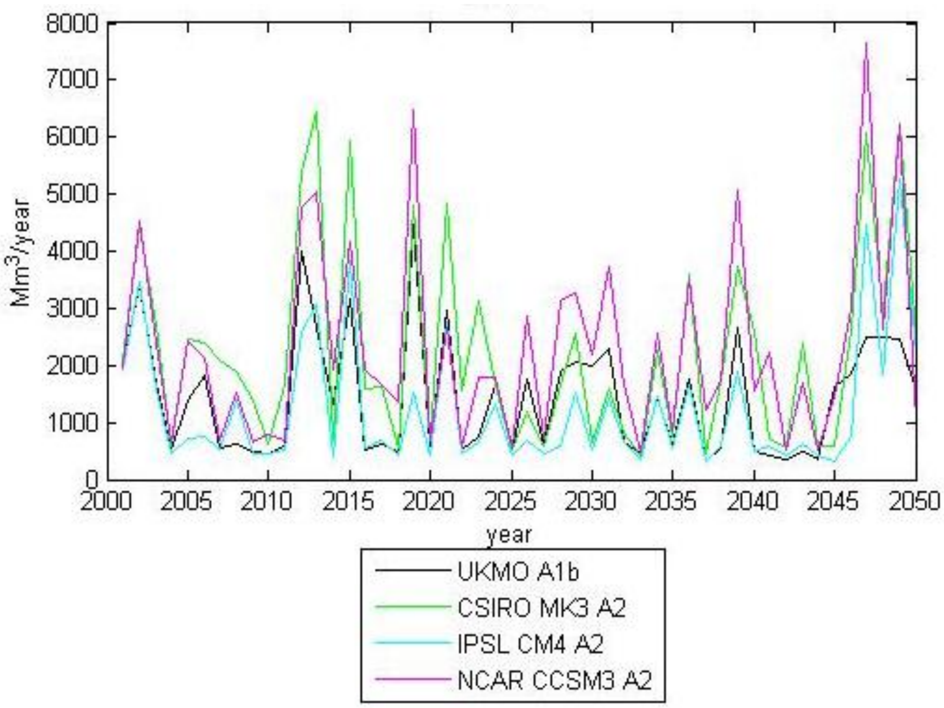


Figure A-16 Historic Runoff Into The Indian Ocean For The Limpopo River Basin

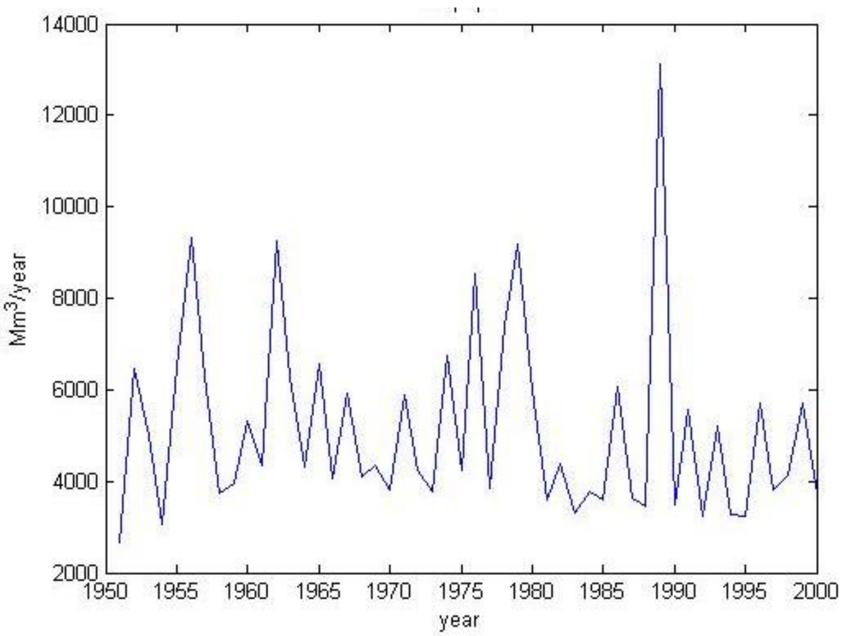


Figure A-17 Future Runoff Into the Indian Ocean For The Limpopo River Basin

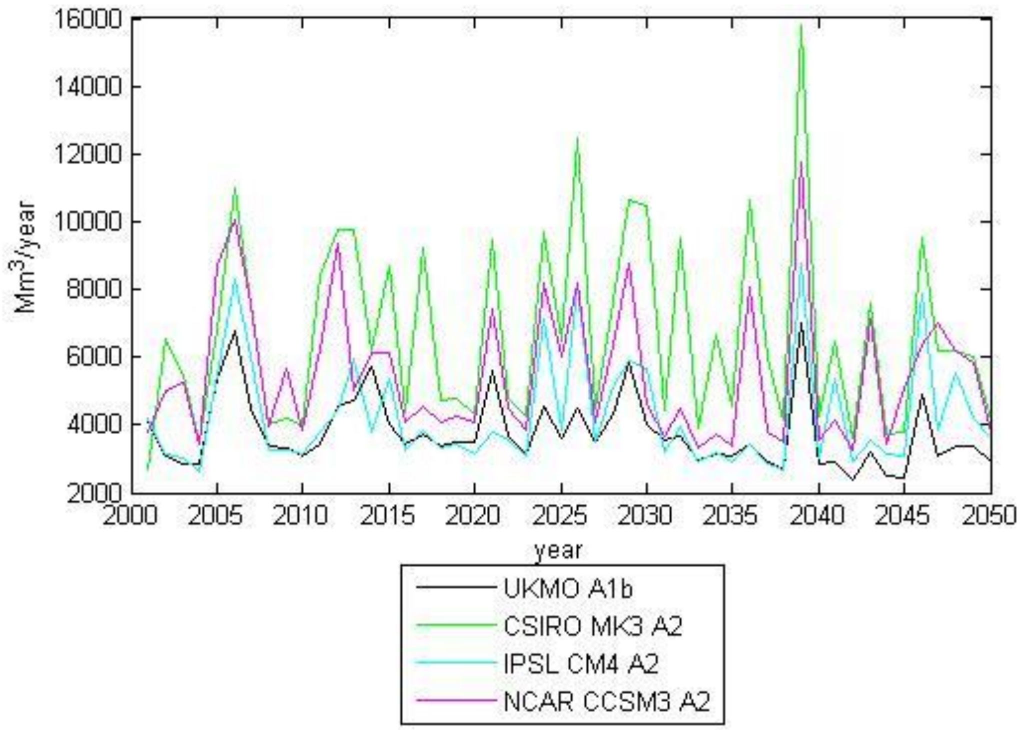


Figure A-18 Historic Runoff Into The Indian Ocean For The Maputo River Basin

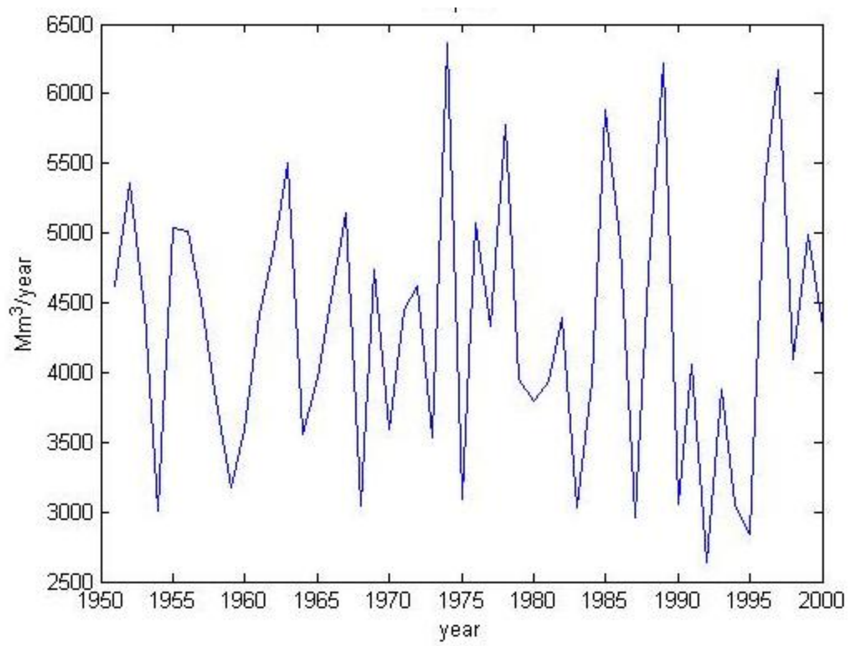


Figure A-19 Future Runoff Into The Indian Ocean For The Maputo River Basin

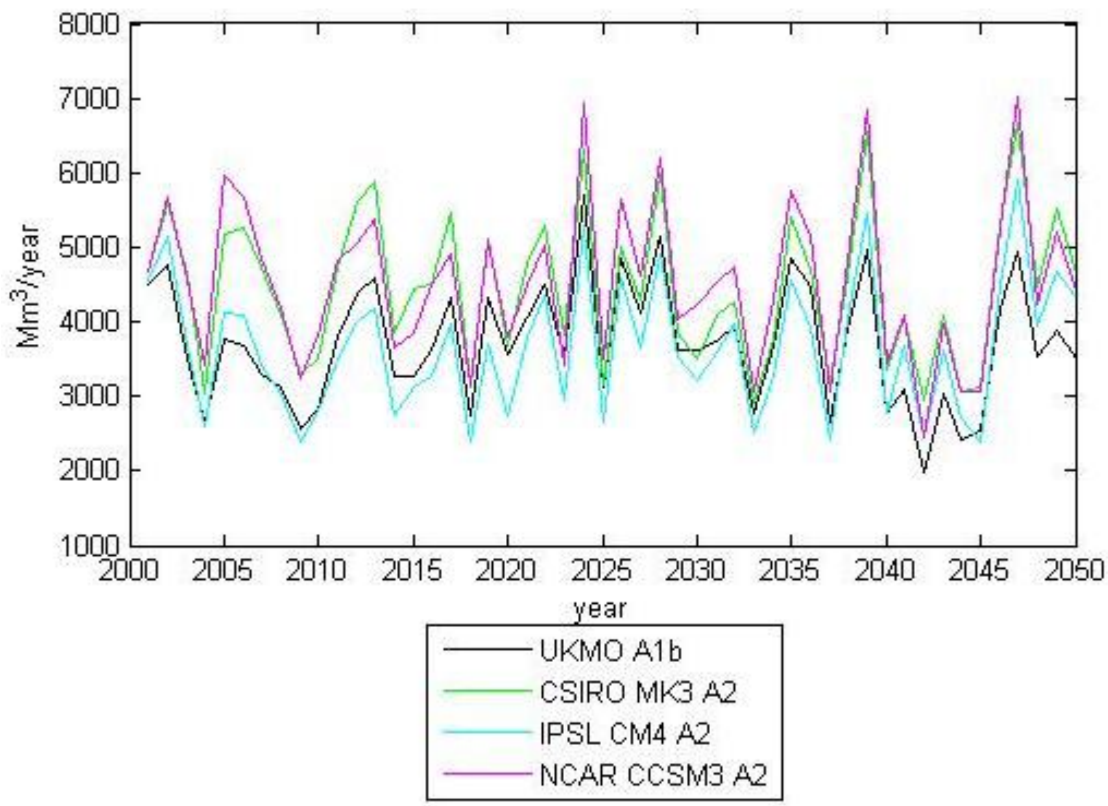


Figure A-20 Historic Runoff Into the Indian Ocean For The Pungoe River Basin

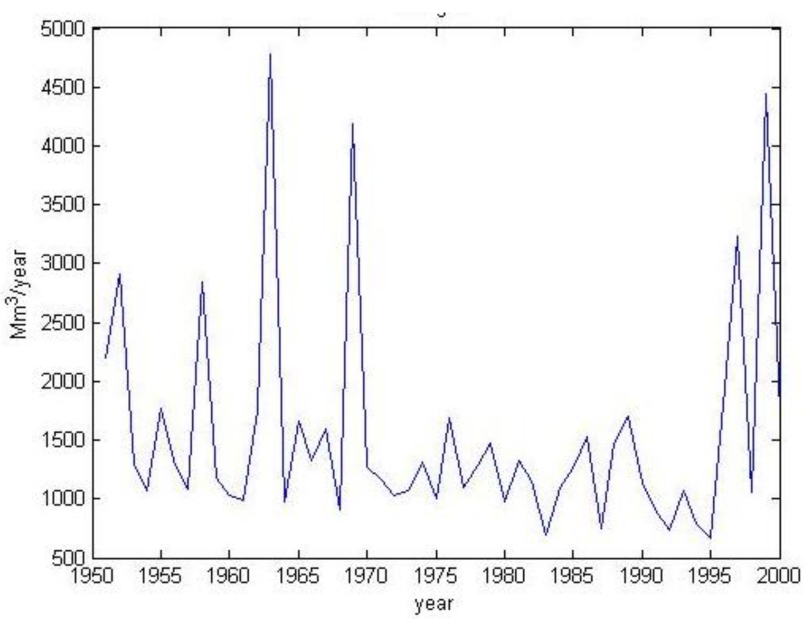


Figure A-21 Future Runoff Into The Indian Ocean For The Pungoe River Basin

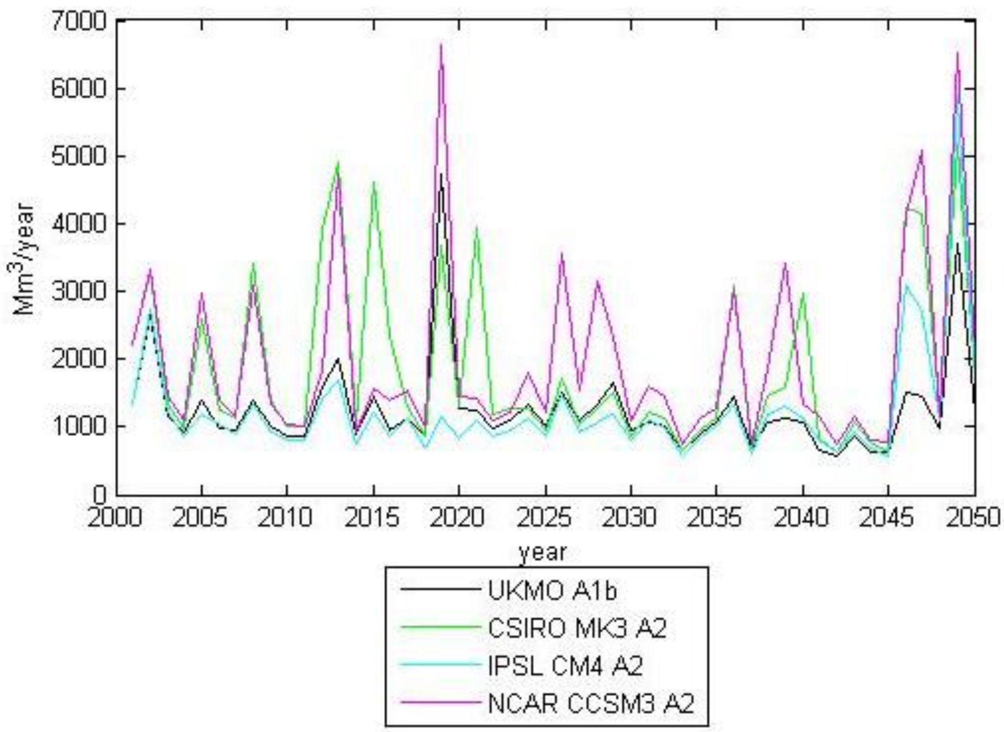


Figure A-22 Historic Runoff Into The Indian Ocean For The Rovuma River Basin

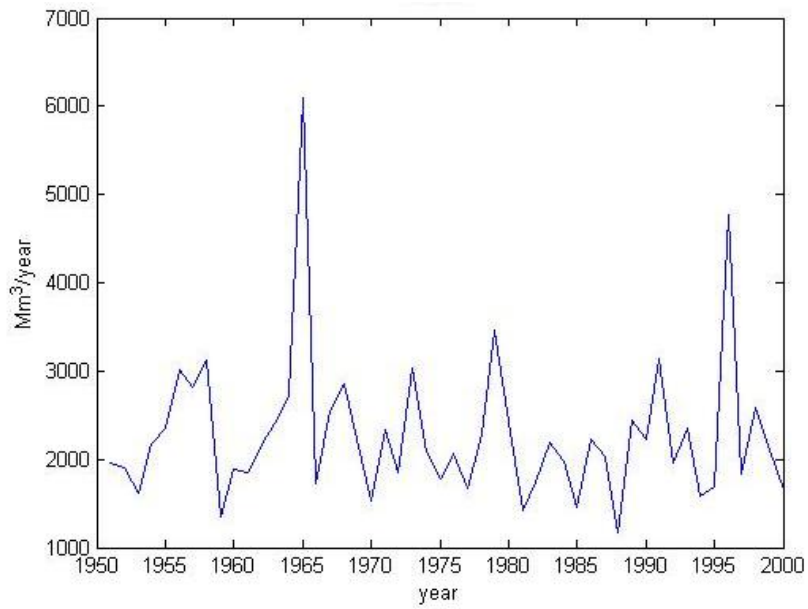


Figure A-23 Future Runoff Into the Indian Ocean For The Rovuma River Basin

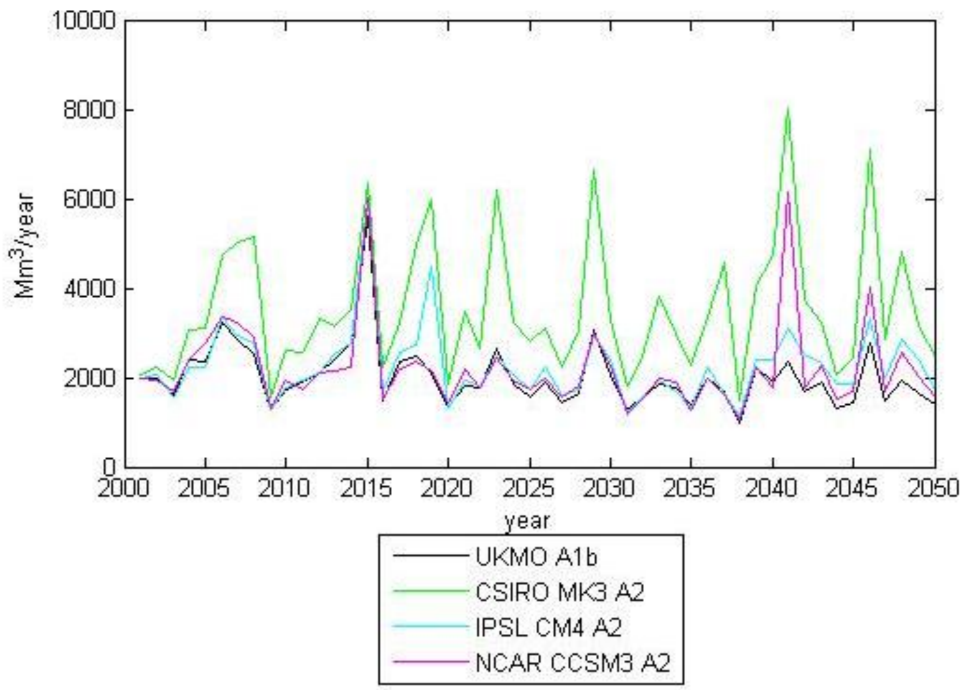


Figure A-24 Historic Runoff Into The Indian Ocean For The Umbeluzi River Basin

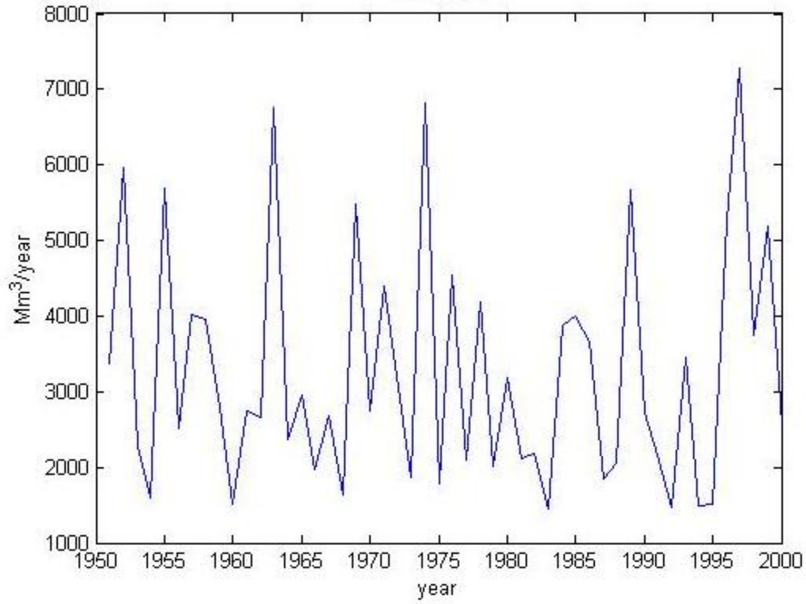


Figure A-25 Future Runoff Into The Indian Ocean For The Umbeluzi River Basin

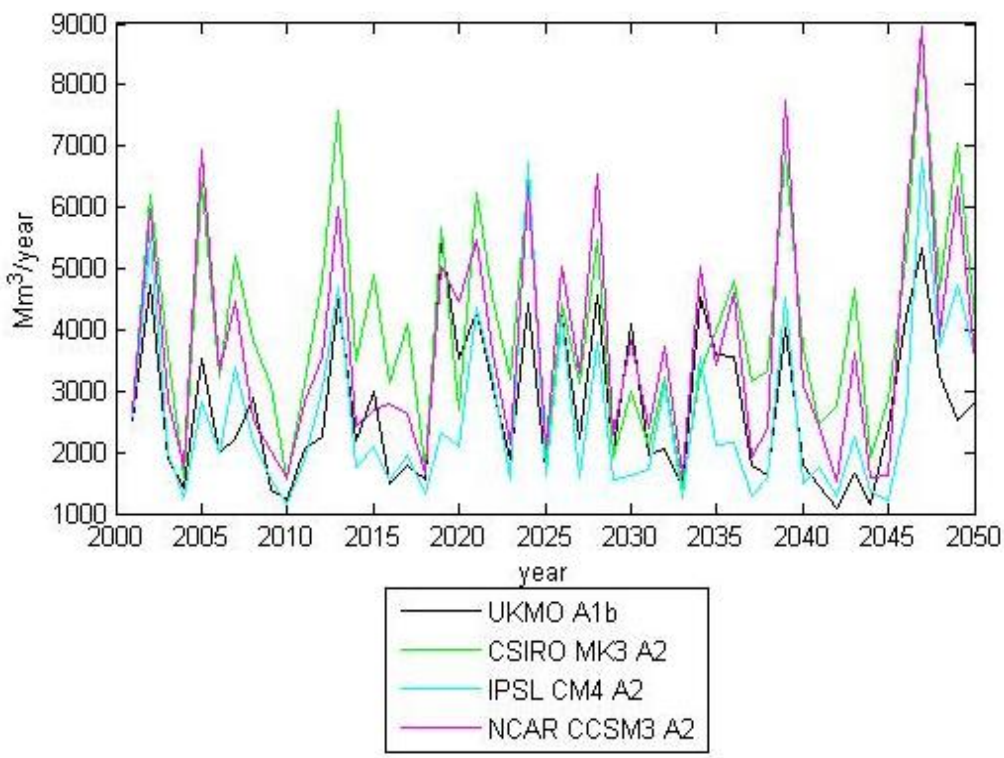


Figure A-26 Historic Runoff Into The Indian Ocean For The Zambezi River Basin

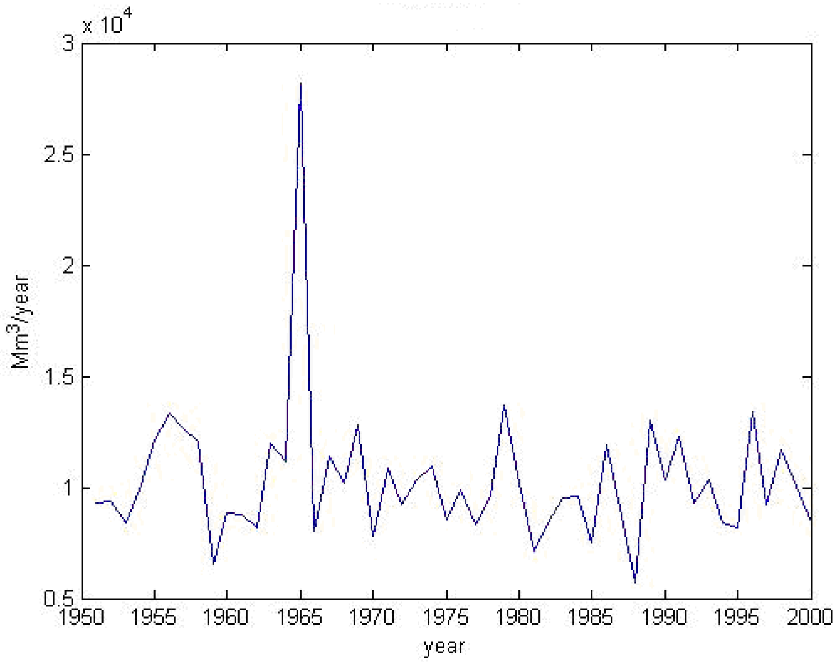
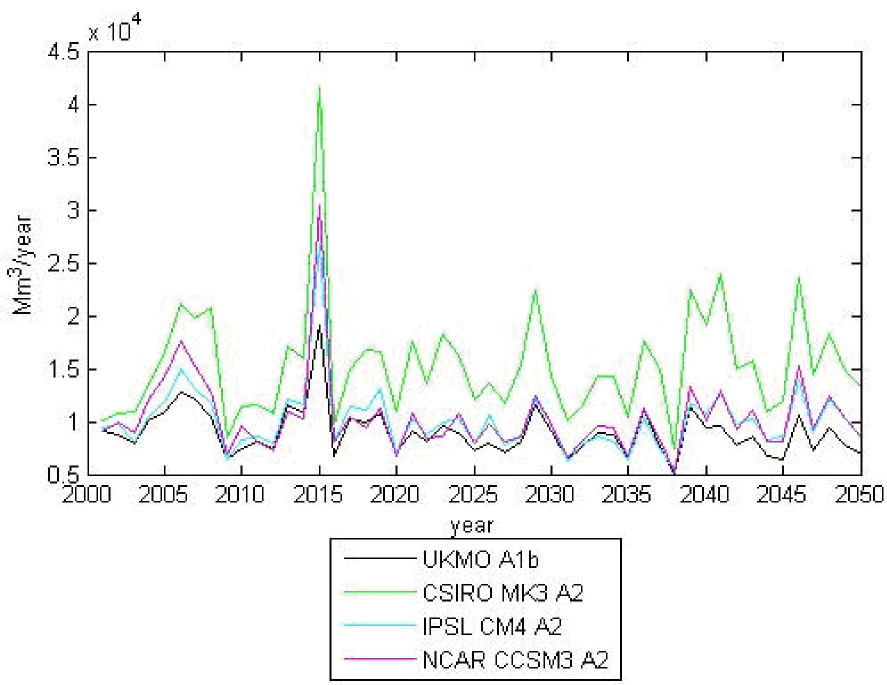


Figure A-27 Future Runoff Into The Indian Ocean For The Zambezi River Basin



Annex 3

The Comprehensive Mozambique Water Resource Model (CMWRM)

Water resources are a very important variable, if not the most important variable, affecting the economics of Southern Africa. According to AQUASTAT's 2005 survey, "Irrigation in Africa in Figures," the combined reservoir capacity of Southern Africa (consisting of Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia, and Zimbabwe) accounts for over 38% of the total reservoir capacity in Africa. Of the five largest dams in Africa, two of them are on the Zambezi River alone, with Kariba storing up to 188 km^3 of water and Cahora