Climate Change Impact Investigation on Hydro-Meteorological Extremes on Zambia's Kabompo Catchment

Stephen Siwila, Meron Teferi Taye, Philippe Quevauviller, Patrick Willems

Abstract: Climate change impact investigation on hydro-meteorological extremes in Kabompo catchment was carried out using three emission scenarios A2, A1B and B1 representing high, middle and low case future climate change scenarios for the 2050s respectively and the subsequent impact on intensity duration frequency curves (IDFs) was assessed. This was done so as to support need for adapting water engineering and related designs to impacts of climate change. The rainfall outputs for three climate models and scenarios were downscaled using the change factor method whereby monthly change factors were first obtained and then applied to daily time series to obtain future (downscaled) time series. The results for CGCM 3.1 and CNRM 3.0 models revealed an upward shift in IDFs while CSIRO MK3.0 gave a slight downward shift. The strengths and weakness of the change factor method have also been outlined. The importance of downscaling has also been discussed. Flood and drought frequency analyses were also carried out to aid in decision support pertaining flood and drought preparedness whereby flow duration frequency (QDF) curves were constructed to aid in the analysis. For flood frequency, it was observed that for a given aggregation level, the highest flow rate corresponds to the highest return period (≈1778 m3/s for T=100) whereas for drought frequency the QDF relations gave lowest flows in the lowest aggregation level (≈36m3/s for T=100). Data and studies on emergency events in Zambia suggest a drastic increase mainly in the flood events. However, they do not vividly show whether this trend is due to an increase in precipitation or whether underlying sensitivity factors such as changes in land-use patterns (e.g. cultivation of flood-prone land, deforestation, etc.) play a more significant role. Lack of continuous data in Zambia's water sector is a big hindrance to reliable information on how climate change will affect Zambia's water resources. There is need to fully operationalize IWRM principles, improve the hydrological network, and for flexible solutions (considering different scenarios).

Keywords: Climate change impact investigation, climate models, scenarios, IDF, QDF, hydro-meteorological extremes, IWRM, Flood and Drought frequency analyses, Kabompo, Zambia

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Introduction

Climate change has already altered, and may continue to alter, many aspects of the water cycle in the world, affecting where, when, and how much water is available for all uses (USCLAR, 2010). It is therefore clear that water security lies at the heart of adaptation to climate change. Changes in the water cycle will include such things increasing atmospheric water vapour, increasing evaporation, changing precipitation patterns and intensity, changing incidence of drought, increasing water temperatures, reductions in river flows and lake levels, and changes in soil moisture and runoff. These changes will and already have impacts across a vast range of socio-economic activities, such as transportation, agriculture, energy production, industrial uses, and other needs, including human consumption (USCLAR, 2010). Hydro-meteorological impact investigations are very vital for management planning of water resources and therefore need to receive more attention as there are still grey areas related to the interfacing of climate and hydrological models (Taye et al., 2011). Besides, given the potential projections of droughts and floods, vulnerable hydrological and water resources are too important to defer the climate change investigations (Taye et al., 2011).

Water is both an important resource and a destructive force. When hydro-meteorogical extremes bring too little rain, plants/crops wither, animals starve or even die, and people starve. When there is too much rain, flash floods can leave trails of destruction, and rising rivers can overflow their banks and swamp whole landscapes (Woodward, 2009). Floodwater can make sewers overflow and contaminate drinking water supplies, wreck power plants and leave peo-

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ple without electricity, and destroy homes and transportation links (Woodward, 2009). Droughts and floods have been part of human experience for centuries, but due to climate change and population growth, drought and flood events are becoming more frequent, and having more devastating impacts (Woodward, 2009). It is therefore highly imperative that climate-induced changes in hydrological systems and processes be better understood, especially, variables such as river flows, groundwater and lake levels, soil moisture, evapotranspiration, etc., as well as subsequent impacts on biodiversity and humanity (Quevauviller, 2011).

Climate and water resources are intimately connected through the water cycle. The water cycle influences climate and weather patterns and thus changes as global climate changes. The normal climate is based on data series of 30 years and any deviation of trends and observations from these average climate data is interpreted by science as climate change (Willems, 2011). Climate change is thus more observed in the changes on long-term trends than explained by single events of climate extremes although such events could also be attributed to climate change (Ludwig et al., 2009). Therefore for climate impact investigation it is advised to use Hydro-meteorological data of at least 30 years so as to cater for both climate variability and climate change.

