ESTIMATING THE EFFECT OF CLIMATE CHANGE ON THE HYDROLOGY OF SSEZIBWA CATCHMENT, UGANDA

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ABSTRACT

This study investigates the potential effects of climate change on the hydrology of Ssezibwa catchment in Uganda. The study employs statistical downscaling techniques, which have of recent proved useful in deriving more detailed and reliable climate change scenarios for use in hydrological models for impact assessment. The first part of this study investigates the current climatic trends in the region. Future climate change scenarios are obtained from the UK Hadley climate model (HadCM3) and downscaled to the local climate of the study area. The downscaled results were used as inputs to the WetSpa hydrological model, a physically based distributed rainfall-runoff model, which was used to simulate the resulting hydrological changes. One of the key findings was that climate change is actually taking place in the study area. The results further showed that precipitation in the study area will generally decrease while temperatures will increase with 1-4°C in the dry periods. These changes will have significant impact on the river discharge by reducing the flows in the dry periods especially between May and September, while heavy floods were simulated for the wet months between November and March. In the 2020's these changes were shown to be small, but they will increase significantly beginning the 2050's. These results provide new findings on the effects of climate change on water resources in Africa. However, since the downscaling process is associated with much uncertainty, the findings should provide a basis for further research of especially the downscaling of precipitation data.

Key words: *Climate change, hydrology, WetSpa, GCMs, Downscaling.*

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1. INTRODUCTION

It is widely accepted that the Earth's climate has significantly changed. The IPCC (2001) projects that over the past 20th century, surface temperatures have increased by 0.6°C while continental rainfalls have increased by 5-10%. Current evidence suggests that these changes are mainly due to human activities primarily through the burning of fossil fuels, which has increased the concentration of atmospheric greenhouse gases and aerosols (IPCC, 2001, Gleick et al. 2000). One of the most severe consequences of climate change (CC) will be the alteration of regional hydrological cycles which poses a threat to many water resources systems in the world (Xu, 2000). This will affect nearly every aspect of human wellbeing from agriculture, hydropower generation, water supply for domestic and industrial purposes and wildlife management. According to IPCC (2001), African countries are more vulnerable to these changes due to lack of institutional capacity and economic development. In Uganda for example, evidence of CC already exist (MWLE, 2002) – such as melting of ice and glaciers on mountain tops such as Mt Rwenzori, rise in temperature and increase in Malaria incidences as noted by Wandiga (2006), erratic rainfalls and floods, increased dry spells and drop in lake levels. Consequently, there is a strong need for CC impact assessment especially at smaller spatial scales. Climate change causes changes in rainfall, runoff and evaporation, which in turn affect the water availability and variability (Phoon et al. 2004). A watershed for which a hydrological model has been developed can be assessed for CC through climate change scenarios. Global circulation models (GCMs) are generally used to simulate the present climate and future climate scenarios with forcing by green house gases (Dibike et al. 2004). In Uganda for example, GCMs were used in a study in 1996 to assess the country's vulnerability, adaptation and mitigation of climate change (MWLE, 2000). GCM's are however too coarse and do not accurately represent the local climate. The use of statistical downscaling models (SDSM) has proved useful in relating GCM outputs or large-scale climate variables into reliable local-scale climate for impact studies. Hence, it is the goal of this research to test the use of the SDSM model for downscaling GCM CC scenarios, and to use the output as input for hydrologic process analysis at a regional level. This methodology is applied in a case study of the Ssezibwa catchment located in central Uganda.

2. THE STUDY AREA

The Ssezibwa catchment comprises approximately 175km^2 (Fig.1). River Ssezibwa is gauged at Ssezibwa falls (0°21′ N and 32°52′E). The river drains northwards into Lake Kyoga. The geology of the area is characterised by rocks from the Precambrian. The topography varies from 1122m in the north to 1353m in the south. The dominant land uses in the study area are agriculture (63%) and ever-green broadleaf trees (30%). The soils are mainly sandy clay-loam. Ssezibwa catchment is characterised by a tropical humid climate influenced by L. Kyoga and L.Victoria (MSOE, 1997) and it experiences two rain seasons (March to May and September to December) with a mean rainfall of 1600-2000mm. The annual evaporation is about 1472mm, which renders the area a rainfall surplus zone. The mean annual maximum temperature is 25-27.5°C while the minimum is 15-17.5°C.