Bassa with 39 km^3 of storage potential. In 2004, Southern Africa withdrew 21 657 million m^3 of water from its surface water sources, 70% of which was for agricultural irrigation alone. Rates of water withdrawal are rising as more countries in Southern Africa begin to exploit their surface water resources, thus making Southern Africa's economy increasingly more dependent on water resources.[1]

Mozambique is downstream of most of the countries in Southern Africa. The Zambezi and Limpopo river basins combine to drain much of Angola, Botswana, Malawi, Mozambique, Namibia, South Africa, Tanzania, Zambia, and Zimbabwe's surface water, all of which must pass through Mozambique before it reaches the sea. Being furthest downstream in large river basins has its advantages. It means that there is plenty of water for storage and, with appropriate planning, sustainable and consistent hydropower and irrigation is available for Mozambique. However, being furthest downstream also means that Mozambique is most vulnerable to flooding, poor water quality, and changes in water policy upstream. Water planners need to take both the advantageous and disadvantageous into account in water resource management in order to responsibly plan for the variable flows passing through Mozambique. This means accounting for all water users, both upstream and within Mozambique.

The Comprehensive Mozambique Water Resource Model (CMWRM) attempts to take into account all major water resource management relative to Mozambique, both within the country and upstream. The CMWRM models water use in nine international river basins shared between Mozambique and its neighbors, as well as seven sub-basins fully contained within Mozambique. The nine international basins and the countries they cover are listed in Table A-1 and pictorially represented in Figure A-28. Of the nine, the Zambezi and the Limpopo are the biggest, accounting for almost 6% of Africa's total landmass with the annual runoff on the Zambezi alone averaging 108 km^3.[2] Surface water storage in the Zambezi basin is over 230 km^3, over doubling the basin's average annual runoff.