ASSESSING THE IMPACT OF CLIMATE CHANGE ON THE WATER RESOURCES OF THE LAKE TANA SUB-BASIN USING THE WATBAL MODEL

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PREFACE

The reports in this special series are the result of a multi-country research activities conducted under the GEF funded project: *Climate Change Impacts on and Adaptation of Agro-ecological Systems in Africa*. The main goal of the project was to develop multipliable analytical methods and procedures to assess quantitatively how climate affects current agricultural systems in Africa, predict how these systems may be affected in the future by climate change under various global warming scenarios, and suggest what role adaptation could play. The project has been implemented in 11 countries: Burkina Faso, Cameroon, Ghana, Niger and Senegal in west Africa; Egypt in north Africa; Ethiopia and Kenya in east Africa and South Africa, Zambia, and Zimbabwe in southern Africa. The study countries covered all key agro-climatic zones and farming systems in Africa. This is the first analysis of climate impacts and adaptation in the Africa continent of such scale and the first in the world to combine cross-country, spatially referenced survey and climatic data for conducting this type of analysis.

The analyses reported in this series focus mainly on quantitative assessment of the economic impacts of climate change on agriculture and the farming communities in Africa, based on both the cross-sectional (Ricardian) method and crop response simulation modeling. The cross sectional analysis also allowed for assessing the possible role of adaptation. Moreover, the project employed river-basin hydrology modeling to generate additional climate attributes for the impact assessment and climate scenario analyses such as surface runoff and streamflow for all districts in the study countries.

The Centre for Environmental Economics and policy in Africa (CEEPA) of the University of Pretoria coordinated all project activities in close collaboration with many agencies in the involved countries, the Agriculture and Rural Development (ARD) Department of the World Bank, the World Bank Institute (WBI), the Food and Agriculture Organization (FAO), Yale University, the University of Colorado, and the International Water Management Institute (IWMI). The project received supplemental funding from TFESSD, Finnish TF, NOAA-OPG, and CEEPA. We are grateful for the invaluable contributions of all these institutions and all individuals involved in this project. All opinions presented in this report series and any errors in it are those of the authors and do not represent the opinion of any of the above listed agencies.

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EXECUTIVE SUMMARY

Ethiopia has a total area of about 1.1 million square kilometers and is divided into 12 watersheds. These watersheds (basins) differ widely in size and in their potential as water resources. To assess the effect of climate change on the water resources and thereby to recommend adaptation measures this study focused on the Lake Tana sub-basin. The vulnerability of runoff to climate change was assessed using the WatBal hydrological water balance model. Various climate change scenarios and their impact on the water resources and the possible adaptation measures are presented in this report. The Lake Tana area is highly vulnerable to climate change especially in the distribution of runoff throughout the year. With climate change, the runoff may become much more seasonal and as a result small streams may completely dry up for part of the year. This will have a severe effect on the socio-economy of the sub-basin, as the agriculture here is totally dependent on rainfall and the rural water supply sources are mostly small streams and springs. The adaptation options suggested in this report are subject to various constraints, the major one being the capital that will be required for constructing dams and other flood prevention structures. Other constraints are social, such as the need to relocate people living in vulnerable areas, and physical, such as the scarcity of suitable land for resettlement.

1. Introduction: The study area

The Lake Tana sub-basin is located at the headwaters of the Abay (Blue-Nile) basin. The drainage area of the lake is 15,319 square kilometers, of which 3100 is the lake area. The geographical location of the Tana basin extends from 10.95°N to 12.78°N latitude and from 36.89°E to 38.25°E longitude. Based on the rainfall pattern, the year is divided into two seasons: a rainy season, mainly centered on the months of June to September, and a dry season from October to March. In the southern parts of the basin the months of April and May are an intermediate season where minor rains often occur. Of the total annual rainfall, 70% to 90% occurs in the June to September rainy season.

The mean annual flow at the outlet of Lake Tana is about 3.5 billion cubic meters and it varies from a maximum of 7 billion cubic meters to a minimum of 1 billion cubic meters in high and low water years respectively.