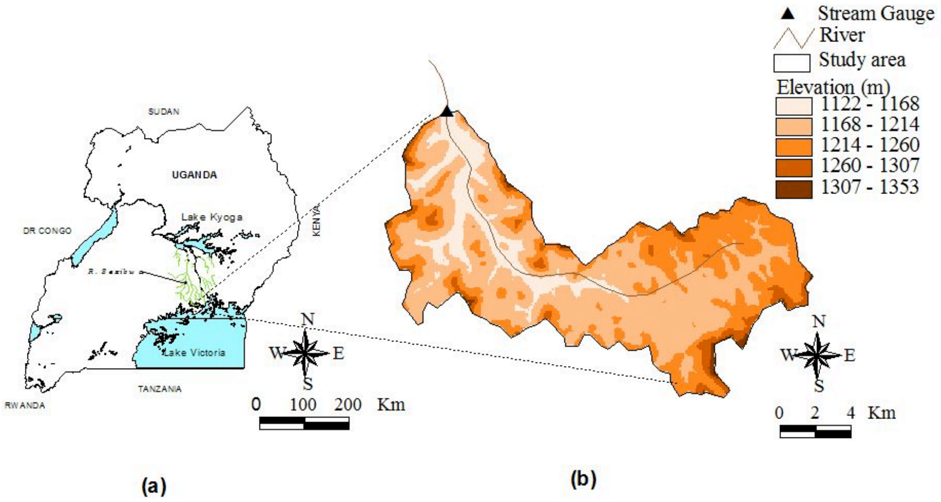

Figure 1: (a) Location map of study area (b) Topography and catchment boundary

3. DATA

Data used in this research included 90m resolution grid maps of elevation, landuse and soil, as well as daily precipitation and potential evapotranspiration data (PET), daily discharge and daily large scale GCM predictors, which are used to predict future climate changes. Meteorological data spanning 1970 to 2001 was obtained from 6 weather stations from the meteorological department Entebbe, Uganda. Three stations Namulonge, Jinja and Kampala were used for PET, while the other three of Lugazi, Kivuvu and Mitono were used for precipitation.

The latter were much closer to the study area and it was necessary to take them into account for the precipitation interpolation since rainfall is highly variable in the study area (Hanna 1970). The PET series were calculated from the available meteorological data using the Penman Monteith formula. Daily discharges of Ssezibwa flows from 1961 to 2005 were obtained from the Directorate of Water Resources Management (DWRM), Entebbe Uganda. These data contained several missing gaps and therefore the study had to be limited to the years 1997-2004. Daily climate predictors were obtained from the UK Hadley Climate model, HadCM3 for the IPCC SRES A2a and B2a emission scenarios for grid location of 0N, 33.75E. The predictors are freely available from the Canadian Climate scenarios project (http://www.cisc.uvic.ca/scenarios/).

4. METHODOLOGY

Generally, a watershed for which a hydrological model has been developed can be assessed for CC through climate change scenarios. According to Phoon et al. (2004), the assessment is evaluated by comparing specified climate change scenarios to the current climate or the baseline climate, which represents conditions in absence of climate change. In this study, this assessment consisted of the four steps of 1. Trend analysis; 2. Distributed hydrological modeling; 3. Statistical downscaling of climate data; and 4. Hydrological response analysis.

4.1. Trend analysis

First, a trend analysis was performed to examine whether climate is really changing in the study area. This trend analysis was performed on discharge, precipitation and mean temperature time series on basis of a software developed by Willems (2006). It uses 13 tests to detect trends and change points such as step jumps in mean and difference in median from two data periods. The software requires that the time series are continuous and independent. Hence, the analysis for precipitation and temperature was performed on monthly time series, which were extracted from daily series. To ensure independence in the discharge series, the analysis was performed on Peak over Threshold (POT) or partial duration series, which were extracted from the daily discharge series using the WETSPRO program (Willems 2004). This program is used to separate flows and to extract independent peaks from discharge series. Since trends are dependent on the period analysed, two periods (1960-1994 and 1994-2004/6) were used in this study for trend analysis.