[1] Kariba, located on the Zambezi River on the border between Zambia and Zimbabwe, has 188 km^3 of storage alone. Storage potential this large can have dramatic effects on downstream water users as the natural timing of the runoff is no longer applicable. The only water allowed downstream is what reservoir managers "allow" downstream. The goal of the CMWRM is to account for both upstream Mozambican and water resource management and development simultaneously.

[1] Irrigation in Africa in Figures, AQUASTAT Survey – 2005

[2] Zambezi River Basin Multi-Sector Investment Opportunities Analysis, Preliminary Report

Figure A-28 International Basins And Sub-Basins Relative To Mozambique

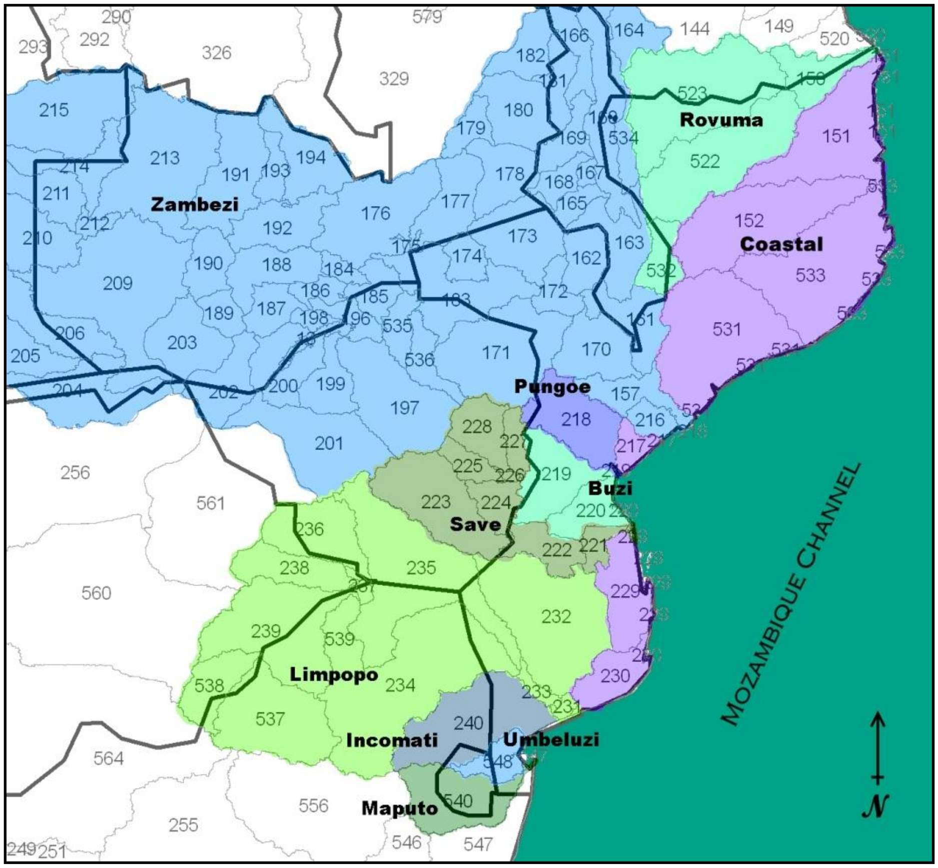


Table A-1 International Basins Shared With Mozambique (Below)

International Basin	Countries
Rovuma	Tanzania
Zambezi	Angola, Botswana, Namibia, South Africa, Swaziland, Tanzania, Zambia, Zimbabwe
Pungoe	Zimbabwe
Buzi	Zimbabwe
Save	Zimbabwe
Limpopo	Botswana, South Africa, Zimbabwe
Incomati	South Africa, Swaziland
Umbeluzi	Swaziland
Maputo	South Africa, Swaziland

Water Input—Rainfall Runoff

The primary source of water into the CMWRM is through rainfall runoff. The model is divided into areas known as sub-catchments. Rainfall runoff is generated at this sub-catchment scale using CliRun at a monthly time-step and translated into streamflow runoff by summing consecutive sub-catchments until an entire basin's streamflow into the ocean is estimated. The CMWRM uses a total of 98 sub-catchments to aid in predicting the streamflow for the nine international basins and Mozambique's internal basins. Future runoff is generated using rainfall and temperature input from the five GCMs. Historic runoff is generated using GCM historic rainfall and temperature simulations such that comparisons made between the historic and future flows are consistent between each GCM. Temperature and precipitation data from each GCM are directly input in to the model to calculate net evapotranspiration at each reservoir.

