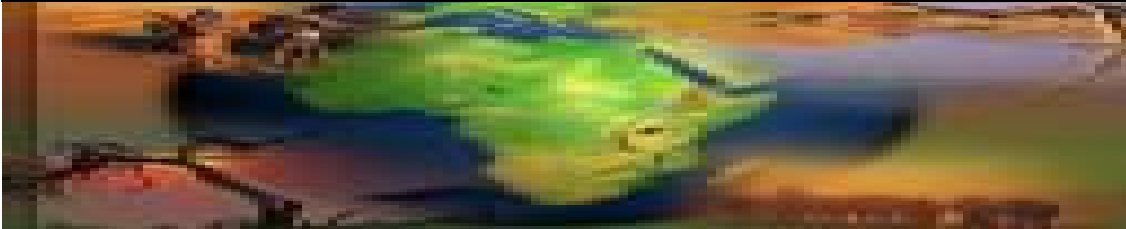


## CLIMATE CHANGE AND AFRICAN AGRICULTURE

*Policy Note No. 13, August 2006, CEEPA*



### **Impacts of climate change on water flows in Africa<sup>1</sup>**

Although considerable research efforts are being made, current understanding of the regional impacts, magnitude, and rate of climate change remain uncertain. Nevertheless, it is generally accepted that in many countries climate change will adversely affect farming, fishing, forestry and many other industries that rely on weather and natural ecosystems. The African continent is particularly susceptible to climate change because it includes some of the world's poorest nations. Furthermore, high spatial and temporal variability in rainfall, as well as high evaporation rates, already place great stress on agricultural systems from which 70% of the continent's population derive their livelihoods. One of the most significant impacts of climate change is likely to be on the hydrological system, and hence on river flows and regional

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<sup>1</sup> This Policy Note is prepared by R Hassan based on Strzepek & McCluskey (2006), District level hydroclimatic time series and scenario analyses to assess the impacts of climate change on regional water resources and agriculture in Africa, *CEEPA Discussion Paper No. 13, CEEPA, University of Pretoria.*

water resources. This will be particularly true in arid and semi-arid areas of Africa where water resources are very sensitive to climate variability, particularly rainfall.

The principal method adopted for studying the sensitivity of African agriculture to climate change in this GEF/World Bank/CEEPA project is the Ricardian approach. This approach presupposes that farmers at any given location have optimized their farming systems (i.e. crops grown and inputs) to maximize their land value and/or farm revenue. It is therefore possible with this approach to derive regression relationships to determine the links between climate variables (e.g. temperature and precipitation) and land values and farm revenues across different locations. The implications of climate change for land values and farm revenues can then be deduced.

The Ricardian method uses measures of temperature and precipitation as the principal climate variables. These meteorological measures, however, often do not perform very well and are not easy to aggregate to define meaningful durations (e.g. growing seasons, etc.). Moreover, farms do not only use rainfall, but also exploit other sources such as surface and ground water that can be remote from the farm. This implies that the climate at the farm (as measured by

received precipitation) may give little indication of the total amount of water accessible to the farm. Alternative hydrological variables such as runoff and river flows or soil moisture are more relevant in this case. This report describes the methods and results of hydrological modeling and analyses to provide alternative measures of water availability for use as inputs in the Ricardian assessment of climate change impacts. The study was conducted in two phases. The principal objectives of the first phase were to: (1) develop an approach that would enable flow and runoff to be derived for the 'districts of interest; (2) develop time series (1961–1990) of runoff and flow for the 'districts which would provide a baseline for climate change scenarios; and (3) provide hydrologically relevant parameters that could be used as independent variables in the Ricardian analyses.

The second phase aimed to: (1) extend the time frame for the hydroclimatic series from 1990 to 2000, using the same modeling methodology used in Phase I and updated input data from the Climate Research Center at the University of East Anglia to calibrate and simulate the hydrological model up to the year 2000; (2) provide results for the new district boundaries for Cameroon and Egypt (which have changed since the Phase 1 results were compiled) for the 1961–1990 period as well as for the proposed future analyses; and (3) provide climate change scenario analyses for the same hydroclimatic variables at district level.