4.2 Distributed hydrological modeling

A distributed-hydrological model was developed to simulate the hydrology of the basin for impact assessment using the river runoff. The river runoff was used since it can be a good average descriptor for the hydrology of a catchment. The basin hydrology was simulated using the GIS-based WetSpa hydrological model (Liu & De Smedt 2004). WetSpa is an acronym for Water and Energy Transfer between Soil, Plants and Atmosphere and is a physically-based distributed hydrological. The main inputs to the model were precipitation, PET, discharge series and spatial GIS grid maps of elevation, landuse and soil type. In areas where snow accumulates, temperature series are also used. The discharge is used to calibrate and validate the model. Three stations Lugazi, Kivuvu and Mitono were used for precipitation while Namulonge, Jinja and Kampala were used for PET. Due to limitation in data, only 3 years (1997-1999) were used for calibrating the model and 3 years (2002-2004) for validating it. The ArcView software was used to derive the spatial distribution of precipitation and PET using the Thiessen method. The landuse, soil and elevation maps were used to derive the spatial parameters of the model using default lookup tables as described by Liu & De Smedt (2004). Such derived parameters include Manning’s and runoff coefficients, time of travel, flow velocity and surface routing parameters. The average runoff coefficient was obtained as 0.46 and the average flow time as 12.8hrs with a maximum of 41hr.

4.3 Statistical downscaling of climate data

Since the assessment of climate change requires greater spatial and temporal detail, downscaling techniques are used to derive more detailed climate scenarios directly from course resolution GCM outputs. In this study, the Statistical Downscaling Model (SDSM; Wilby et al. 2002) was used to downscale observed maximum and minimum temperature (TMAX and TMIN) and precipitation (PRCP). The SDSM model calculates relationships, which relate large scale GCMs variables (predictors) to local scale meteorological series (predictants). The GCM predictors for the current period (1961-2001) and future period (1961-2099) were obtained from the UK Hadley global circulation model, HadCM3 using IPCC SRES A2a (or high) and B2a (or low) emission scenarios. Emission scenarios predict the emission of greenhouse gases, which are the main driving factors of the GCM predictions (O’Hare et al.

2005). The current GCM predictors are derived from the NCEP (National Centre for Environmental Protection) dataset and are used along with the locally observed data to calibrate and validate the SDSM model. Local observed data or predictants were available from 1970 to 2001. During downscaling, the screening process is an important step where potential GCM predictors are identified. The screening is achieved using linear correlation analysis and scatter plots between the NCEP predictors and predictant variables for the current period 1961-2001. The potential predictors identified for temperature were relative humidity at 500 hPa and 850 hpa potential heights, mean temperature, 850 hpa geopotential heights and relative humidity. For precipitation, the potential predictors were mainly near surface specific humidity, relative humidity, 500 hpa geopotential height, relative humidity at 850 hPa height and mean sea level pressure. Generally, the correlations, R^2 were generally poor especially for precipitation. This could be attributed to lack of surface flow predictors, which are not provided in the HadCM3 GCM predictors at the equator where the catchment is located. The selected predictors were then used to calibrate and validate the SDSM models. The downscaled temperature was analyzed using the mean and variance while for precipitation the mean, variance, % wet days and dry series length were used. For the simulations, the ensemble mean was used. Generally, temperature was well modeled but precipitation showed variable results. The verification of the downscaling process for precipitation is provided in Fig. 2 and shows a good match.