Current Upstream Water Withdrawals—Irrigation, Municipal, & Industrial

Southern Africa withdrew a total 21,657 Mm^3 of water in 2004: 15,134 Mm^3 for agriculture, 5,194 Mm^3 for municipalities, and 1,330 Mm^3 for industry. This accounted for 10% of the total surface water withdrawal in all of Africa.[1] The agricultural sector in particular is a huge consumer of surface water—and there is an estimated 3.46 million ha of potential irrigable land left to be developed in the Limpopo and Zambezi basins alone. With such a huge potential for surface water withdrawal looming on the horizon, it is crucial that irrigation withdrawals upstream of Mozambique be taken into account. Listed below are the current surface water withdrawals estimated a) for each country upstream of Mozambique and b) within Mozambique. They are gathered from the AQUASTAT 2005 survey, "Irrigation in Africa in Figures." These withdrawals are the data input into the CMWRM as current irrigation withdrawal.

Botswana

- **Total water withdrawal:** 194 million m^3/year
    - Irr./livestock: 80 million m^3/year
    - Domestic: 79 million m^3/year
    - Industry: 35 million m^3/year
- **Total population:** 1,795,000 inhabitants
    - Rural: 48 %
- **Population density:** 3 inhabitants/km^2
- **Per inhabitant:** 112 m^3/year
    - **% of total:** 1.6 %
- Groundwater supplies 2/3 of rural population for water consumption (very dependent on groundwater)
- Water from dams and surface water resources contributes the remaining 1/3
- Citrus and vegetables are the main irrigated crops

Malawi

- **Total water withdrawal:** 1005 million m^3/year
    - Irrigation: 810 million m^3/year
    - Domestic: 148 million m^3/year
    - Industry: 47 million m^3/year
- **Total population:** 1 2,337,000 inhabitants
    - Rural: 83 %
- **Population density:** **104** **inhabitants/km^2**
- **Per inhabitant:** 88 m^3/year
    - % of total: 5.8 %
- **Total irrigation area:** 56390 ha
    - Groundwater: 0.05 %
    - Surface water: 99.95 %
- **Irr. land growth rate (1992-2002)** 7.3 %

Namibia

Total water withdrawal:	300	million m^3/year
Irrigation:	136	million m^3/year
Livestock:	77	million m^3/year
Domestic:	73	million m^3/year
Industry:	14	million m^3/year
Total population:	2,011,000	inhabitants
Rural:	67	%
Density:	2.4	inhabitants/km^2
Per inhabitant:	150	m^3/year

South Africa

Total water withdrawal:	12496	million m^3/yr
Irr. + livestock:	7836	million m^3/yr
Domestic:	3904	million m^3/yr
Industry:	756	million m^3/yr
Population:	45214000	inhabitants
Rural:	42	%
Per capita:	284	m^3/yr
Full or partial control irr.:	1,498,000	ha
Groundwater:	8.5	%
Surface water:	91.5	%
Avg. increase in irr.:	2.8	%

Swaziland

Total water withdrawal:	1042	million m^3/year
Irrigation:	993	million m^3/year
Livestock:	13	million m^3/year
Domestic:	24	million m^3/year
Industry:	12	million m^3/year
Total population:	1,083,000	inhabitants
Rural:	76	%
Density:	6	inhabitants/km^2
Per inhabitant:	998	m^3/year

United Republic of Tanzania

Total water withdrawal:	5184	million m^3
Irr:	4425	million m^3
Livestock:	204	million m^3
Domestic:	527	million m^3
Industry:	25	million m^3
Population:	37,671,000	inhabitants
Rural:	63	%
Density:	40	inhabitants/km^2
Per person:	143	m^3/inhabitant

Mozambique

Below are preliminary numbers based on the AQUASTAT 2005 Survey. Further coordination between World Bank staff, INGC, MDP, and the EACC team is needed to compile a complete agricultural, industrial, and municipal withdrawal scheme for the current situation.

- **Total Withdrawal:** 635 million m^3/year
  - Irr. & livestock 550 million m^3/year
  - Domestic 70 million m^3/year
  - Industry 15 million m^3/year

- **Total Population:** 9,182,000 inhabitants
  - Rural 63 %
  - Density 24 inhab/km^2
  - Renewable water resources p.c.: 11,318 m^3/year/person

- **Groundwater Potential Is Considerable In The Alluvial Formations Near The Rivers:**
  - Zambezi and Incomati groundwater: 70,000 m^3/day
  - From Zambezi R.: 66 %

- **Irrigation Potential (FAO):** 3,072,000 E3 ha
  - % in Zambezi prov: 60 %
  - S. provinces have highest need for irrigation but only a small portion of the land suitable for irrigation

- **Irrigation History:**
  - 1968 65,000 ha
  - 1973 100,000 ha
  - 1975 - early 80s 120,000 ha

- **Currently Equipped For Irrigation:** 118,120 ha
  - Actually irrigated: 40,063 ha

- **Most Irrigation Schemes Use Surface Water:**
  - Small sector irrigation uses groundwater to a limited extent

- **Irrigation Schemes:**
  - Small (class A) <50 ha 6389 ha total
  - Medium (class B) 50 - 500 ha 19647 ha total
  - Large (class C) >500 ha 92084 ha total

Table A-2 Irrigation Statistics by Region In Mozambique

Item	North		Centre		South		Total	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Area Equipped for irrigation:								
Class_A	592	17	1428	4	4369	6	6389	5
Class_B	1760	53	6653	17	11234	15	19647	17
Class_C	1000	30	30949	79	60135	79	92084	78
Total	3352	100	39030	100	75738	100	118120	100
Area actually irrigated:								
Class_A	200	30	624	4	2452	11	3276	8
Class_B	461	70	1584	10	2635	11	4680	12
Class_C	0	0	14049	86	18058	78	32107	80
Total	661	100	16257	100	23145	100	40063	100
Part of equipped area actually irrigated:								
Class_A	-	34	-	44	-	56	-	51
Class_B	-	26	-	24	-	23	-	24
Class_C	-	0	-	45	-	30	-	35
Total		20		42		31		34
Irrigation technology in actually irrigated area:								
Surface irrigation	656	99	4200	26	12000	52	16856	42
Sprinkler irrigation	0	0	11530	71	8330	36	19860	50
Localized irrigation	5	1527	3	2815	12	3347	8	
Total	661	100	16257	100	23145	100	40063	100
Main irrigated crops:								
Sugar cane	0	0	13799	90	10059	50	23858	67
Vegetables	301	100	210	2	6500	32	7011	20
Rice	0	0	480	3	3650	18	4130	11
Tobacco	0	0	445	3	0	0	445	1
Citrus	0	0	370	2	0	0	370	1
Total	301	100	15304	100	20209	100	35814	100

Annex 3

WEAP21 Model Description[3]

Background

Many regions are facing formidable freshwater management challenges. Allocation of limited water resources, concerns regarding environmental quality, planning under climate variability and uncertainty, and the need to develop and implement sustainable water use strategies are increasingly pressing issues for water resource planners. Conventional supply-oriented simulation models are not always adequate for exploring the full range of management options.

Over the last decade, an integrated approach to water development has emerged that places water supply projects in the context of demand-side management, water quality, and ecosystem preservation and protection. The resulting Water Evaluation and Planning (WEAP) System, a microcomputer tool for integrated water resources planning, incorporates these issues into a practical tool for water resource planning and policy analysis. WEAP provides a comprehensive, flexible and user-friendly framework for planning and policy analysis. WEAP places demand-side issues such as water use patterns, equipment efficiencies, re-use strategies, costs, and water allocation schemes on an equal footing with supply-side topics such as stream flow, groundwater resources, reservoirs, and water transfers.

WEAP operates on the basic principle of a water balance and can be applied to municipal and agricultural systems, a single watershed, or complex transboundary river basin systems. Moreover, WEAP is distinguished by its integrated approach to simulating a broad range of natural and engineered components of these systems, including rainfall runoff, baseflow, and groundwater recharge from precipitation; sectoral demand analyses; water conservation; water rights and allocation priorities, reservoir operations; hydropower generation; pollution tracking and water quality; vulnerability assessments; and ecosystem requirements. A financial analysis module also allows the user to investigate cost-benefit comparisons for projects. This integrated approach gives planners a more comprehensive view of the broad range of factors that must be considered in managing water resources for present and future use.

WEAP operates in many capacities:

- **Water balance database:** WEAP provides a system for maintaining water demand and supply information.
- **Scenario generation tool:** WEAP simulates water demand, supply, runoff, streamflows, storage, pollution generation, treatment and discharge and instream water quality.
- **Policy analysis tool:** WEAP evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems.

The WEAP Approach

The WEAP analysis represents a system in terms of its various supply sources (e.g., rivers, creeks, groundwater, reservoirs, and desalination plants), withdrawal, transmission and wastewater treatment facilities, water demands, pollution generation, and ecosystem requirements. The data structure and level of detail can be easily customized to meet the requirements and data availability for a particular system and analysis.

WEAP Applications Generally Include Several Steps:

Study definition: The time frame, spatial boundaries, system components, and configuration of the problem are established.

Current accounts: A snapshot of actual water demand, pollution loads, resources and supplies for the system are developed. This can be viewed as a calibration step in the development of an application.

Scenarios: A set of alternative assumptions about future impacts of policies, costs, and climate—on, for example, water demand, supply, hydrology, and pollution—can be explored. (Possible scenario opportunities are presented in the next section.)

Evaluation: The scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

Examples of WEAP Scenario Analyses

Scenario analysis is central to WEAP. Scenarios are used to explore the model with an enormous range of "what if" questions, such as:

- What if population growth and economic development patterns change?
- What if reservoir operating rules are altered?
- What if groundwater is more fully exploited?
- What if water conservation is introduced?
- What if ecosystem requirements are tightened?
- What if a conjunctive use program is established to store excess surface water in underground aquifers?
- What if a water recycling program is implemented?
- What if a more efficient irrigation technique is implemented?
- What if the mix of agricultural crops changes?
- What if climate change alters demand and supplies?
- How does pollution upstream affect downstream water quality?
- How will land use changes affect runoff?

