FLOW ANALYSIS AND CHARACTERIZATION OF THE BLUE NILE RIVER BASIN SYSTEM

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ABSTRACT

The flow characteristic of the Blue Nile River (BNR) basin is presented. The study presents low and high flow, flow duration curve (FDC) and trend analysis of the BNR and its major tributaries. Different probability density functions were fitted to better describe the low and high flow of BNR at Bahir Dar. Flow duration curves were developed and low flow (below 50% exceedance) and high flow (over 75% exceedance) of the curves were analyzed and compared. The Gravity Recovery and Climate Experiment (GRACE) satellite-based maps of monthly changes in gravity converted to water equivalents from 2003-2006 for February, May and September showed an increase in the moisture influx in the BNR basin for the month of September and loss of moisture in February and May. It was also shown that 2004 and 2005 were drier with less moisture influx compared to 2003 and 2006. Based on the Kolmogorov-Smirnov, Anderson-Darling and Chi-square tests goodness of fit, Gen. Pareto and Gen. Extreme Value and Gumbel Max distributions best describe the low and high flows within the BNR basin. This will be beneficial in developing flow hydrographs for similar ungauged watersheds within the BNR basin. The below 50% and above 75% exceedance on the FDC for five major rivers in addition to BNR showed different characteristics depending on size, land cover, topography and other factors. The low flow frequency analysis at BNR@ Bahir Dar showed 0.55 m^3/s as the monthly low flow with recurrence interval of 10 years.

Key Words: Blue Nile River, low and high flow, PDF, GRACE, flow duration curve, trend analysis

INTRODUCTION

Spanning over ten countries, the Nile River basin (White and Blue Nile Rivers) is the home of over 160 million people. Though Nile River is the longest river in the world, the total volume of water in the Nile River system is much smaller than Amazon and Mississippi Rivers. But the river is historically important and is the livelihood of many people is dependent on it. The basin is characterized as one of the most degraded mainly due to rapid population growth, poverty, political instability, poor watershed management, poor or absence of effective water use policy and frequent natural disasters.

Contributing over 57% of the Nile flow, the Blue Nile River (BNR) is one of the most ecologically, economically and environmentally important rivers of Ethiopia. Regardless of its large volume of water contribution to the Nile River system, the hydrological and other geomorphologic characterization studies are little. Only a few studies of this portion of the watershed have been conducted and the information available on the hydrology of the river and the basin is incomplete (Gamachu, 1977; Conway, 1997, 2000; Bewket and Sterk, 2004; Mishra et al., 2004). The population pressure in the highlands covering the upper basin of BNR, the land-use changes mainly for agriculture and the climate change impact on the hydrology of the region have contributed to the reduction of the flow from the river in recent years. Hydrometeorologic studies of the basin will benefit efforts to manage water and ecological resources of the basin.

Issues Related To Hydrologic Alterations

Water resources of the BNR basin is facing multifaceted problems ranging from destruction of critical forest reserves which maintain the dry season flows to poor water use and watershed management policy, which can lead to watershed and water resources degradation and pollution and also unsustainable utilization of water resources.

Land Clearing/Deforestation

High population growth, limited alternative livelihood opportunities and the slow pace of rural development are inducing deforestation, overgrazing, land degradation and declining in agricultural productivity. The absence of alternative sources of energy other than biomass, has put the available forest resource at risk. Forest clearing in hydrological sensitive areas like that of the head waters can lead to low dry season flows and reduction in recharge.

Siltation/Soil Degradation

Blue Nile River and its tributaries erode the top fertile soils of the highlands and transport thousands of tons of alluvial soil to receiving water bodies and lower basin countries. Sediment from watershed erosion is deposited in Lake Tana, source of BNR. Soil erosion has been the main problem in the reduction of agricultural productivity, poor water quality, loss of biodiversity and water level fluctuation in the basin.