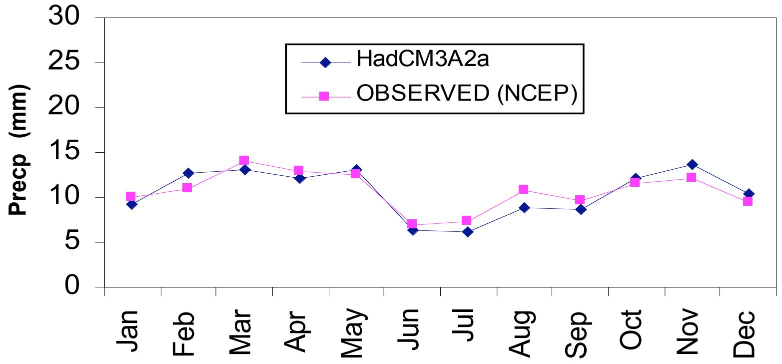

Figure 2: Mean daily precipitation at Lugazi (Stn 4): 1961-1990

The calibrated temperature and precipitation models were then used to downscale future climate scenarios for 3 future periods; the 2020's (2010-2039), 2050's (2040-2069), 2080's (2070-2099).

4.4 Hydrological response analysis

This analysis was carried out using both the downscaled climate and future hypothetical scenarios. The latter were used to investigate the sensitivity of the catchment to CC. The current, future and adjusted time series of daily precipitation and PET corresponding to CC scenarios were input into the WetSpa model for simulation of the runoff responses. The PET in mm was calculated from the mean temperature (T_m) using the temperature-based Blaney-Criddle Equation;

$$PET = Kp(0.46T_m + 8.13) \qquad (1)$$

Where p is the percentage of total daytime hours (daily or monthly) out of total daytime hours of the year (365×12), with p is 0.27 at the equator (Xu 2002). K is the monthly consumptive use coefficient, depending on vegetation type, location and season. This method was selected because it is easy to use and has been extensively used. K was obtained by calibration using the current PET series.

6. RESULTS

6.1 Trend analysis results

Table 1 summarises the results from the trend tests and change point analyses. The null hypothesis of no change was used for the analysis. The Linear regression analysis of the trends is presented in Fig.6 in the Annex. It should be noted that the times series axis was replaced by serial times to ensure the series are continuous for the trend analyses. From Table 1 and Fig. 6, it is evident that the discharge series do not show trends when analyzed for the entire period from 1960-2006. However, when analyzed over a shorter period from 1994 to 2006, the discharge series showed decreasing trends significant at 99% confidence level and indicating a 50% decrease per decade. A similar analysis was done for precipitation series, however no significant trends were observed neither for the entire nor for the short period of 1990 to 2006 (Fig. 6 and Table 1).

Table 1: Trend analysis results

	ACCEPT (□) OR REJECT (X) NO CHANGE					
Methods	Test	Disch. (1960-2006)	Disch. (1994-2006)	Precip. (1960-2004)	Precip. (1990-2004)	Temp. (1960-2004)
confidence level ➔		*0.05*	*0.01*	*0.05*	*0.05*	*0.01*
1. Mann-Kendall test	Trend	□	x	□	□	x
2. Spearman's Rho test	Trend	□	x	□	□	x
3. Wald-Wolfowitz	Trend	□	x	□	□	x
4. Linear regression test	Trend	□	x	□	□	x
5. Distribution free CUSUM	step jump	□	□	x	X	□
6. Cumulative deviation test	step jump	□	x	□	□	x
7. Worsley likelihood ratio	step jump	□	x	□	□	x
8. Rank-sum test	difference	x	x	□	□	x
9. Student's t-test	difference	x	x	□	□	x

6.2 Calibration and validation results of the WetSpa Model

The WetSpa model was calibrated by adjusting the models global parameters using daily flows from 1/1/1997 to 31/12/1999. The calibration was done both manually and automatically using the Automatic Parameter Estimator (PEST) (Doherty 2002). The results of the calibration were validated using an independent data set from 1/1/2002 to 31/12/2004. A graphical comparison of the simulated and observed flows for the validation period is shown in Fig. 3. The model was run using the semi-distributed model and its performance was considered satisfactory with a Nash-Sutcliff 62.9%. The performance of the model on validation was 79.8%.