WEAP Development

The Stockholm Environment Institute provided primary support for the development of WEAP. The Hydrologic Engineering Center of the US Army Corps of Engineers funded significant enhancements. A number of agencies, including the UN, World Bank, USAID, US EPA, IWMI, AwwaRF and the Global Infrastructure Fund of Japan have provided project support. WEAP has been applied in water assessments in dozens of countries, including the United States, Mexico, Brazil, Germany, Ghana, Burkina Faso, Kenya, South Africa, Mozambique, Egypt, Israel, Oman, Central Asia, India, Sri Lanka, Nepal, China, South Korea, and Thailand.

Annex 3
Crop Modeling

Introduction

Crop models are used to predict future yields, estimate the effects of new agricultural management techniques on yields, and to understand the effects of crop and soil type on food productivity and soil fertility. Many crop models have been developed over the last thirty to forty years in response to new research and more accessible computer technology. While crop simulators continue to be primarily used for academic purposes, farmers and policy makers are beginning to trust and use them.

The biggest question surrounding crop modeling is whether or not crop models can predict future yields. Unfortunately, like most computer models of physical, chemical, or biological processes, the model's accuracy is heavily dependent on the model's input. All crop simulators require information on soil type, crop type, and weather, because these three factors have great effects on crop production. Soil parameters can be measured in a field one point at a time, but soil properties can change drastically on a small scale both vertically and horizontally. The growth of different crop types, which is based on complicated biological and chemical processes, also varies greatly by genotype geographic region, and even the individual plant. Weather, because of its chaotic behavior and dependence on both the large-scale and small-scale changes in the land and atmosphere, also continues to be very difficult to predict. In spite of these uncertainties, research in crop simulation continues because the human race is almost completely dependent on cultivated food. So, although the accuracy of crop models could be dwindled down to a "best guess" at yield estimations, the understanding of the crop's sensitivity to policy and decisions made by farmers is important.

There are many existing crop models. Each model has been built to solve a specific range of problems. The model's input and calculations depend on the input available and the accuracy that is required. For example, CropWat, a model developed by the Food and Agriculture Organization of the United Nations, is a very simple 1-dimensional crop model. CropWat requires very limited input and assumes no vertical differences in soil moisture, and assumes that soil moisture cannot exceed field capacity. CropWat also simulates water stress on crops, ignoring any nutrient or solar stresses on a daily time-step. But CropWat is a tool to plan irrigation patterns for use by poor farmers in arid to semi-arid regions. So, CropWat does not need to calculate the effects of waterlogging or daily precipitation patterns. The model can assume that the farmer will irrigate and will not over-irrigate. SWAP, Soil-Water-Atmosphere-Plant, on the other hand, is a much more complicated soil moisture scheme, implementing Richard's equation on a time-step less than 30 minutes. SWAP requires more input and a faster computer, but models the movement of moisture in the soil layer using a more dynamic approach, allowing SWAT to claim more confidence in its solution.

CliCrop was developed because there were no existing models that the authors of this paper found to be adequate to solve certain problems. Specifically, these problems include modeling two water management techniques, zai holes and mulching, and also estimating the effects of climate change on crop yields, including both water stress from insufficient and excess water. The larger vision of CliCrop, which will continue beyond this paper, is that CliCrop can be a tool used to find agricultural techniques that could possibly offset the damages climate change may have on crop yields.

At the beginning, CliCrop was to be a modification of CropWat, and CropWat could still be considered the base of CliCrop. But as CliCrop developed, it began to look less and less like

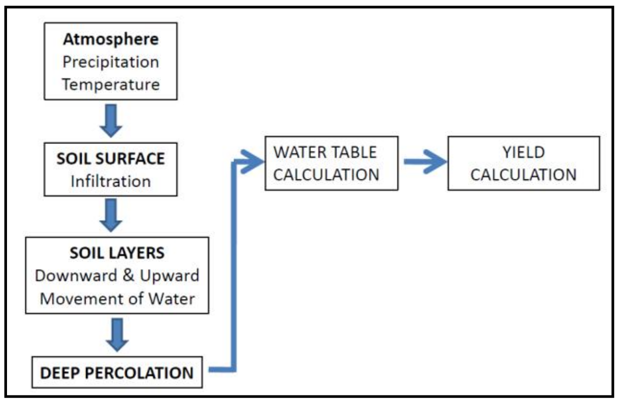
CropWat. CliCrop, as it stands now, maintains the same minimal input required by CropWat while reaching a more accurate yield estimation for both rainfed and irrigated agriculture.

In order to model the negative effects of waterlogging, a dynamic soil profile needed to be added to CropWat. This modification proved to be the most difficult. Many other crop models were reviewed for guidance, and some of their methods were borrowed for the development of CliCrop. Both the mathematics and the GUI were written in Matlab.

Structure of CliCrop

Figure A-29 below shows the modeling process as a whole. Each individual process is explained in detail in this annex.

Figure A-29 Schematic of The CliCrop Model Procedure



The effects of the atmosphere are modeled indirectly in the soil layer through the extraction of evapotranspiration and the infiltration into the soil layers. The model uses the soil properties and precipitation amount to calculate the infiltration using the US$A Curve Number method. Then the model calculates the soil moisture in each soil layer. The model then calculates the amount of moisture allowed to percolate into the deep soil layers. The water table is then measured and a yield is calculated.

Input

CliCrop was designed for large-scale yield calculations, using both future and historical weather data and available soil data. Inputting data into CliCrop is simple and the amount of required input is minimized in order to avoid as much error as possible involved with the input.

Precipitation

Since CliCrop runs on a daily timescale, total daily precipitation data are required in millimeters per day. The historic precipitation data currently built into the model come from the Collaborative Historical African Rainfall Model (CHARM). The CHARM database contains 36 years (1961-1996) of daily historic rainfall data for all of Africa estimated by satellite and rain gauge data (Funk, et al., 2003).

Potential Evapotranspiration

Potential evapotranspiration (ET) is a measurement of the atmosphere's ability to extract moisture from the soil both through evaporation and transpiration measured in mm/day. Table A-3 below shows the range of potential ET for different climatic regions (Allen, et al. 1998).

Table A-3 Range of Potential ET

Average ET for different agroclimatic regions in mm/day

Regions	Mean daily temperature (°C)		
	Cool ~10°C	Moderate 20°C	Warm >30°C
Tropics & subtropics			
humid & sub-humid	**2 - 3**	**3 - 5**	**5 – 7**
arid & semi-arid	**2 - 4**	**4 - 6**	**6 - 8**
Temperate Region			
-humid & sub-humid	**1 - 2**	**2 - 4**	**4 – 7**
-arid & semi-arid	**1 - 3**	**4 - 7**	**6 - 9**

Potential Evapotranspiration is estimated based on a mean daily temperature, daily temperature range, and latitude. The modified Hargreaves equation (Hargreaves, ASCE and Allen 2003) is used to find the potential ET based on these parameters.

Crop Type

All of the crop parameters used by CliCrop were first developed by FAO in CROPWAT (Allen, et al. 1998). When CliCrop runs, it retrieves the crop parameters based on the crop specified by the user. These parameters include:

- **Single (time averaged) crop coefficients, K_c:** These values are used in the calculation of actual and potential evapotranspiration. There are three coefficients for each crop. These values are used to create a coefficient for each day of the growing season (see Table 12 in FAO Drainage Paper No. 56) (Allen, et al. 1998).
- **Basal Crop Coefficient, K_{cb}:** These values are only used to find the reduction in potential evapotranspiration caused by mulching. There are three coefficients for each crop similar to K_c. These values can be used to calculate actual and potential transpiration (see Table 17 in FAO Drainage Paper No. 56) (Allen, et al. 1998).
- **Crop Stage Durations:** The length in days of each of the four stages in the growing season. These stages include the initial, development, middle, and final.
- **Yield Coefficients:** Values used to weight the effect of water losses on the yield for each of the four stages of growth. These values are used in the yield calculation equation.
- **Root Growth Per Day:** Roots will grow at this length (in mm) per day when growth is allowed.
- **Initial Root Depth:** It is assumed that the root zone starts at an initial depth. This concept and value are both borrowed from CROPWAT and Irrigation and Drainage Paper No. 56 (Allen, et al. 1998).
- **Growing Season Duration:** Length of growing season in days. This value is the sum of the Crop Stage Durations explained above.

Soil Properties

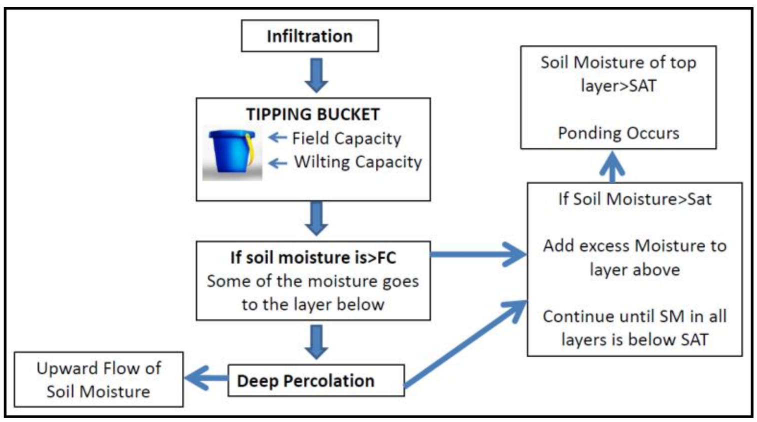
Estimations if *Unknown* is selected: the only soil properties required for CliCrop to run are hydraulic conductivity, wilting point, field capacity, and saturation. These parameters are estimated based on the location. A dataset was acquired from the FAO Soil Map of the World that contains clay and sand content. The wilting point and field capacity are estimated based on methods developed by the National Center for Atmospheric Research (NCAR) (Oleson et al. 2004). A semi-impervious layer is assumed to be at a depth of 2 meters from the soil surface. The semi-impervious layer allows soil moisture to percolate at a rate of 1% the hydraulic conductivity when excess soil moisture exists in the bottom layer.

When either the Wise Soil Profile is used or the soil parameters are known, the model assumes a semi-impervious layer at the bottom on the soil profile, as described above. When the soil parameters are known, the model also assumes a semi-impervious layer at 2 meters.

Water Transport

Figure A-30 below is a schematic of the process used by the model to solve for soil moisture in each soil layer. By default, the model has 20 layers, each 10 cm deep. If the WISE soil profile is used, the number of layers is determined by the number of layers in the WISE soil profile.