Eucalyptus

Since its introduction over 100 of years ago from Australia, eucalyptus tree has been the main source of fuel wood, timber and construction in Ethiopia. Despite its popularity due to its fast growth even under moisture stress condition, its complex multi-dimensional impacts on soil moisture and ground water, on the soil fertility, on other plant life and on soil fauna undermine potential of land for biological productivity has been criticized. Poore and Fries (1985) indicated the strong surface roots compete vigorously with ground vegetation and with neighboring crops in situations where water is in short supply and largely displace original ecosystems. Van Lill et al. (1980) and Scott and Lesch, (1997) reported that afforestation of grassland (with Eucalyptus grandis and Pinus patula) reduced annual flows at Mokobulaan, Transvaal, South Africa. Zhou et al. (2002) found in Southern China that the water table level in a watershed planted with eucalypts (Eucalyptus exserta) was 80 cm lower than that under a bare watershed, whereas while it was only 30 cm lower in another watershed under mixed forest.

The recent replacement of agricultural fields along the main roads in northwestern Gojjam and at other places with eucalyptus plantation has been going at an alarming rate. It has been found that it is a good source of cash and shown to have more return than agricultural crops. If this practice is continuing, the ecological, hydrological and socioeconomic implications can be higher.

Poor Watershed Management

Land degradation, soil erosion and eventual deposition to surface waters have been attributed to poor watershed management. The need for diverting more water to irrigation canals and construction of dams without proper engineering design addressing location, size and improved watershed management has been a practice in some cases in the region. History has shown that most dam and irrigation project failures are associated with siltation resulting from little or no watershed management activities.

Poor Water and Watershed Management Policy

Land and water use policies which do not result in improved land and water use management and promote the conservation and protection of sensitive water resources, wetlands and recharge areas will contribute to the degradation of watersheds and water resources. Empowering local and national institutions to coordinate and implement appropriate water monitoring, protection and water use activities, lead and coordinate community participation and educate and train water users on the integrated water resources management are important actions yet to be taken.

Poor Headwater and Wetland Protection

Headwaters and wetlands are important parts of the any hydrological systems and their protection is vital for maintaining stream flow and groundwater recharge. Encroaching of these sensitive ecosystems for grazing land and agricultural practice has put the wetlands in danger and led to their shrinkage. Such practice can lead to irregular flows and reduces the minimum flow during the dry season.

Lack of Baseline Data/Information

Unlike part of the Nile basin in the lower basin, the upper Blue Nile River basin in Ethiopia has little baseline information on its biological resources, hydrological and hydraulic characteristics of the river. Information on soils, land cover and other socio-economic settings are limited and scattered. Sediment and water quality data and detailed biodiversity information is not available. Any future effort to plan and implement sustainable water and land resources management should have this information.

The major objective of this study is to characterize the BNR system based on the historical low and high flow records and understands the trend of the critical flow (dry season low flow).

STUDY AREA AND DATASETS

Study Area Description

Originating from Lake Tana (1830 m amsl) in north western part of Ethiopia (Figure 1), the BNR is a major source of water for the economy of lower basin countries. With drainage area of approximately 324,530 km^2, the upper Blue Nile basin covering mainly parts of the highlands in Ethiopia has been characterized as one of the most degraded with natural and human-induced processes. The basin faces environmental and natural resources degradation attributed to anthropogenic (forest degradation, poor or no watershed management practices, overgrazing, poor agricultural water and soil conservation practices and others) and climate change-induced (droughts, unpredictability of rainfall volume and distribution, increased temperature leading to alterations in ecosystem structure). About 66% of the area of this densely populated basin falls in the highlands and hence receives fairly high levels of rainfall (800 to 2,200 mm). This volume of rainfall has a higher spatiotemporal variability leading to higher moisture stress and complete crop failures in some years. Figure 2 shows the mean monthly basin-wide rainfall for the BNR basin.

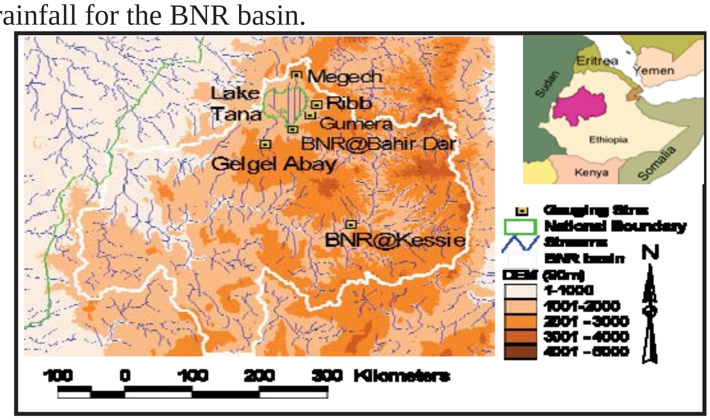

Figure 1. Location of stations and the BNR Basin as it exits Ethiopia.