2. Description of the WatBal model

The WatBal water balance hydrological model was used in this study to assess the impact of climate change on the water resources of the Lake Tana basin. This model was chosen because it suited the objectives of the study and the data availability and is recommended as giving good results in assessing the effect of climate change on water resources. It is a lumped conceptual model which represents the water balance in the use of continuous functions of relative storage to represent surface outflow, sub-surface outflow and evapotranspiration (Yates & Strzepek 1994). It has essentially two main modeling components. The first is the water balance component that uses continuous functions to describe water movement into and out of a conceptualized basin. The second is the calculation of potential evapotranspiration using the well-known Priestly Taylor radiation approach. The mass balance is written as a differential equation and storage is lumped as a single, conceptualized 'bucket' (Figure 1) with the components of discharge and infiltration being dependent on the state variable relative storage (Yates 1994).

The water balance component of the model contains five parameters: direct runoff, surface runoff, sub-surface runoff, maximum catchment water-holding capacity, and base flow. See Yates (1994) for a full description of the model structure and parameters.

3. Data availability and analysis

The WatBal model requires meteorological and hydrological input data in a monthly time-step for rainfall, temperature, relative humidity, sunshine hours and monthly flow data at the sub-basin outlet. Monthly cumulative rainfall, mean maximum and minimum temperatures, mean relative humidity and mean sunshine hours data were compiled for all available stations in the basin. Most of the stations for which data were collected are located inside the basin and some are located around it. The length of record of these stations varies from few years to more than 30 years. The monthly river flow data of Abay at Bahir-Dar, located at the outlet of the lake, is available for more than 35 years.

Taking into account the length of record, continuity of data availability, concurrent period of observation and the distribution of stations in the sub-basin, nine meteorological stations were selected for the study. These are listed in Table 1.

The distribution of these stations within the sub-basin is not even. Hence, to minimize the error introduced by spatial variability, the Thiessen Polygon method was used to estimate the areal rainfall. For temperature, humidity and sunshine hours, the arithmetic means of the stations' data were used. The period selected for both calibration and validation was from 1978 to 1997.

4. Modeling of the Lake Tana basin

In order to test/verify the WatBal model's ability to simulate runoff in the basin, the record was split into two parts. The data for the first ten years (1978–1987) were used for calibration purposes and the second ten years (1988–1997) for validation. To determine the value of each model parameter during calibration, a trial and error procedure with a range of logical values was used. The simulated and observed runoff values were plotted simultaneously and visual examination of the plots was carried out in each run to determine the best combination of parameter values. In addition, statistical measures were used to measure the difference between the observed and simulated values. The statistical measures used were the correlation coefficient(r), the coefficient of efficiency (R2) and the average monthly error in mm/day.

After calibration, the model parameters were validated for their ability to simulate runoff. If the graphical observation and the statistical measures gave satisfactory results in both the calibration and the validation periods, the parameter values and the modeling work was taken as satisfactory. The parameter values for the sub-basin are given in Table 2, the plots of the observed and simulated runoff in the calibration and validation periods are shown in Figures 2a and 2b, and the correlation coefficient, coefficients of determination and monthly average error in mm/day are shown in Table 3.

5. Climate change scenarios

To assess the impacts of climate change, it is first necessary to obtain a quantitative representation of the changes in climate themselves. The methods available do not provide a confident prediction of future climate; instead, it is customary to specify a number of plausible future climates. The types of climate scenarios used in this study are synthetic or incremental scenarios and scenarios from General Circulation Models (GCMs).

5.1 Synthetic scenarios

Synthetic scenarios describe techniques where particular climatic elements are changed by a realistic but arbitrary amount, according to a qualitative interpretation of climate model prediction for a region (IPCC Technical Guidelines, 1994). Synthetic scenarios are used to assess the sensitivity of the basin to climate change. For this study a different set of possible climate changes in temperature and rainfall was considered: an increase in temperature of 2^{o}C and 4^{o}C, and changes in the amount of rainfall by -20%, -10%, 0%, +10% and +20%.

5.2 GCM scenarios

GCMs produce estimates of climatic variables for a regular network of grid points across the globe. There are a number of GCMs worldwide which evaluate the equilibrium response of the global climate to an abrupt increase, commonly doubling of atmospheric concentration of CO_2, by 2075 (equilibrium response). Recently, simulations have been made of climate response to a time dependent increase in greenhouse gases (transient response), (IPCC 1994).