Figure A-30 Schematic of The Soil Moisture Process Used By CliCrop



Once infiltration is calculated, the total amount of moisture infiltrated into the soil layer is added to the first layer. That layer is filled from wilting point to field capacity. Most of the moisture over field capacity is allowed to percolate to the layer below. The model then checks if the soil moisture in the layer is above saturation. If so, the model adds the moisture above saturation to the layer above until all moisture has found "space." If the top layer is saturated and excess soil moisture remains, the excess is considered lost to ponding. The model does this for each layer from the top to the bottom soil layer. At the bottom soil layer, the model calculates deep percolation, which allows some of the moisture in the bottom soil layer to percolate past the semi-impervious layer. This moisture is considered lost to the deep soil layers. The model then checks one more time for any layer whose soil moisture is above saturation. Once all of this is finished, the model calculates the upward flow of soil moisture.

Effective Precipitation

Once the model retrieves the precipitation, the runoff is calculated based on the hydraulic conductivity of the first soil layer, the moisture content of the first soil layer, and the cover type using the National Resource Conservation Services' (NRCS) Curve Number Method. The curve number is estimated by a graph created by NRCS and printed in the Drainage Manual produced by the Bureau of Reclamation, a part of the U. S. Department of the Interior (see graph in the appendix) (Bureau of Reclamation, 1993).

Evapotranspiration

The effective precipitation is then added to the moisture of the first layer of the soil profile. CliCrop then calculates the soil moisture, one layer at a time, starting with the top layer and moving down to the bottom of the soil profile. During the dormant season, evaporation is removed from the top 12.5 cm of the soil profile using the following equations from FAO Irrigation and Drainage paper No. 56: (Allen, et al. 1998)

Equation 1 $TEW^l = (FC^l - 0.5 \cdot WP^l) \cdot delZ$

$$K_r^{l,t} = \frac{SM^{l,t-1} - 0.5 \cdot (WP^l \cdot delZ)}{(1 - pe) \cdot TEW^l}$$

$$ETS^{l,t} = \frac{(ET0^t \cdot asm)}{nls0}$$

$$ETSA^{l,t} = ETS^{l,t} \cdot K_r^{l,t}$$

TEW^l = total evaporable water of layer l (mm)
FC^l = field capacity of layer l
WP^l = wilting point of layer l
delZ = thickness of layer l (mm)
$K_r^{l,t}$ = limiting coefficient of the evaporation for layer l at day t, $0 \le K_r^{l,t} \le 1$
$SM^{l,t-1}$ = soil moisture of layer l at the day before t (mm)
Pe = 0.4, fraction of TEW value for maximum evaporation
$ETS^{l,t}$ = maximum evaporation from layer l (mm)
$ET0^t$ = potential ET at day t (mm)
asm = 0.30, antecedent moisture coefficient; fraction of ET0 as evaporation
nls0 = number of layers in evaporation zone (top 12.5 cm)
$ETSA^{l,t}$ = soil moisture removed from layer l at time t due to evaporation (mm)

CliCrop contains two methods for determining ET: the single crop coefficient method and the dual crop coefficient method. If the single crop coefficient method is used, during the growing season, ET is removed from the root zone using the following equations from FAO Irrigation and Drainage paper No. 56 (Allen, et al. 1998):

Equation 2 $ETC^{l,t} = \dfrac{ET0^t \cdot K_C^t}{nlsr^d}$

$$p = p_{tab} + 0.04 \cdot (5 - ETC^{l,t})$$

$$TAW^l = delZ \cdot (FC^l - WP^l)$$

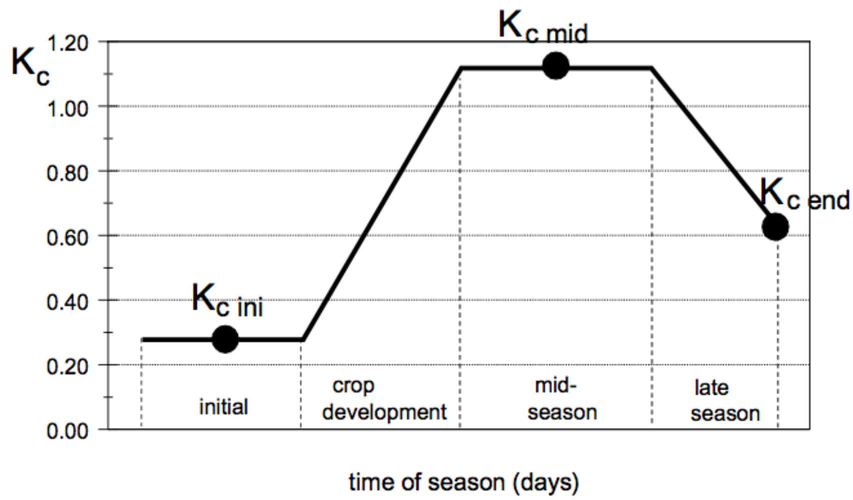
$$K_s^{l,t} = \frac{SM^{l,t-1} - WP^l \cdot delZ}{(1 - p) \cdot TAW^l}$$

$$ETA = K_s^{l,t} \cdot ETC^{l,t}$$

$ETC^{l,t}$ = crop specific ET demand (mm)
$ET0^t$ = potential ET at day t (mm)
K_C^t = crop coefficient at day t
$nlsr^d$ = number of layers in root zone
p = soil water depletion fraction
p_{tab} = soil water depletion fraction for no stress
(Listed in table 22 of FAO Irrigation and Drainage Paper No. 56)
TAW^l = total available water of layer l (mm)
delZ = thickness of layer l (mm)
FC^l = field capacity of layer l
WP^l = wilting point of layer l
$K_s^{l,t}$ = limiting coefficient for the calculation of actual ET for layer l at day t, $0 \le K_r^{l,t} \le 1$
$SM^{l,t-1}$ = soil moisture of layer l at the day before t (mm)
$ETA^{l,t}$ = soil moisture removed from layer l at time t due to ET (mm)

Figure A-31 below shows a typical change in the crop coefficient, and therefore crop ET demand for the four development stages.

Figure A-31 Evolution of Crop Coefficient during the Growing Season



If the dual crop coefficient method is used, transpiration and evaporation are calculated separately during the growing season. In order to apply the changes made to transpiration caused by CO_2 fertilization, transpiration needs to be separated from evaporation. In general, this method is also taken from FAO Irrigation and Drainage Paper No. 56 (FAO 56) (Allen, et al. 1998). In this method, a different crop coefficient is used: the basal crop coefficient (K_{cb}).

First, using a ratio of the precipitation and potential ET of the growing season, a climate classification method was used to find the minimum relative humidity (RH_{min}) for the growing season (Cazalac, PHI/UNESCO n.d.). Next, the crop height (h) is estimated based on the maximum crop height given in FAO 56 multiplied by a ratio of the crop-specific demand of that day and the maximum crop specific demand. The crop height does not decrease, it only increases. Then K_{Cmax} (representing an upper limit on the evaporation or transpiration from any cropped surface) is calculated based on equation 72 in FAO 56, and shown below:

Equation 3 $$K_{C\max} = \max(\{1.2 + [0.04(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3}\}, \{K_{cb} + 0.05\})$$

K_{Cmax} is then used to calculate the fraction of the ground covered by vegetation (f_c) using the equation below (equation 76 in FAO 56).

Equation 4 $$f_c = \left(\frac{K_{cb} - K_{c\min}}{K_{c\max} - K_{c\min}}\right)^{(1+0.5h)}$$

Where K_{cmin} is minimum K_c for dry bare soil, estimated to be 0.175 based on FAO 56. The fraction of soil surface that is moist, and therefore exhibits moist soil evaporation (f_{ew}) is calculated using the following equation, equation 75 from FAO 56.

Equation 5 $$f_{ew} = \min(1 - f_C, f_W)$$

Where f_W is taken from Table 20 in FAO 56, based on the type of irrigation, if any, that is used. Then a dimensionless evaporation reduction coefficient, K_r, is calculated using equation 74 in FAO 56 shown below.

Equation 6 $$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \text{ for } D_{e,i-1} > REW$$

Where TEW is the total evaporable water (FC – 0.5*WP), REW is the readily available water and is calculated using Table 19 in FAO 56. $D_{e,i-1}$ is the cumulative depth of evaporation, calculated from the previous day. The soil evaporation coefficient, K_e, is calculated using equation 71 in FAO 56 shown below.

Equation 7 $$K_e = K_r(K_{C\max} - K_{cb})$$

The ET demand (ETC) is then calculated as

Equation 8 $$ETC = \frac{(K_{cb} + K_e)ET_0}{nlsr}$$

and the actual ET removed from the soil layers is calculated in the same manner as the single crop coefficient method, only using the above equation for ETC.

Soil Layer Percolation

Once ET is removed from the soil layer, percolation from the layer above is added based on the soil water excess equation borrowed from SWAT (Neitsch, Arnold, et al. 2005).

Equation 9 $$TT = \left(\frac{SAT^l - FC^l}{HC^l}\right) \cdot delZ$$

$$SW_{excess}^{l,t} = SM^{l,t} - FC^l$$

$$Perc^{l,t} = SW_{excess}^{l,t} \cdot \left[1 - \exp\left(\frac{-\Delta t}{TT}\right)\right]$$

TT = travel time (hr)
SAT^l = moisture content at saturation of layer l
FC^l = moisture content at field capacity
HC^l = hydrualic conductivity (mm/hr)
delZ = thickness of layer (mm)
$SW_{excess}^{l,t}$ = soil water excess, $SW_{excess}^{l,t} \geq 0$ (mm)
$SM^{l,t}$ = soil moisture of layer l (mm)
$Perc^{l,t}$ = moisture to percolate to layer below (mm)
Δt = length of one time step (hrs)
Soil moisture is moved to the layer below only if the soil layer exceeds field capacity.

Ponding

After ET and percolation are removed, if the layer's soil moisture exceeds saturation, any soil moisture above saturation is added to the layer above until either all of the soil moisture has been placed or ponding occurs at the soil surface. Any ponding is considered lost.

Deep Percolation

If percolation, as described above, continues to the bottom layer of the soil profile, deep percolation occurs. The most that is allowed to percolate out of the soil profile is 1% of the hydraulic conductivity per day. The rest is added to the layer above until either all layers have reached saturation (in which case ponding occurs), or until all moisture has been placed.

Soil Water Upward Flow

The following equations are used to estimate the movement of soil moisture against gravity. The method was borrowed from the DSSAT model.

Equation 10

$$THET1 = SW(L) - LL(L)$$

$$THET2 = SW(L+1) - LL(L+1)$$

$$DBAR = (0.88 cm^2 day^{-1}) \times \exp(35.4 \times (THET1 \times 0.5 + THET2 \times 0.5)$$

$$FLOW = DBAR \times (THET2 - THET1)/((DLAYR(L) + DLAYR(L+1)) \times 0.5)$$

THET1 = volumetric water content of layer L, changes daily (cm)
THET2 = volumetric water content of layer L+1, changes daily (cm)
SW = soil moisture, changes daily (cm)
LL = soil layers lower limit (cm)
DBAR = assumed average diffusivity (cm day^{-1})
FLOW = soil moisture moved from layer, L + 1, to layer, L
DLAYR = thickness of soil layer

Water Table

The water table is used to determine losses due to waterlogging. The height of the water table is measured from the bottom soil layer to the furthest saturated layer. If no layers are saturated, the height of the water table is considered to be zero. If the first layer is saturated, the height of the water table is equal to the depth of the soil profile. So, the height of the water table is not necessarily the height to which the soil is saturated. The water table height is independent of the moisture of all soil layers except the saturated layer closest to the surface.