Dataset

For this study, hydrometeorological data (rainfall and flow) and Gravity Recovery and Climate Experiment (GRACE) satellite data were acquired and processed. Daily rainfall data for selected stations in the basin beginning 1950 were acquired from the Ethiopian Metrological Agency. Similarly, monthly flow values for the six major gauging stations (Blue Nile at Bahir Dar, Gelegel Abay, Chemoga, Kessie, Gumera and Ribb) were acquired and processed for the analysis.

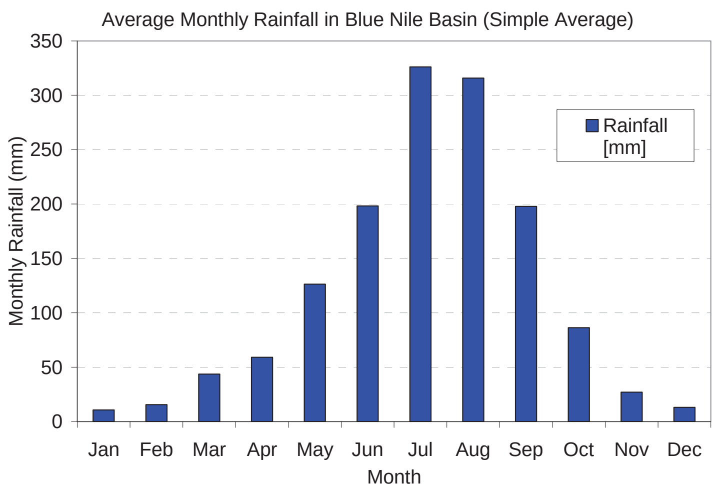

Figure 2. Mean monthly rainfall of the BNR Basin.

METHODOLOGY

GRACE Data

Gravity Recovery and Climate Experiment (GRACE) (http://www.csr.utexas.edu/grace/), twin satellites were launched in March 2002 to make detailed measurements of Earth's gravity field which will lead to discoveries about gravity and Earth's natural systems. The changes in gravity can be due to changes in runoff and ground water storage and fluxes on land masses (http://www.csr.utexas.edu/grace/). In this study, monthly changes in gravity converted to equivalent of water derived from the GRACE Stateline data for the period of 2003-2006 for the months of February, May and September were used to understand the seasonal and annual changes in the basin's water resources. The method for converting the change sin earth's gravity to water equivalent is shown in Wahr et al. (1998).

Probability Density Frequency Curves and Goodness-of-Fit Tests

In order to understand the probability distribution of the river flow (low and high flows), over 40 distributions were evaluated using three most commonly used goodness-of-fit tests: Kolmogorov-Smirnov (K-S), the Anderson-Darling test and chi-square test. The Kolmogorov-Smirnov test (Chakravart et al., 1967) is used to evaluate if a sample comes from a population with a specific distribution. The K-S test statistic itself does not depend on the underlying cumulative distribution function being tested. It is also an exact test (the chi-square goodness-of-fit test depends on an adequate sample size for the approximations to be valid).

The Anderson-Darling test (Stephens, 1974) is a modification of the Kolmogorov-Smirnov (K-S) test and gives more weight to the tails than does the K-S test.

The chi-square test (Snedecor and Cochran, 1989) is an alternative to the Anderson-Darling and Kolmogorov-Smirnov goodness-of-fit tests. The chi-square goodness-of-fit test can be applied to discrete distributions such as the binomial and the Poisson. The Kolmogorov-Smirnov and Anderson-Darling tests are restricted to continuous distributions.

Flow Duration Curve (FDC) and Low-Flow Frequency Analysis

Flow duration curve shows the percentage of time that a given flow rate is equaled or exceeded. Constructed from flow data of fixed time period (eg., daily, monthly, annual), the shape of the FDC can indicate the hydrogeological characteristics of a watershed (Smakhtin, 2001). Flow duration curves from the mean monthly flow data of the BNR and four other major tributaries were constructed to understand the low and high flow end of the rivers and also characterize the rivers based on the slopes of the two end of the curve. High slopes in the low flow tail (<50%) will indicate a less sustained low flow during the dry seasons than a low slope FDC. This indicated less and/or variable base flow in the dry seasons. Similarly, high slopes in the high flow end of the FDC indicates less contribution from natural storages like groundwater.