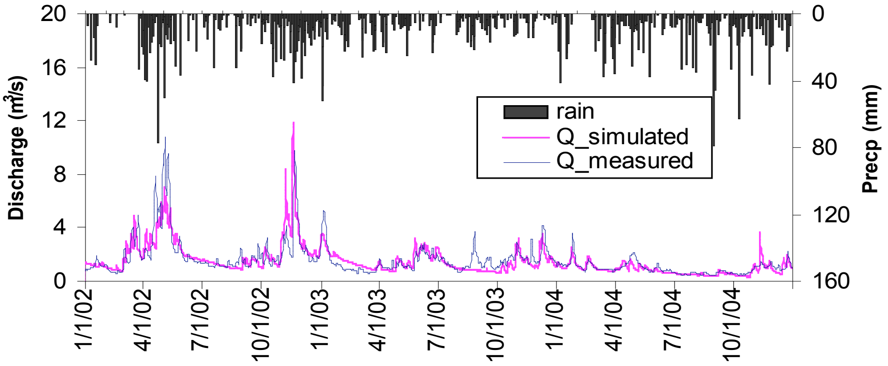

Figure 3: Comparison of measured and simulated discharge

6.3 Results of downscaled climate

Fig. 4 compares the current (NCEP) and downscaled climate scenarios. These results are only presented for the precipitation at Lugazi station and temperature at Jinja station because these datasets had fairly good data sets. Precipitation in particular showed variable results for the other stations, which is attributed to poor calibrations. These results indicate that precipitation will generally decrease in the dry periods from May and August while heavy rains will be experienced in the Wet months between November and March. The months of May till September are expected to experience gradual increases in temperature in the range of 1-4ºC between the 2020's and the 2080's, mean daily temperatures may rise till 33ºC in the 2080's.

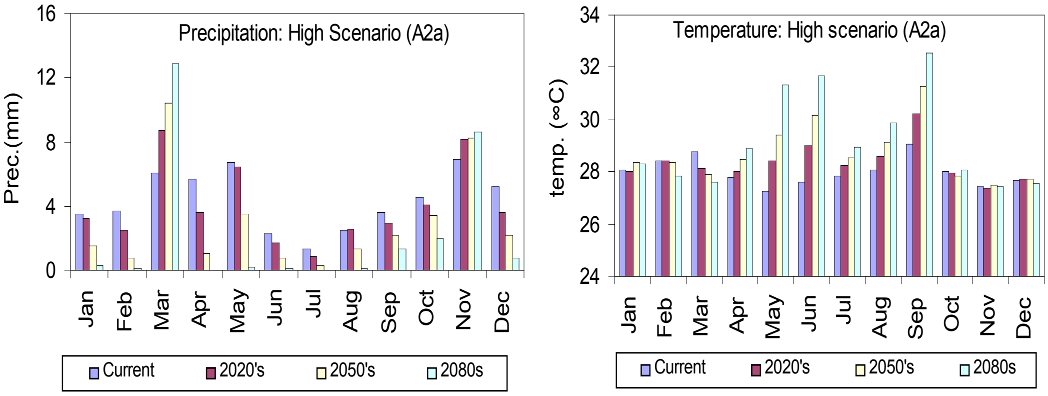

Figure 4: Comparison of climate scenarios of downscaled precipitation at Lugazi (left) and temperature at Jinja (right) using the HadCM3 A2a experiment

6.4 Hydrological response analysis

6.4.1 Hypothetical scenarios results

Fifteen (15) hypothetical scenarios were derived to analyze the sensitivity of the catchment to CC. These included combinations of +1, 2 and 4 ºC for temperature and 0%, +/-10% and +/-20% for precipitation. They were drawn from the IPCC (2001) estimates of future CC in the region (ΔT = 1.4-5.8 ºC, ΔP = 10-20 %). Table 2 presents the resulting annual changes in the river runoff.