Yield Reductions/Improvements & Adjustments To Crop Behavior Due To Climate

Yield calculations are based primarily on the ratio of actual ET and potential ET. Five yield values are calculated; one for each of the four development stages and one for the whole season. The least of the five, considered the limiting yield, is reported as the true yield. Each yield value is calculated by the equation below, which was borrowed from FAO 56 (Allen, et al. 1998).

Equation 11

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y^d\cdot\left(1-\frac{ETC^d}{ETA^d}\right)$$

$$\%Yield^d=\frac{Y_a}{Y_m}$$

Y_a = predicted actual yield
Y_m = maximum yield
K_y^d = yield coefficient, different for development stage d
ETC^d = sum of daily ET crop demand for development stage d
ETA^d = sum of daily actual ET for development stage d
$\%Yield^d$ = ratio of actual yield over maximum yield, value reported by CliCrop

Waterlogging

The reduction in yield due to waterlogging is simulated in CliCrop with two functions: an oxygen loss reduction coefficient, SEW_{30}, and the root growth hindrance.

SEW30

SEW_{30} was proposed by Sieben in 1964 and is a method to calculate waterlogging losses based on experimental data. SEW_{30} is a measurement of the magnitude and duration of the root zone's saturation.

Equation 12

$$SEW_{30}=\sum_{t=1}^{DUR}(30-x^t)$$

$$RY=\begin{cases}0.91-0.00031\cdot SEW_{30} & SEW_{30}>200\\ 1-0.00076\cdot SEW_{30} & SEW_{30}\le 200\end{cases}$$

SEW_{30} = sum of excess water, only calculated when the height of the water table is within 30 cm of the soil surface
t = day of growing season
DUR = duration of growing season
x^t = distance from soil surface to water table at day t
RY = reduced yield due to waterlogging
Yield = yield of season
$Yeild_{wwl}$ = yield without waterlogging losses
(Mohanty, et al. 1995)

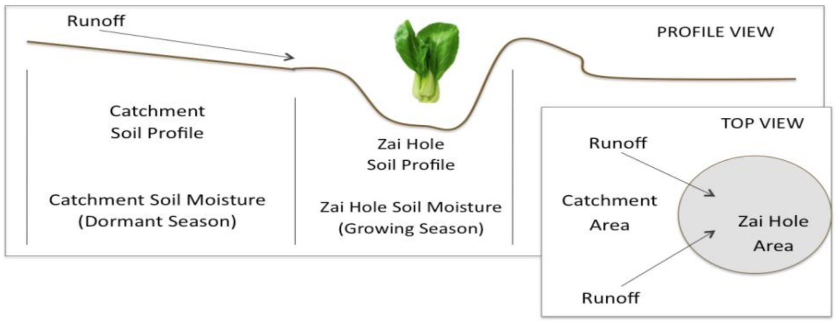
Root Growth

When the water table height is measured to be within the root zone, the roots are not allowed to grow for that day. This growth hindrance could cause yield reduction due to water losses for the crop in the future since the roots may not be deep enough to access soil moisture in the deeper soil layers.

Zai Holes

Since there are no preceding models that have estimated the effect of zais on crop yields, and therefore no modeling process has been established or tried, the following, designed by the creators of CliCrop, is a first attempt to simulate the process dynamically. The effects of the zai holes are simulated with two separate soil profiles: catchment soil profile and zai hole soil profile. Both soil profiles have the same soil parameters; the only difference is the amount of effective precipitation that infiltrates into the profile. At the end of the growing season, the moisture in the soil profile is assumed to be an average of the two profiles for dormant season calculations. Figure A-32 shows a diagram of the zai hole modeling process.

Figure A-32 Diagram of The Zai Hole Modeling Process



Catchment Soil Profile

The catchment soil profile is treated very similarly to the profile in the dormant season. Evaporation is removed based on FAO 56 and the soil moisture transport between layers is calculated using the SWAT method. A water table height is not calculated because it is never used.

Zai Hole Soil Profile

The runoff from the catchment area is assumed to drain into the zai hole based on the catchment efficiency (determined by the user). If the catchment efficiency is 100%, all of the runoff from the catchment enters the zai hole soil profile. If the catchment is 0%, only 50% of the runoff enters the zai hole soil profile and the other 50% is assumed lost. For any value between 0% and 50% catchment efficiency, the runoff caught by the zai hole is calculated using a linear relationship.

Equation 13

$$\text{Runoff Caught} = \left(\frac{\text{Catchment Efficiency}}{2} + 50 \right) \cdot \mathit{Runoff} \cdot \text{Zai Ratio}$$

Runoff refers to the runoff from the catchment soil profile and *Zai Ratio* is the zai area over the total area.

Mulching

None of the crop models that were studied prior to the construction of CliCrop included a process for modeling the effects of mulch on crop yields. However, research has been done on this topic and is used here. The effects of mulching are simulated in three separate ways: reduction in evapotranspiration, runoff reduction, and organic matter increase.

Reduction In Evapotranspiration

Organic mulch has been proven to reduce the temperature at the soil surface, thus decreasing evapotranspiration. FAO 56 proposed a simple method to mathematically simulate this reduction by reducing the crop coefficients based on the amount of ground that is covered by mulch.

Equation 14 $K_{C1}^{t}{}' = K_{C1}^{t} \cdot (1 - mulch/2)$

$$K_{C2}^{t}{}' = K_{C2}^{t} - mulch/2 \cdot (K_{C2}^{t} - K_{Cb2}^{t})$$

$$K_{C3}^{t}{}' = K_{C3}^{t} - mulch/2 \cdot (K_{C3}^{t} - K_{Cb3}^{t})$$

$K_{C1}^{t}{}'$ = crop coefficient for the initial stage after reduction due to mulching
K_{C1}^{t} = crop coefficient for the initial stage before reduction due to mulching
mulch = percent of ground covered by organic mulch
$K_{C2}^{t}{}'$ = crop coefficient for the middle stage after reduction due to mulching
K_{C2}^{t} = crop coefficient for the middle stage before reduction due to mulching
K_{Cb2}^{t} = basal crop coefficient for the middle stage
$K_{C3}^{t}{}'$ = crop coefficient for the late stage after reduction due to mulching
K_{C3}^{t} = crop coefficient for the late stage before reduction due to mulching
K_{Cb3}^{t} = basal crop coefficient for the late stage

So, for every 10% of the ground that is covered by mulch, the crop coefficient is reduced by 5%. The crop coefficient for the initial stage is reduced much more than the second and third stages because the difference between the basal crop coefficient and the original one is usually fairly small. Accordingly, most of the benefit from ground cooling occurs at the beginning of the season (Allen, et al. 1998).

Runoff Reduction

Runoff is reduced by organic mulch because the mulch causes more friction and an increase in the travel path. Due to a lack of available research on this phenomenon, a very simple method was chosen. When mulch is used, the curve number is reduced based on the following equation:

Equation 15 $CN' = CN - mulch \cdot 30$

CN' = reduced curve number due to organic mulching
CN = curve number before mulch reduction
mulch = % of ground covered by mulch

Adjustments to Crop Coefficients Due To Climate Changes

Whether the single crop coefficient method (K_c) or the dual crop coefficient method (K_{cb}) is used, the crop coefficients change due to climate changes. This means that the crop's demand for water responds to changes in precipitation and Potential ET. FAO 56 suggests a method for adjusting these crop coefficients based on these weather changes. The CliCrop code adjusts these coefficients using the method presented by FAO 56 (Allen, et al. 1998).

During the initial stage, the majority of ET is evaporation, while during the other three stages the majority of ET is generally transpiration. As a result, the initial crop coefficient is calculated differently depending on whether the single or the dual crop coefficient method is used. If the single crop coefficient method is used, the crop coefficient for the initial stage ($K_{C\ init}$) is calculated using the following equation.

Equation 16 $$t_W = \frac{L_{ini}}{n_W + 0.5}$$

$$E_{SO} = ET_0 \cdot 1.15$$

$$t_1 = REW / E_{SO}$$

$$K_{C\,\mathrm{ini}} = \frac{TEW - (TEW - REW)\exp\left(\frac{-(t_W - t_1 \cdot E_{SO}\left(1 + \frac{REW}{TEW - REW}\right))}{TEW}\right)}{t_W \cdot ET_0}$$

Where L_{ini} is the length of the initial stage; n_w is the number of wetting events in the initial stage; ET_0 is the average potential ET in the initial stage; REW is the readily available water estimated using the average wilting point of the soil, the average field capacity of the soil, and Table 19 from FAO 56; and TEW is the total evaporable water (FC – 0.5*WP). For the other two crop coefficients, $K_{c\ mid}$ and $K_{c\ end}$, the following equation is used.

Equation 17 $$K_c = K_c + 0.004(RH_{\min} - 45)\left(\frac{h}{3}\right)^{0.3}$$

Where the minimum relative humidity (RH_{min}) is calculated over the development stage and mid-season stage, for $K_{c\ mid}$ and $K_{c\ end}$, respectively.

If the dual crop coefficient method is used, the basal crop coefficients are estimated by the following equation.

Equation 18 $$K_{cb} = K_{cb} + 0.004(RH_{\min} - 45)\left(\frac{h}{3}\right)^{0.3}$$

Where the minimum relative humidity (RH_{min}) is calculated over the initial stage, development stage, and mid-season stage, for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$, respectively.

Adjustments to Crop Stage Lengths Due To Climate Changes

The crop stage lengths also respond to changes in climate. As temperature increases, the stage lengths shorten. The following equation was used to change all four of the crop stage lengths. (Wahaj, Maraux and Munoz 2007)

Equation 19 $$\Delta D_0 = \frac{D_0 \cdot \Delta T}{(T_{Ave} - T_{base})}$$

Where ΔD_0 is the change in the stage length (days) rounded to the nearest integer; D_0 is the original length of the crop stage, supplied as input; ΔT is the average change in temperature from the base temperature and the year of simulation during the given crop stage; T_{Ave} is the average temperature of the given crop stage; and T_{base} is a crop-specific parameter, supplied as input.

CO_2 Fertilization

Studies have shown that with increased CO_2, crop transpiration decreases due to increased stomatal resistance. In one such study, ratios are provided for C3 and C4 crops.[3] CliCrop uses these ratios to reduce the transpiration demand as CO_2 increases using the following equations. (Rosenzweig and Iglesias 1998)

Equation 20

$$CO_{2\,\mathrm{fert}} = \left[\left(\frac{SR-1}{555-330}\right)(CO_2 - 330) + 1\right]$$

$$T_{cb} = T_{cb} / CO_{2\,\mathrm{fert}}$$

Where SR is the stomatal resistance coefficient (for C3 crops SR = 49.7/34.4, and for C4 crops SR = 87.4/55.8); CO_2 is the amount of CO_2 in the atmosphere in parts per million; and T_{cb} is the crop transpiration demand.