A Low-flow frequency analysis shows the number of years when a low-flow rate is exceeded. This depicts the recurrence interval, the average interval (in years) that the river discharge falls below a given rate, and can also be used to represent base flow conditions. The curve is generated from the series of annual minimum flow values extracted from the stream monitoring data. High slope of the low-flow curve can be taken as indicator of variable low flow.

RESULTS AND DISCUSSIONS

GRACE Water Equivalent Maps

The GRACE water equivalent maps (Figure 3) show the monthly change in water storage in the basin (cm) for the months of February, May and September from 2003-2006. The months were selected to represent different levels seasons and rainfall volumes.

Seasonal Comparison

It is shown that the months of February and May have shown a deficit in the water equivalent (negative value) due to loss of water from the BNR basin. On the other hand, September has shown a consistent gain in water (positive value) resulting from the wet season flows.

Annual Comparison

Comparison of the changes in moisture or water storage in the BNR basin from 2003- 2006 from GRACE maps (Figure 3) shows that 2004 was drier than the rest of the years for the month of September. This can be driven mainly by the amount of precipitation. On the other hand, the February changes in water storage in the BNR basin was less in 2003 than the rest of the years. This indicates during the dry season water loss due to evapotranspiration will be the dominant mechanism. The change in water storage for May has a similar trend that 2003 has less change in storage than the period of 2004-2006. The month of May is considered to receive some rainfall in the basin (Figure 2) and is also characterized as one of the months with high temperatures.

Probability Density Frequency Curves

The probability distribution curves for the minimum and maximum flows of the Blue Nile at Bahir Dar gauging station was constructed and based on the goodness-of-fit test, the and General Pareto and Generalized Extreme Value distributions best describe the maximum minimum flows, respectively. Figure 4 shows the PDFs.

Flow Duration Curves

The FDC curves from the six major stations in the BNR basin is shown in Figure 5. The FDC curves show that the flows at Kessie and BNR at Bahir Dar have a large and sustained flow than the other stations with a relatively flatter slope in the high flow tails of the curves. The flow at Gelegel Abay has also a much sustained dry season flow like that of the Kessie and BNRat Bahir Dar but with relatively smaller discharge.

Flow from the tributaries of the BNR (Ribb, Gumera and Megech) are relatively smaller and the high flow tail end of the FDC from these rivers show a less sustained flow as shown by higher slopes of the curve in Figure 5. The base flow from these rivers during the dry seasons can be small as they tend to have high slope FDC curve on the high flow tail.

Low Flow Analysis

The low flow frequency curve shows the recurrence intervals of a particular selected low flow for the river system. Figure 6 shows the recurrence interval of the low flows from the BNR at Bahir Dar. It is shown that assuming the low flow occurring every 10 years, the monthly average low flow was found to be 0.55 m^3/sec for BNR at Bahir Dar.

Maximum and Minimum Flow Trend

Temporal trend of the maximum and minimum monthly flows at two selected stations were analyzed and shown in Figure 7. The historical maximum monthly flow of the Gelegel Abay has shown little variation over the period of time. On the other hand the mean monthly minimum flow indicated a decline beginning early 1990s. Similarly the Chemoga average monthly flow showed little visible variation but the minimum monthly flow has shown a declining trend since 1994.