Table 2: Changes in runoff under hypothetical climate change scenarios

	P=+0%	**P=+10%**	**P=+20%**	**P=-20%**	**P=-10%**
T = +1°C	-4%	22%	50%	-49%	-28%
T = +2°C	-9%	17%	45%	-52%	-32%
T= + 4°C	-16%	8%	54%	-57%	-38%

The results indicate that the catchment is highly sensitive to climate change. The correlation is strong with changes in precipitation; temperature on the other hand shows a lower correlation with an estimated 5% decrease in runoff per 1 ºC rise in temperature.

6.4.2 Responses to downscaled climate

Discharges corresponding to downscaled climate were obtained for the current period (1961-1990) and the future periods 2020’s (2010-2039), 2050’s (2040-2069) and analyzed on a mean monthly basis. The results are given in Fig. 5 for the two emission scenarios A2 (high scenario) and B2 (low scenario). The results suggest that there will be no significant changes in river runoff in the 2020’s (i.e. in the coming 20 years). However, beginning the 2050’s, significant reductions in river flows may be observed especially in the dry periods between May and September. The wet months on the other hand, will experience heavy floods especially between November and March. Between the 2020’s and 2080’s, the river flows are expected to increase by 30-50% in the wet months. Simulations for the 2080’s showed the river may run dry between July and September. The results for B2 emission scenario follow the same trend as the A2 scenario but with a lower magnitude. No linear relationship was observed between the outputs of A2 and B2.

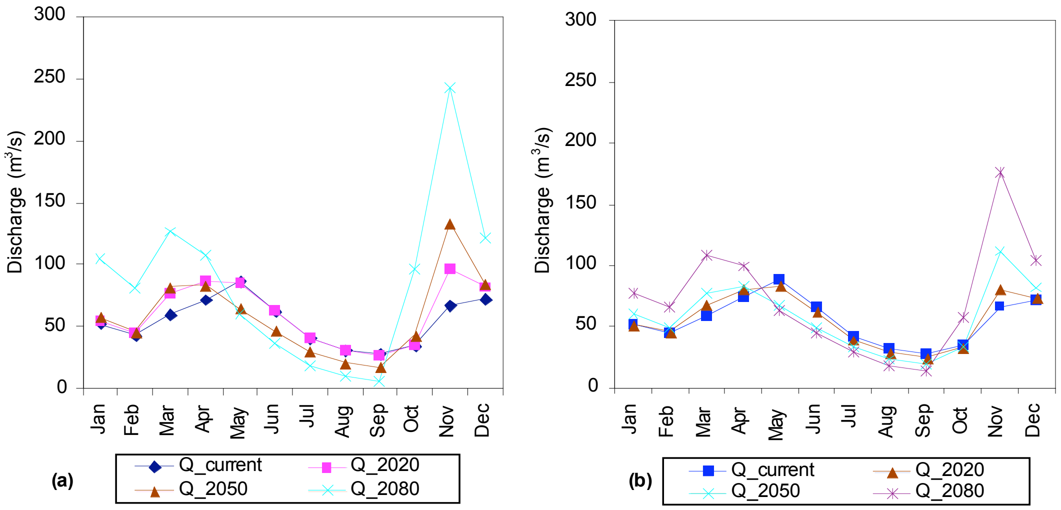

Figure 5: River Ssezibwa flow responses to HadCM3 climate change scenarios; (a) A2 or high emission simulation and (b) B2 or low emission simulation

7. CONCLUSIONS AND RECOMMENDATIONS

Future climate change scenarios generally show that climate will escalate with more heavy rains in the wet months, while the dry months will experience increased temperatures. This is expected to impact the river flows by causing floods in the wet months due to an increase in river flows with up to 50%. In the dry months, the results suggest that the river may experience significant reduction in flows. It is important to realize that statistical downscaling has uncertainties (Scibek, 2005). The limitation in the data further adds to these uncertainties. The findings of this research for the Ssezibwa catchment should be translated with care to other catchments. However, recognizing the inherent uncertainty in climate change predictions, the results of this study will be highly useful in future studies and decision making in water resources management for the region. It is recommended to collect additional data of especially rainfall to improve the model results. Further more, it should be investigated what the influence is on the results of using other GCM models and as such specify better the uncertainty in the predictions. It results from this research that that there is a strong need to quantify the effects of climate change on hydrological cycles in Africa and that this should receive a high priority in further research, so as to specify ways for adaptation, since climate change is hard to reverse.