Although various GCMs outputs are available, their predictions of the amount climate change differ. After comparing the GCMs' results with the trend of historical data for the country, three GCM results, namely CCCM, GFD3 and UK89, were selected to assess the impact of climate change for the sub-basin. For the stations used in the modeling, the monthly change in temperature and rainfall predicted by these models under a $2xCO_2$ scenario were used to assess the possible impact on the water resources of the sub-basin. The plots of the expected changes in temperature and rainfall for Bahir-Dar station, as predicted by these GCMs, are shown in Figures 3a and 3b.

6. Vulnerability assessment

The vulnerability of the water resources of the Lake Tana sub-basin to climate change was assessed based on the above two climate change scenarios.

For the synthetic scenarios, changes in temperature and rainfall were applied to the historical record for 1978–1987. The calibrated model was run for each combination of possible change in monthly bases. The simulated runoff was then compared with that of the present situation, i.e. without change in climate. The results are presented in Table 4.

For the GCM scenarios, the vulnerability of the Lake Tana sub-basin was assessed on the basis of the CCCM, GFD3 and UK89 climate change predictions for rainfall and temperature. The University of Colorado provided the predicted change in rainfall and temperature on a monthly basis for the stations considered in the study (IWMI & University of Colorado 2003). These changes were applied to the observed data and the change in runoff as compared to the present situation was computed and is shown in Table 5. Table 6 presents the extreme impacts predicted.

7. Adaptation

By 'adaptation' is meant the responses to both the adverse and the beneficial effects of climate change. The term refers to any adjustment, whether passive, reactive or anticipatory, that can respond to anticipated or actual consequences associated with climate change (IPCC 1994). Reactive adaptation means responding to climate change after it occurs while anticipatory adaptation means taking steps in advance of climate change to minimize any potentially negative effects.

In this study the overall goal in assessing adaptation options was to reduce the effect of potential climate change on the water resources of the Tana sub-basin. The specific objectives were to minimize risk due to increase in frequency and magnitude of flood and drought, to minimize economic losses and to increase institutional response in preparing for the adverse effects of climate change.

The degrees of impact predicted, using different models in different months, vary widely, and the months in which floods and drought predicted to occur also vary from model to model. But all the models agree that there will be a reduction of river flow from 15% to 80% of the monthly mean in some months of the year all over the basin.

The decrease in river flow might cause small streams to dry up completely and in the medium to large rivers the magnitude of flow will decrease significantly. There is no reservoir in the sub-basin so most of the existing water supply schemes of small-scale water developments draw directly on rivers or natural lakes. The supply of drinking water for humans and livestock depends mainly on river flow, so a decrease in the flow will have a severe effect. Because agriculture in the basin is mainly rainfed, an uneven distribution of rainfall and a decrease in or total failure of rainfall will cause crops to fail.

On the other hand, the predicted increase in river flow in some months of the year will cause floods, as the natural river and stream channels may not be able to accommodate the increase. Overflowing of the channels of the minor and major rivers and an abnormal rise in the level of the lakes will flood agricultural fields and human settlements.

8 Adaptation options

The technological, economic and policy adaptations available will differ greatly depending on the hydro-climatic zone, the level of economic development and the relative sensitivity of the water resource system to potential climate change (IPCC 1994). The IPCC Technical Guidelines (IPCC 1994) list six generic types of behavioral adaptation strategy for coping with the negative impacts of climate:

- Prevention of loss: involving anticipatory actions to reduce the susceptibility of an exposure unit to the impacts of climate.
- Tolerating loss: where adverse impacts are accepted in the short term because the exposure unit can absorb them without long-term damage.
- Spreading or sharing loss: where actions distribute the burden of impact over a larger region or population beyond those directly affected by the climate event.
- Changing use or activity, involving a switch of activity or resource use from one that is no longer viable following a climatic perturbation to another that is, so as to preserve a community in a region.
- Changing location: where preservation of activity is considered more important than its location, and migration occurs to areas that are more suitable under the changed climate.
- Restoration: which aims to restore a system to its original condition following damage or modification to climate. This is not strictly adaptation to climate, as the system remains susceptible to subsequent comparable climatic events.