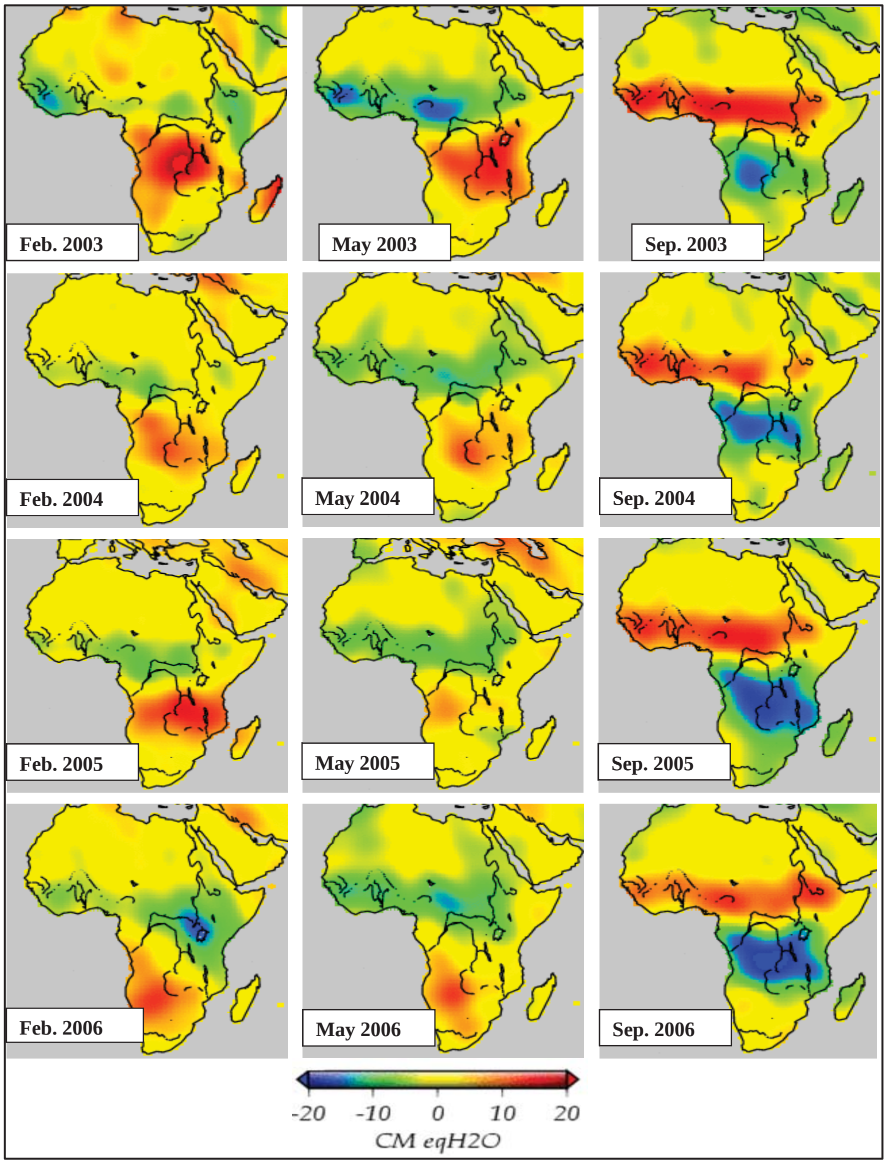

Figure 3. GRACE maps of monthly changes in water equivalent for Africa.

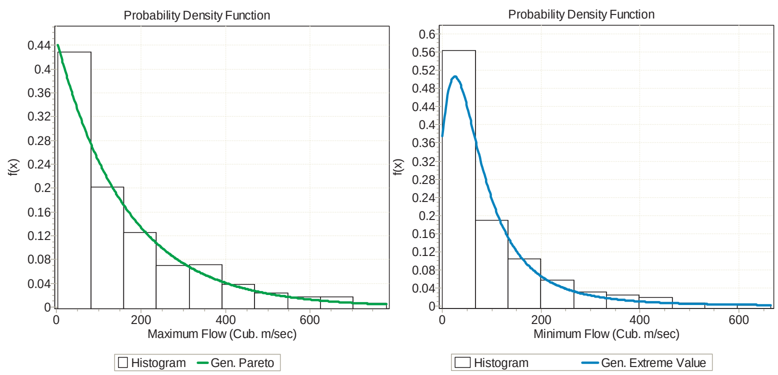

Figure 4. Probability Density Function curves of the monthly Blue Nile River flow at Bahir Dar, a) Maximum flow, b) Minimum flow.