[3] "C3" and "C4" refer to whether the first products of photosynthesis are compounds with three or four carbon atoms, respectively.

Annex 3

Detailed Description of the CGE Model

The Mozambique CGE model contains 56 activities/commodities, including 24 agricultural and 7 food-processing sectors (see Thurlow, 2008).[4] Five factors of production are identified: three types of labor (unskilled, semi-skilled and skilled), agricultural land, and capital. The agricultural activities and land are distributed across the three regions of Mozambique (North, Center and South). This level of detail captures Mozambique's economic structure and influences model results. Within the existing structure and subject to macroeconomic constraints, producers in the model maximize profits under constant returns to scale, with the choice between factors governed by a constant elasticity of substitution (CES) function. Factors are then combined with fixed-share intermediates using a Leontief specification. Under profit maximization, factors are employed such that marginal revenue equals marginal cost based on endogenous relative prices. Substitution possibilities exist between production for domestic and foreign markets. This decision of producers is governed by a constant elasticity of transformation (CET) function that distinguishes between exported and domestic goods, and by doing so, captures any time- or quality-related differences between the two products. Profit maximization drives producers to sell in markets where they can achieve the highest returns. These returns are based on domestic and export prices; the latter is determined by the world price times the exchange rate adjusted for any taxes. Under the small-country assumption, Mozambique faces a perfectly elastic world demand curve at a fixed world price. The final ratio of exports to domestic goods is determined by the endogenous interaction of the relative prices for these two commodity types.

Substitution possibilities also exist between imported and domestic goods under a CES Armington specification. This takes place both in intermediate and final usage. These elasticities vary across sectors, with lower elasticities reflecting greater differences between domestic and imported goods. Again, under the small country assumption, Mozambique faces infinitely elastic world supply at fixed world prices. The final ratio of imports to domestic goods is determined by the cost-minimizing decision-making of domestic demanders based on the relative prices of imports and domestic goods (both of which include the relevant taxes). The model distinguishes among various institutions, including enterprises, the government, and five rural and five urban representative household groups in each region. Households and enterprises receive income in payment for the producers' use of their factors of production. Both institutions pay direct taxes (based on fixed tax rates) and save (based on marginal propensities to save). Enterprises pay their remaining incomes to households in the form of dividends. Households, unlike enterprises, use their incomes to consume commodities under a linear expenditure system (LES) of demand. The government receives revenues from activity taxes, sales taxes, direct taxes, and import tariffs, and then makes transfers to households, enterprises and the rest of the world. The government also purchases commodities in the form of government consumption expenditures, and the remaining income of the government is saved (with budgets deficits representing negative savings). All savings from households, enterprises, government and the rest of the world (foreign savings) are collected in a savings pool from which investment is financed.

The model includes three macroeconomic accounts: government balance, current account, and savings-investment account. In order to bring about balance in the macro accounts, it is necessary to

[4] Tables A1, A2 and A3 present the models variables, equations and dimensions, respectively.

specify a set of “macroclosure” rules, which provide a mechanism through which balance is achieved. A savings-driven closure is assumed for the savings-investment account, such that households’ and enterprises’ marginal propensities to save are fixed, and investment adjusts to income changes to ensure that investment and savings levels are equal. For the current account, a flexible exchange rate adjusts in order to maintain a fixed level of foreign savings (i.e., the external balance is held fixed in foreign currency terms). Finally, in the government account, the fiscal deficit is assumed to remain unchanged, with government revenues and expenditures balanced through changes in direct tax rates to households and enterprises. Labor is assumed to be mobile across sectors and fully employed. Under the full employment closure, expanding biofuels production implies reduced use of labor elsewhere in the economy. The assumption of full employment is consistent with widespread evidence that, while relatively few people have formal sector jobs, the large majority of working-age people engage in activities that contribute to GDP. The model numeraire is the consumer price index (CPI).

The CGE model is calibrated to a 2003 social accounting matrix (SAM) (McCool et al., 2009), which was constructed using national accounts, trade and tax data, and household income and expenditure data from the 2002 national household survey (INE, 2004). Trade elasticities are from the Global Trade Analysis Project (Dimaranan, 2006). The model is calibrated so that the initial equilibrium reproduces the base-year values from the SAM.

The features described above apply to a single-period “static” CGE model. However, because climate change will unfold over a decades, the model must be capable of forward-looking growth trajectories. Therefore, the model must be “dynamized” by building in a set of accumulation and updating rules (e.g. investment adding to capital stock, labor force growth by skill category, productivity growth). In addition, expectation formations must be specified. Expectations are a distinguishing feature of macroeconomic models. In our CGE model, a simple set of adaptive expectations rules are chosen so that investment is allocated according to current relative prices under the expectation that climate realization in the upcoming year will be an average of recent experience. A series of dynamic equations “update” various parameters and variables from one year to the next. For the most part, the relationships are straightforward. Growth in the total supply of each labor category and land is specified exogenously, sector capital stocks are adjusted each year based on investment, net of depreciation. Factor returns adjust so that factor supply equals demand. The model adopts a “putty-clay” formulation, whereby new investment can be directed to any sector in response to differential rates of return, but installed equipment remains immobile (e.g. a factory cannot be converted into a railroad). Sector- and factor-specific productivity growth is specified exogenously. Using these simple relationships to update key variables, we can generate a series of growth trajectories, based on different climate scenarios.

Table A-4 Model indices, variables and parameters (Below)

	Indices		
c	Commodities and activities	h	Representative households
f	Factors (land, labor and capital)	t	Time periods
Exogenous Parameters (Greek characters)			
αp	Production function shift parameter	θv	Value-added share of gross output
αq	Import function shift parameter	π	Foreign savings growth rate
αt	Export function shift parameter	ρp	Production function substitution elasticity
β	Household marginal budget share	ρq	Import function substitution elasticity
γ	Non-monetary consumption quantity	ρt	Export function substitution elasticity
δp	Production function share parameter	σ	Rate of technical change
δq	Import function share parameter	τ	Foreign consumption growth rate
δt	Export function share parameter	υ	Capital depreciation rate
ε	Land and labor supply growth rate	φ	Population growth rate
θi	Intermediate share of gross output	ω	Factor income distribution shares
Exogenous Parameters (Latin characters)			
ca	Intermediate input coefficients	pwm	World import price
cab	Current account balance	qfs	Total factor supply
cd	Domestic transaction cost coefficients	qgov	Base government consumption quantity
ce	Export transaction cost coefficients	qinv	Base investment demand quantity
ci	Capital price index weights	rf	Factor foreign remittance rate
cm	Import transaction cost coefficients	sh	Marginal propensity to save
cpi	Consumer price index	tf	Factor direct tax rate
cw	Consumer price index weights	th	Personal direct tax rate
ga	Govt consumption adjustment factor	tm	Import tariff rate
gh	Per capita transfer from government	tq	Sales tax rate
pop	Household population	wh	Net transfer from rest of world
pwe	World export price		
Endogenous Variables			
AR	Average capital rental rate	QG	Government consumption quantity
FS	Fiscal surplus (deficit)	QH	Household consumption quantity
IA	Investment demand adjustment factor	QI	Investment demand quantity
PA	Activity output price	QK	New capital stock quantity
PD	Domestic supply price with margin	QM	Import quantity
PE	Export price	QN	Aggregate intermediate input quantity
PM	Import price	QQ	Composite supply quantity
PN	Aggregate intermediate input price	QT	Transaction cost demand quantity
PQ	Composite supply price	QV	Composite value-added quantity
PS	Domestic supply price without margin	WD	Sector distortion in factor return
PV	Composite value-added price	WF	Economywide factor return
QA	Activity output quantity	YF	Total factor income
QD	Domestic supply quantity	YG	Total government revenues
QE	Export quantity	YH	Total household income
QF	Factor demand quantity	X	Exchange rate

Table A-5 Model equations

Prices	
PMct=pwmc·1+tmc·X+c'PQc't·cmc'c	1
PEct=pwec·Xt-c'PQc't·cec'c	2
PDct=PSct+c'PQc't·cdc'c	3
PQct·1-tqc·QQct=PDct·QDct+PMct·QMct	4
PXct·QXct=PSct·QDct+PEct·QEct	5
PNct=c'PQc't·cac'c	6
PAct·QAct=PVct·QVct+PNct·QNct	7
cpi=ccwc·PQct	8
Production & Trade	
QVct=αctp·fδfcp·QFfct-ρcp-1ρcp	9
WFft·WDfct=PVct·QVct·f'δf'cp·QFf'ct-ρcp-1·δcp·QFfct-ρcp-1	10
QNct=θci·QAct	11
QVct=θcv·QAct	12
QAct=αct·δct·QEctρct+1-δct·QDctρct1ρct	13
QEctQDct=PEctPSct·1-δctδct1ρct-1	14
QQct=αcq·δcq·QMct-ρcq+1-δcq·QDct-ρcq-1ρct	15
QMctQDct=PDctPMct·1-δcqδcq11+ρct	16
QTct=c'cdcc'·QDc't+cmcc'·QMc't+cecc'·QEc't	17
Incomes & Expenditures	
YFft=cWFft·WDfct·QFfct	18
YHht=fωhf·1-tff·1-rff·YFft+ghh·popht·cpi+whh·X	19
PQct·QHcht=PQct·γch+βch·1-shh·1-thh·YHht-c'PQct'·γc'h	20
QIct=IAt·qinvc	21
QGct=gat·qgovc	22
YGt=hthh·YHht+ftff·YFft+ctmc·pwmc·QMct·X+tqc·PQct·QQct	23
Equilibrium Conditions	
qfsft=cQFfct	24
QQct=c'cacc'·QNc't+hQHcht+QGct+QIct+QTct	25
cpwmc·QMct+f1-tff·rff·YFft·Xt-1=cpwec·QEct+hwhh+cabt	26
YGt=cPQct·QGct+hghh·popht·cpi+FSt	27
hshh·1-thh·YHht+FSt+cabt·Xt=cPQct·QIct	28
Capital Accumulation & Allocation	
ARft=YFftqfsft	29
QKfct·c'PQc't·cic'=QFfctqfsft·WFft·WDfctARft·c'PQc't·QIc't	30
QFfct+1=QFfct·1-υ+QKfct	31
Land and labor supply, technical change, population growth, and other dynamic updates	
qfsft+1=qfsft·1+εf	32
αct+1p=αctp·1+σc	33
popht+1=popht·1+φh	34
gat+1=gat·1+τ	35
cabt+1=cabt·1+π	36

Table A-6 Model Activities, Factors & Households

Activities	Maize; sorgum and millet; rice; wheat; root crops; pulses and oilseeds; vegetables; fruits; groundnuts; cashews; other crops; tobacco; sugarcane; cotton; livestock; forestry; fisheries; mining; food processing; other agro-processing; textiles; wood and paper; chemicals; metals; machinery; electricity; hydro electricity for export; water; construction; trade and hotels; transport and communication; government, education and health; other private services.
Regions	North; Center; South; Maputo metropolitan area
Factors	Skilled/semi-skilled/unskilled labor; family farm labor by region.
Households	Rural expenditure quintiles by region; urban expenditure quintiles.