8. REFERENCES

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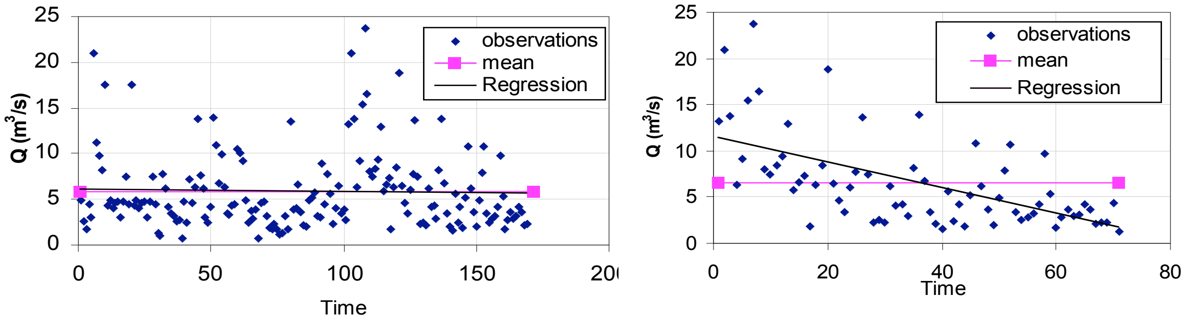
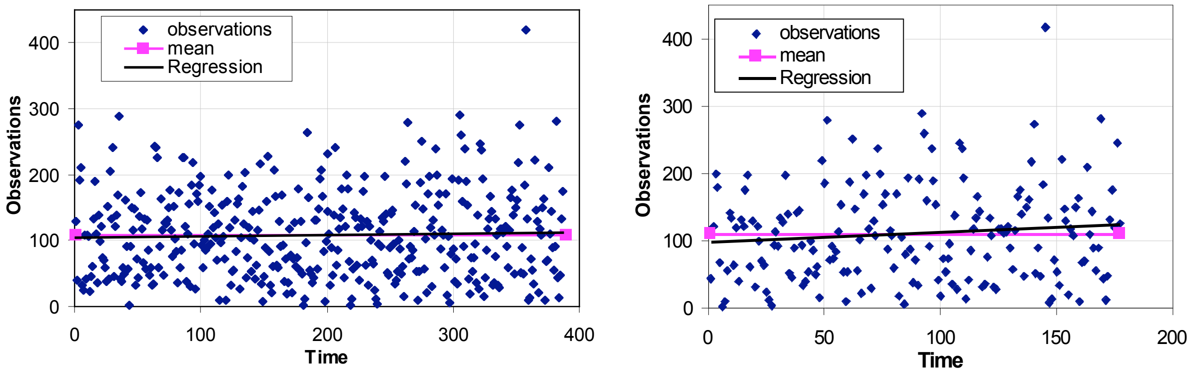
ANNEX: TREND ANALYSIS PLOTS



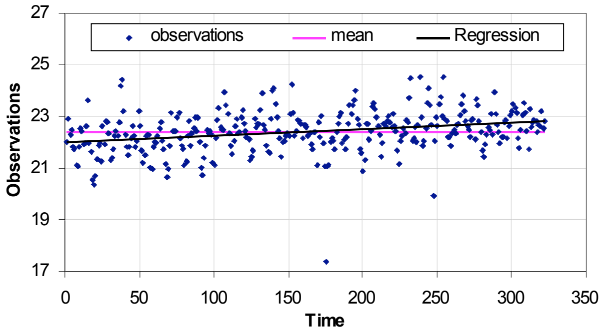
(a) Discharge (1960-2006)

(b) Discharge (1994-2006)



(c) Precipitation (1960-2004)

(d) Precipitation (1990-2004)



(e) Temperature (1960-2004)

Figure 6: Trend Analysis Plots