Study Area description

The study was carried out on Kabompo catchment a sub-catchment of the Zambezi river basin. Kabompo River is one of the main tributaries of the upper Zambezi River and flows entirely in Zambia, rising to the east of the source of the Zambezi, in North-Western Province along the watershed between the Zambezi and Congo River basins (UNEP, 2010). It flows south-west through miombo woodland, then a remote Cryptosepalum dry forest ecoregion, with the West Lunga National Park on its west bank. After flowing past the town of Kabompo, it develops a swampy floodplain up to 5 km wide (UNEP, 2010). Kabompo River enters the Zambezi north of the town of Lukulu, at the north end of the Barotse Floodplain and has two major tributaries namely Western Lunga and Dongwe (UNEP, 2010).

Hydro-meteorological description

The climate of Kabompo catchment is sub-tropical, with an elevation of between 1000 and 1400 meters above sea level. Zambia's national annual average rainfall, based on a 30 year period from 1976 to 2006 is approximately 967.3 mm (MEWD, 2010). The Kabompo catchment receives more than 1,000 mm and up to 1,400 mm of annual rainfall and is mainly tropical with two distinct seasons (wet season from November to April and a dry season from May to October). The tropical climate is modified by altitude; rainy season (October to April). From November onwards, the Inter-Tropical Convergence Zone (ITCZ) is the main rain-bearing mechanism (MTENR, 2008). During summer rainfall, October to April, the El Nino/Southern Oscillations (ENSO) phenomenon is recognized as major factor in determining precipitation patterns in the catchment. ENSO affects the ITCZ and CABS, the main rain bearing mechanisms. The opposite phenomenon, La Nina, brings more rainfall, which normally results in floods (MTENR, 2008). The ITCZ phenomenon is contrasted by the Botswana Upper High Influence (BUHI) which controls drought episodes and uneven rainfall distribution and creates an unfavourable condition for rainfall by pushing the rain-bearing ITCZ and active westerly cloud bands out of the region and Zambia (MTENR, 2008). The catchment is located 14:02:00 S and 23:37:30 E and has a drainage area of about 41,359 km2 with an estimated Mean Annual Run-off (MAR) of about 619 million m3. The prevailing dry season (July) wind direction is from east to south east with mean and maximum wind speeds of 2.4m/s and 9.2m/s respectively and mean number of calm days in July being 7.5.

The prevailing wet season (January) wind direction is from the north and northwest with minimum and maximum wind speeds of 1.4m/s and 6.7m/s respectively and mean number of calm days in January is 12 (CEC, 2011). Table 1 gives monthly evaporation data from Meteorological Station No. 3570 at Solwezi for the historical period 1962-1994 representative of the study catchment.

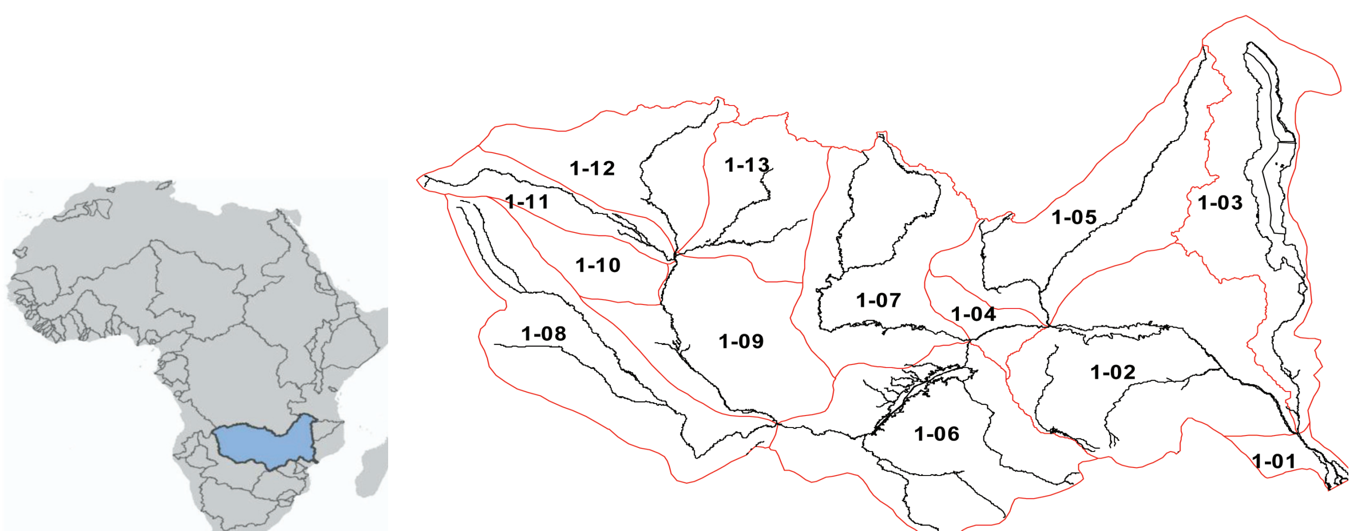

Fig. 1: *Zambezi basin in blue (left) and position of Kabompo catchment (1-13) on Zambezi basin (right) (UNEP, 2010).*