Another way to adapt is to modify the threat, i.e. to attempt to control the environmental phenomenon itself. For example, a flood may be controlled by flood control structures and a drought may be alleviated by cloud seeding. The main way to modify long-term climate change is to slow its rate by reducing greenhouse gas emissions and eventually stabilizing the concentration of these gases in the atmosphere. Table 7 lists some ways the Tana sub-basin might adapt to the negative effects of floods and drought.

9. Discussion of results, and conclusion

The impact of climate change on the water resources of the Lake Tana sub-basin will be significant. If the temperature is increased by 2^{o}C and there is no change in rainfall, the mean annual flow will be decreased by 11.3%. But if the rainfall is decreased by 10% and 20% the decrease in runoff will be 29.3% and 44.6% respectively. On the other hand, if the rainfall is increased by 10% and 20%, the mean annual runoff will increase by 6.6% and 32.5% respectively. This shows that the sub-basin is more sensitive to changes in rainfall than temperature.

The CCCM and GFD3 GCMs predict a reduction of 18.2% and 12.6% respectively in the annual runoff , while the UK89 GCM predicts wetter conditions and as a result an increase of 2.5% in annual runoff.

The change in the monthly runoff values is more important than the overall annual change and is significant in the sub-basin The first two GCMs predict a reduction of monthly runoff by as much as 32% and 28% in the main rainy month of July. They also predict a significant reduction in rainfall in the short February to April rainy season.

In conclusion, the water resources of the Lake Tana area are highly vulnerable to climate change, especially in the distribution of runoff throughout the year. With climate change, the runoff may become much more seasonal and as a result small streams may completely dry up for part of the year. This will have a severe effect on the socio-economy of the sub-basin, as the agriculture here is totally dependent on rainfall and the rural water supply sources are mostly small streams and springs. The adaptation options suggested above are subject to various constraints, the major one being the capital that will be required for constructing dams and other flood prevention structures. Other constraints are social, such as the need to relocate people living in vulnerable areas, and physical, such as the scarcity of suitable land for resettlement.

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Table 1: Meteorological stations and their weighted area

Sub-basin	Met. station	Weighted area %	Met. station	Weighted area %	Hydrological station
Lake Tana	Aykel	4.8	A/Zemen	3.8	Abay at Bahir-Dar
	B/Dar	23.6	D/Tabor	10.6	
	Gonder	5.8	Enjebara	15.0	
	Maksegnit	4.8	Gorgora	18.3	
			Woreta	13.3	

Table 2: Calibrated model parameter values

Parameter	Values	Parameter	Values
Maximum storage, Smax (mm)	670	Direct runoff coefft., β	0.0
Sub-surface coefft., γ	1.8	Ground covers index, GC	0.2
Sub-surface coefft., α	4.5	Priestly Taylor coefft.	1.26
Surface runoff coefft., ε	3.0	Base flow (mm/day)	0.04
Initial storage, Z	0.23	Latitude (degree, north)	12

Table 3: Model efficiencies in calibration and validation periods

Station	Period	Correlation coefft.	Coefft. of efficiency	Av. error mm/day
Abay at Bahir-Dar	Calibration	0.88	0.73	0.17
	Validation	0.84	0.69	0.32

Table 4: Monthly percentage change in runoff under synthetic scenario

Climate scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
T+2;P+0%	-3.6	-1.1	-0.6	-1.5	-4.4	-8.1	-9.4	-10.4	-13.3	-17.8	-20.2	-12.7	-11.3
T+2;P+10%	-2.8	-0.9	-0.1	1.1	4.3	9.0	15.2	13.9	5.2	-4.1	-10.7	-8.9	9.6
T+2;P+20%	-2.0	-0.7	-0.5	3.9	13.9	28.5	43.4	40.7	24.9	10.1	-0.8	-4.8	32.5
T+2;P-10%	-4.3	-1.3	-1.1	-3.8	-12.3	-23.0	-29.6	-31.0	-30.2	-30.8	-29.2	-16.3	-29.3
T+2;P-20%	-4.9	-1.4	-1.5	-5.9	-19.3	-35.8	-46.5	-48.3	-45.1	-42.9	-37.7	-19.5	-44.6