### **The hydrology model**

To address scientific issues at the continental scale, hydrological models must characterize the dispersed nature of

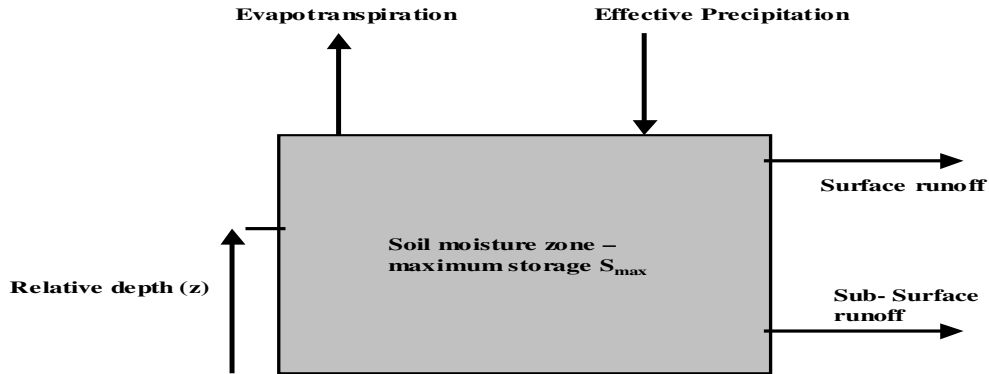
climate and hydrology over space and time while avoiding excessive complexity. In the current study, simplification was required not only to ensure reasonable computing time, but also to develop a generic form of the model applicable to a wide range of conditions across the continent.

The model used is a version of a conceptual rainfall-runoff model called WatBal (Yates 1996), which can be applied to gridded data. The model simulates changes in soil moisture and runoff. It is essentially an accounting scheme based on a conceptualized, one-dimensional bucket that lumps together both the root and upper soil layer. The model comprises two elements. The first is a water balance component that describes water movement into and out of a conceptualized basin (Figure 1). The second is the calculation of potential evapotranspiration, which, in the gridded version of the model, is computed using the FAO Penman-Monteith approach (Monteith 1965). The simplified representation of soil moisture dynamics has been shown to adequately represent runoff changes due to climate fluctuations (Yates 1997).

The model was applied to a regular latitude/longitude grid covering the whole continent. Each of the  $0.5^\circ$  cells (which have an area ranging from about  $2500\text{km}^2$  to  $3100\text{km}^2$ ) depending on latitude) is regarded by the model as a small catchment. The model parameters, which define the size of the store and the rate of water removal from it, are derived in part from physical characteristics and in part by calibration. The inputs are the monthly rainfall and climatic data required to estimate potential evapotranspiration. Water enters the soil moisture store through

precipitation and is removed either by evapotranspiration, surface runoff or subsurface runoff. The water balance component of the model comprises three

parameters related to i) surface runoff, ii) subsurface runoff and iii) maximum catchment water-holding capacity.



**Figure 1: Simplified version of the WatBal model that is used to compute gridded runoff**

As recommended by the UN Food and Agriculture Organization (FAO), potential evapotranspiration is computed using the Penman-Monteith method (FAO 1992). A non-linear relationship (based on Kaczmarek 1993) is used to compute actual evapotranspiration from potential evapotranspiration.

Surface runoff is described in terms of the storage state and the effective precipitation. A calibration parameter allows surface runoff to vary non-linearly with storage. Subsurface runoff is a function of the relative storage state. Total runoff for each time step is the sum of the two runoff components ( $R_{total} = R_s + R_{ss}$ ) (Yates 1996).

### Data requirements

The modeling process is highly data intensive because of the number of cells (16,000) across Africa. The data types required for this study can be broadly divided into four types: geographical data, climate data for model input, physiological data and model calibration

data. A summary of data sources is provided in Table 1.