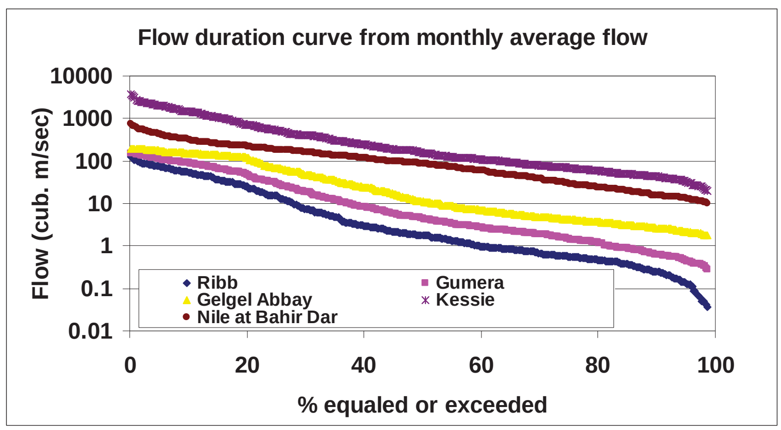

Figure 5. Flow duration curves of the BNR and its tributaries.

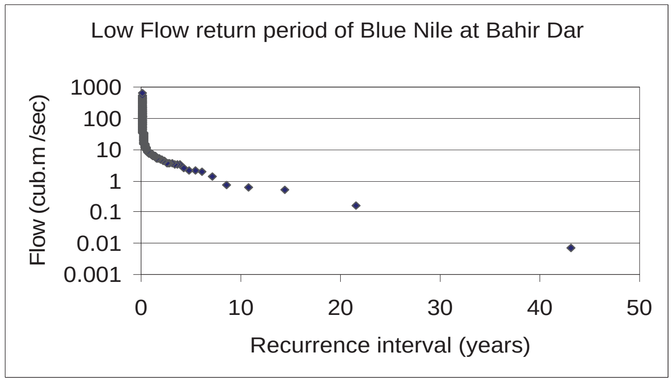

Figure 6. Low flow return period for the Blue Nile River Flow at Bahir Dar.

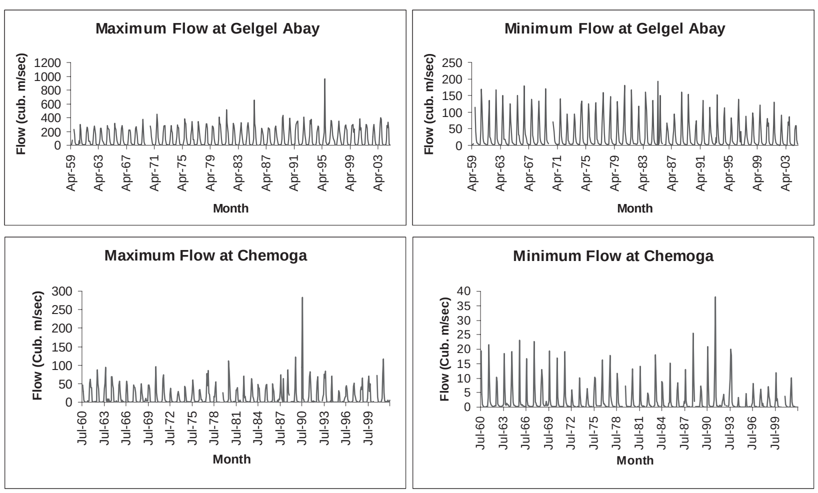

Figure 7. Average maximum and minimum flows at Gelegl Abay and Chemoga stations.

SUMMARY

Despite the large volume of water contribution to the Nile River System, presence of major hydrological issues that require scientific studies, monitoring and analysis, the technical information and research pertinent to the hydrology of the basin is very limited. In this analysis, Hydrometrological analysis is conducted. Monthly flow characterization and analysis were conducted for the BNR and its major tributaries. Using GRACE satellite water equivalent monthly deviation, seasonal and annual variation in the water fluxes of the BNR was studied.

From the flow analysis, flows at Kessie and BNR at Bahir Dar has shown a sustained flows with a relatively flatter slope of the FDC at both ends. Flows from the other rivers with the exception of the Gelgel Abay, has very low base flow contribution as shown from the stepper sloes of the FDC in the high flow tail end. The Low flow analysis of the BNR at Bahir Dar also shows a 10-year recurrence of 0.55 m^3/sec monthly average flow. Tend analysis of flow two stations shows a recent decline in the low flow compared to a no significant change in the high flow values.

The GRACE satellite based monthly changes in water equivalent values indicated the seasonality and also annual variability of the moisture fluxes in the basin. The analysis shows a moisture deficit in the months of February and May and a gain in moisture in September mainly driven by the wet season rainfall.

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