Table 5: Monthly percentage change in runoff under GCM scenario

GCM	Jan	Feb	Mar	Apr.	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
CCCM	-8.3	-6.3	-4.6	-7.0	-25.2	-29.3	-32.5	-23.3	-13.5	-25.0	-29.9	-16.9	-18.2
GFD3	-6.7	-4.3	-3.9	-2.7	-7.7	-17.3	-28.2	-20.5	-5.1	-16.9	-26.0	-14.8	-12.6
UK89	-2.0	-0.2	-0.5	-5.7	-20.9	-22.4	28.9	34.4	4.9	8.4	6.6	-4.2	2.5

Table 6: Predicted extreme impact over the Lake Tana sub-basin

GCM	Impact predicted for the seasons	
	Max. decrease in %	Max. increase in %
CCCM	-32 in Jul	--
GFD3	-28 in Jul	--
UK89	-22 in Jun.	+34 in Aug.

Table 7: Adaptation options

Adaptation option	Option effectiveness for:	
	Floods	Drought
Construction of reservoirs for hydropower, irrigation, water supply, flood control and/or multipurpose uses.	High	Medium
Construction of dykes	Medium	-
Use of ground water	-	Medium
Relocation of settlements from flood prone areas	Medium	-
Afforestation	Medium	Medium
Improvement of water management systems	Medium	Medium
Establishment of flood forecasting and drought monitoring system	High	Medium