### Model calibration

In WatBal, hydrological processes are simulated on the basis of a conceptual approximation. It is therefore necessary to adjust or optimize parameters until the model output is an acceptable estimate of the observed runoff regime. In order to do this it is necessary to have runoff data against which to calibrate parameter values. Given the limited resources available for this study, it was decided to calibrate the model against the existing model output rather than observed data. Clearly this is not ideal, but it was the best that could be achieved given the constraints of limited time and resources. Hence, for the calibration, simulated runoff data obtained from the CD of runoff fields were used to calibrate the WatBal model against simulated runoff data derived from a climate driven Water Balance Model (WBM) which is very similar to WatBal.

**Table 1: Sources of data used in this study**

Data	Description and Source
District boundaries	Politically defined district boundaries – shape files. <i>Source:</i> USAID, FEWS, EDC-International Program and the US Geological Survey under the Africa Data Dissemination Service (ADDS) and Yale University. Ghana and Kenya map provided by UNESCO (1997) through UNEP/GRID-Sioux Falls and Yale University.
Land use	13 land classes – 0.5° grid. International Institute for Applied Systems Analysis (IIASA) – obtained directly by personal communication.
Rivers of Africa	Digitized map of African rivers – polylines. <a href="http://www.fao.org/geonetwork/srv/en/metadata.show?id=12&amp;currTab=summary">http://www.fao.org/geonetwork/srv/en/metadata.show?id=12&amp;currTab=summary</a>
Irrigation potential	Global map of irrigated areas – 0.5° grid. <i>Source:</i> <a href="http://www.fao.org/waicent/faoinfo/agricult/agl/aglw/aquastat">http://www.fao.org/waicent/faoinfo/agricult/agl/aglw/aquastat</a>
Maximum soil moisture capacity	Values between 0 and 1,000mm – 0.08° grid. <i>Source:</i> <a href="http://www.fao.org/geonetwork/srv/en/metadata.show?id=5018&amp;currTab=summary">http://www.fao.org/geonetwork/srv/en/metadata.show?id=5018&amp;currTab=summary</a>
Precipitation, temperature, vapor, wind speed, pressure and cloudiness	CRU-CL 1.0 dataset. A dataset of mean monthly surface climate over global land areas, excluding Antarctica. Interpolated from station data to 0.5 degree lat./long. for a range of variables: precipitation and wet-day frequency, mean temperature and diurnal temperature range (from which maximum and minimum temperature can be determined), vapor pressure, sunshine, cloud cover, ground-frost frequency and wind speed – 0.5° grid. <a href="http://ipccddc.cru.uea.ac.uk/asres/baseline/climate_download.html">http://ipccddc.cru.uea.ac.uk/asres/baseline/climate_download.html</a>
Drainage network	Topographically generated drainage lines (polylines) for each 0.5° grid cell. Named STN-30p. <i>Source:</i> University of New Hampshire CD – UNH/GRDC Composite runoff fields V1.0.
Calibration runoff	Simulated runoff (avg monthly totals in mm) 0.5° grid. University of New Hampshire CD-UNH/GRDC Composite runoff fields V1.0.

Model parameters were calibrated for each cell by simulating runoff for 30 years (1961–1990) and minimizing the root mean square error of the WatBal simulated average monthly runoff and the UNH simulated runoff data. This approach tends to maximize the ‘goodness of fit’ of the total volume of runoff, but will not necessarily produce a good fit in periods of extreme high and/or low runoff events. However, since this study is primarily concerned with water resources, it was felt that total volume was the most important aspect of the runoff regime to simulate correctly. A comparison between average annual runoff generated using WatBal and the

UNH runoff data, at the scale of ‘food production units’ (of which there are 97 in Africa) shows a reasonable fit.

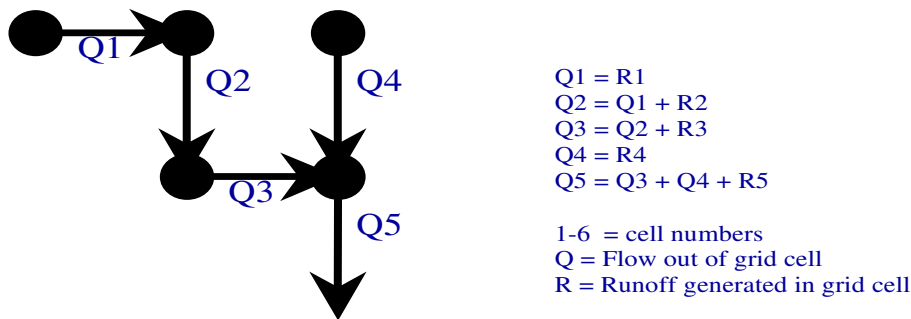
**Runoff simulation.** When the model was calibrated it was run to estimate runoff, on a monthly time step, for all grid cells for the period 1961–1990. The cell data were then converted to runoff in each district. The percentage of each district’s area in each associated grid cell was determined. For example, at any given time step, all districts in the same grid cell will have the same runoff. However, if a district was divided across a number of grid cells, runoff for that district was calculated based on the

percentage area of the district in each of the grid cells.

**Flow simulation.** The flow routing model uses the STN-30p drainage network that shows the direction of flow in each grid cell and which upstream cells are contributing to its flow. Runoff from each grid cell is accumulated along the drainage network, providing the stream flow in each grid cell (Figure 2). After stream flow had been calculated in

each grid cell, the same weighted average procedure described above was used to disaggregate the stream flow to each district. Since the drainage network represents directions of flow rather than actual rivers, and because the volumes have been weighted by percentage area, the flow values computed are indicative of, rather than an estimate of actual, flow within a district.

Figure 2: Example of runoff accumulation to generate flow in the drainage network

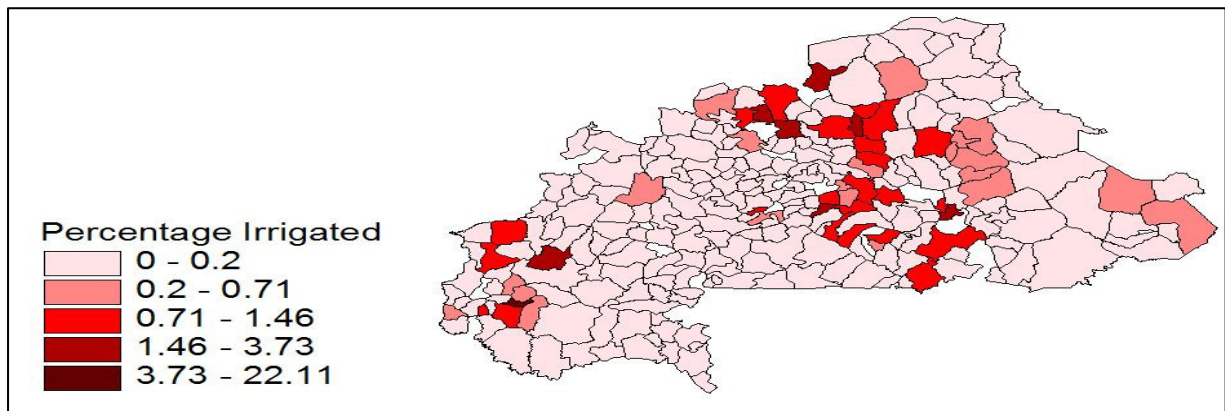


**River density index.** A river density index is an indicator of stream frequency and hence surface water availability within each district. It is possible that this could be a geographical feature that significantly influences land value and/or farm revenue. Consequently it was determined for each of the districts.

likely to influence land value and farm revenue. Consequently, an estimate of the percentage area irrigated within each district was derived from the FAO's irrigated area map of Africa (Figure 3). It was calculated using the weighted average estimate of grid cell contribution to the area of each district, determined when computing runoff.