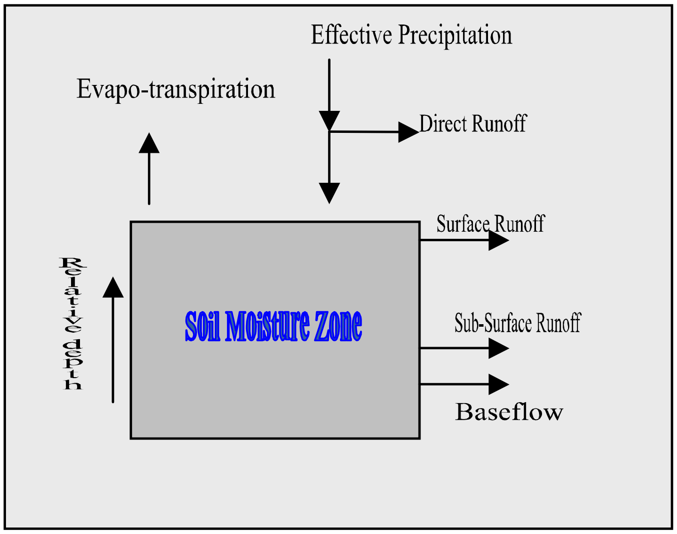

Figure 1: Conceptualization of WatBal model

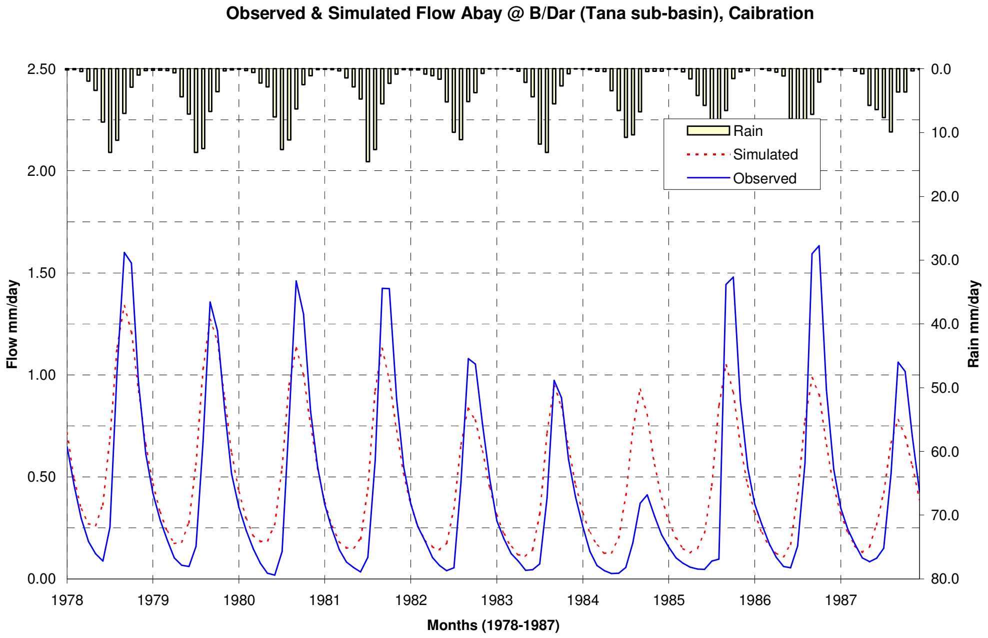

Figure 2a: Plot of observed and simulated runoffs – Calibration

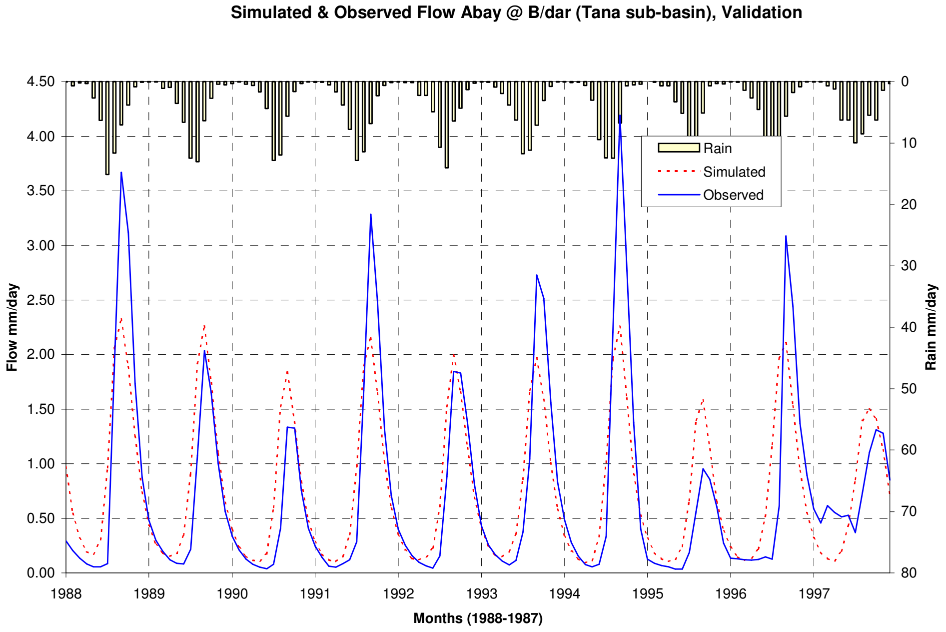

Figure 2b: Plot of observed and simulated runoffs – Validation

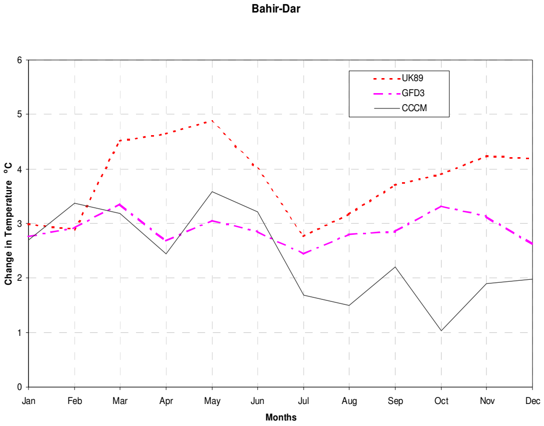

Figure 3a: Plot of expected change in temperature for Bahir-dar Station

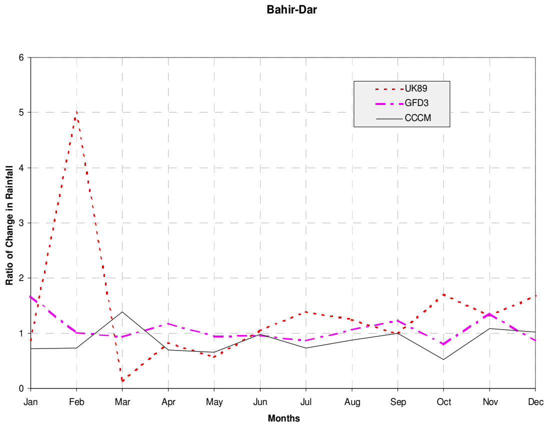

Figure 3b: Plot of expected change in rainfall for Bahir-dar Station