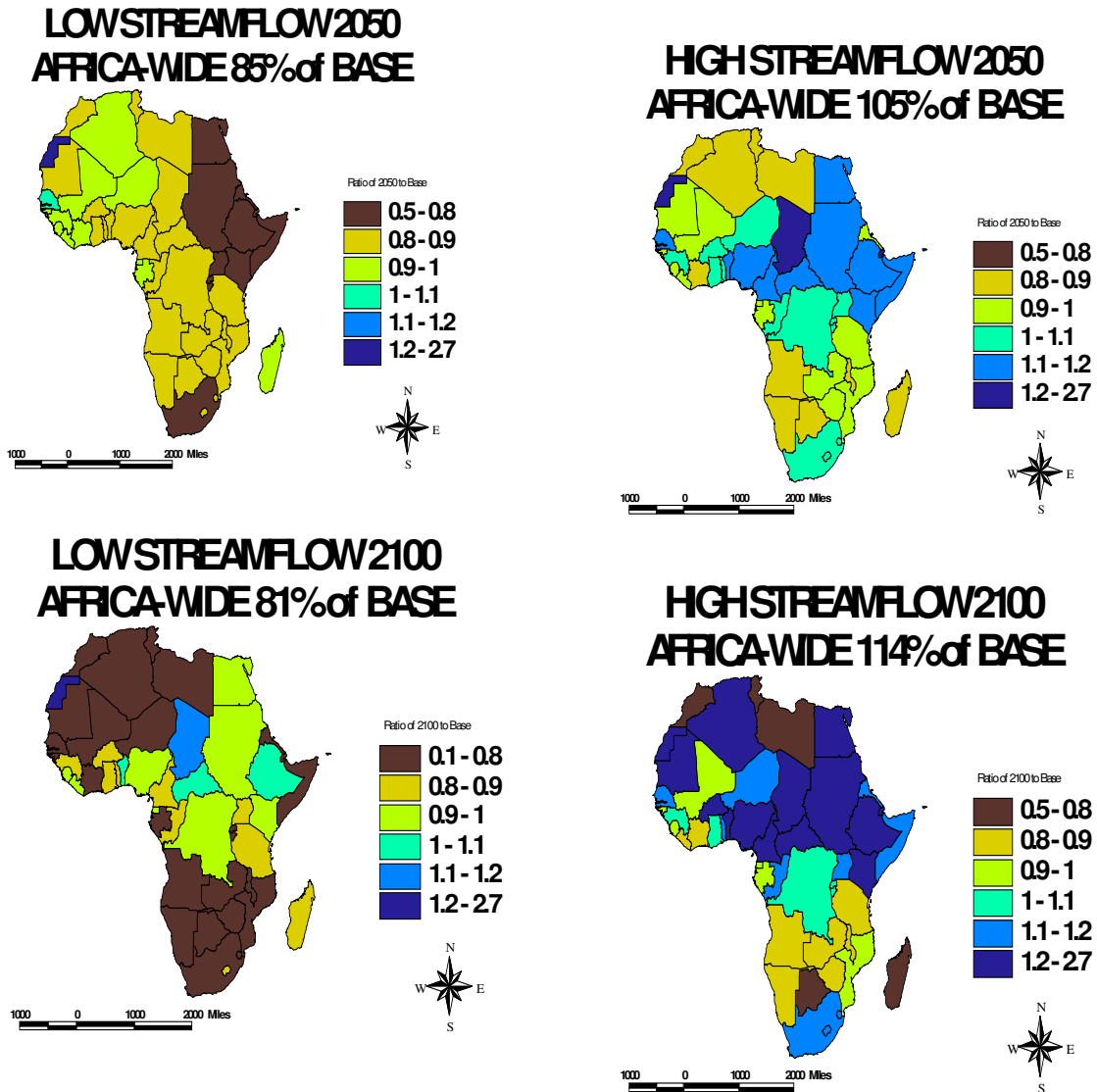
**Area irrigated.** The extent of irrigation within a district is another factor that is

Figure 3: Burkina Faso: Average percentage irrigated by district



Climate Research Unit (CRU) for which data are available at 0.5° x 0.5° for the globe was employed to represent a range of equally plausible future climates with differences attributable to the different climate models used and to different emission scenarios that the world may follow.

**Figure 4: Stream impacts**



This study derived 16 scenarios using four different models (CSIRO2, HadCM3, CGCM2, ECHAM and PCM) based on four different emission scenarios (i.e. A2 & B2). The WatBal

model was used to determine the impact of these different scenarios on runoff and actual evaporation and hence flow in the districts under study (Figure 4). The generated hydroclimatic series and scenario analyses were used as inputs into various Ricardian regressions measuring the likely impacts of climate change on the agricultural economies of Africa.

### Conclusions

This study was conducted in two phases. Phase I generated the following monthly

time series for the years 1961–1990 for each of the politically delineated districts in the 11 countries of the study: runoff (mm); relative soil storage (0-1), potential evapotranspiration (mm), actual evapotranspiration (mm), temperature (°C), precipitation (mm), and streamflow (m<sup>3</sup>). A river density index and the percentage area irrigated were also derived for each district. These data were available for the country teams to validate, and for the derivation of appropriate independent variables for use in the Ricardian analysis.

These results were provided for all districts in Africa, not just those identified for analysis using the Ricardian approach under this project. Consequently, data were provided for 1421 political districts in total. These data are stored in individual Excel spreadsheets for each country. Within each spreadsheet the different data types (e.g. runoff, relative soil moisture storage, etc.) are stored in separate sheets, with the districts identified by a unique district number. The district numbers were obtained from the ArcView coverages provided by each country.

In Phase II, the climate change impact analysis was performed. Ten climate change scenarios, and five models for A2 and B2 were run through the hydrologic model to produce monthly results for the 100 years from 2001–2100, producing 1200 monthly values. As requested by the economic modelers, the 1200 monthly values were processed into decadal average values (monthly) for precipitation, temperature and streamflow. This data was provided in two formats:

- i) Absolute value for the base case and ten sets of decadal average *absolute* values of precipitation, temperature and streamflow.
- ii) Absolute value for the base case and ten sets of decadal average *changes* from the *base* for values of precipitation (% change from base), temperature (delta T in degrees from base) and streamflow (% change from base).

Two interesting insights can be gleaned from the results presented (Figure 4):

- i) The possible range of Africa-wide climate change impacts on streamflow increases significantly between 2050 and 2100. The range in 2050 is from a decrease of 15% to an increase of 5% above the 1961–1990 base for a range of 20%. For 2100 the range is from a decrease of 19% to an increase of 14% for a range of 33%.
- ii) For southern Africa for all four scenarios almost all countries except South Africa experience significant reduction in streamflow. And even for South Africa the increases under the two high scenarios are modest at under 10%.

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*The agricultural sector in sub-Saharan Africa is predicted to be especially vulnerable to climate change because this region already endures high heat and low precipitation, provides the livelihoods of large segments of the population, and relies on relatively basic technologies, which limit its capacity to adapt. This series of Policy Notes reports on the methods and results of the first continent-wide study of this kind assessing how the economic well-being of African farming communities is currently affected by climate, predicts how future climate change effects may unfold under various possible global warming scenarios, and evaluates the roles adaptation to climate change could play. The study is based on collaborative research efforts conducted in 11 countries: Burkina Faso, Cameroon, Egypt, Ethiopia, Ghana, Kenya, Niger, Senegal, South Africa, Zambia and Zimbabwe. The sampled districts used as the unit of analysis cover all key agro-climatic zones and farming systems in Africa. This is the first analysis of climate impacts and adaptation in Africa on such a scale and the first in the world to combine cross-country, spatially referenced survey and climatic data for conducting an analysis that uses economic impact assessment methods, river-basin hydrological modeling and crop growth simulation techniques.*

All the reports produced under this GEF/WB/CEEPA funded project, *Regional Climate, Water and Agriculture: Impacts on and Adaptation of Agro-ecological Systems in Africa*, are found on CEEPA e-Library at its website link ([www.ceepa.co.za/discussionp2006.html](http://www.ceepa.co.za/discussionp2006.html)) and can also be accessed directly through the project link ([www.ceepa.co.za/Climange\\_Change/project.html](http://www.ceepa.co.za/Climange_Change/project.html))

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Core funding from the GEF and supplementary funding from TFESSD, Finnish TF, NOAA-OPG, and CEEPA in support of this project's activities are all gratefully acknowledged. The project was coordinated by CEEPA and managed in the World Bank by the Agricultural and Rural Development Department and World Bank Institute.



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