Tab. 1: *Z*Monthly Evaporation data for Kabompo catchment (Source: CEC, 2011).

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Evaporation (mm)	256	198	146	136	133	152	164	179	174	203	239	282

Methodology and study data

Hydrological and Meteorological data

The River flow data for Kabompo River (measured at Watopa Pontoon) was obtained from Zambezi River Authority for the period 2000-2011 while rainfall data was obtained from Zambia Meteorological Department for the period 1990-2003 from Meteorological Station No. 3570 in Solwezi district representative of the study catchment. The missing data was filled in by linear interpolation and by putting zeros for dry periods in the case of rainfall. Rainfall data for each GCM used in the study was obtained from the IPCC website: http://www.ipcc-data.org/ar4/gcm_data.html by providing climate variable of interest, latitude and longitude.

GCMs and Climate Scenarios

Three climate models namely (i) CSIRO Mark version 3.0 (Mk3.0, R1), (ii) General Circulation model version 3.1 [CGCM3.1 (T47)], R1 and (iii) cnrm.cm3 were selected after a thorough literature review on the most commonly used GCMs in Zambia.

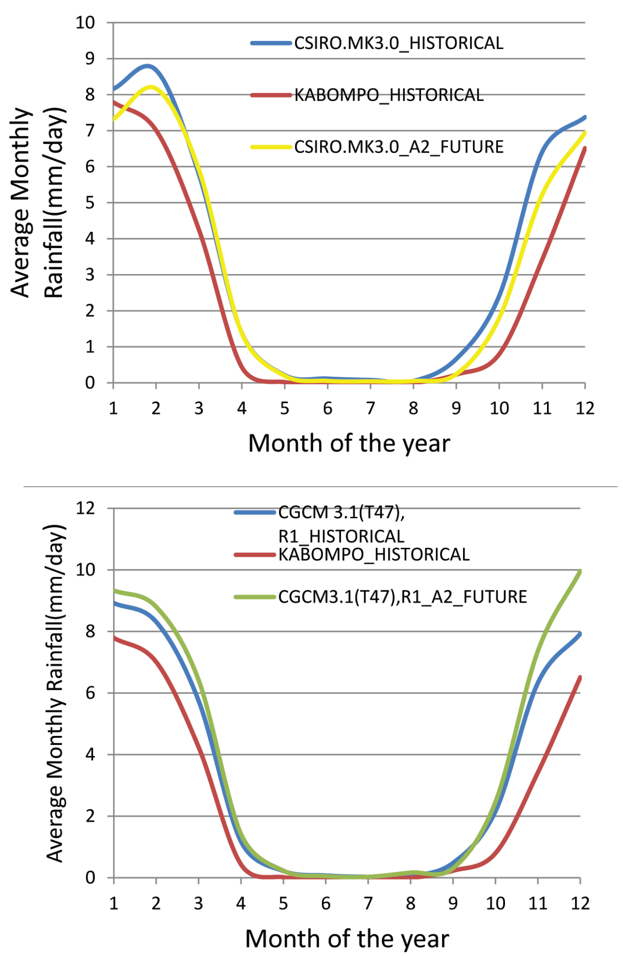

Fig. 2: *Performance evaluation of the CSIRO MK3.0 and CGCM3.1 GCMs with respect to Kabompo Historical observations.*

For quality control the mean monthly outputs for commonly used GCMs (Shongwe et al., 2009) and observed rainfall data for Kabompo were plotted on the same graph and visually checked and three GCMs with a similar rainfall pattern to Kabompo catchment were picked. Figure 2 gives an example of why CSIRO MK3.0 and CGCM3.1 (T47), R1 were selected as appropriate for the study. As can be seen both the historical and future GCM monthly averages of rainfall outputs have the same monthly pattern with Kabompo rainfall observations.

Three climate change scenarios usually used within water models being the IPCC B1, A1B and A2 scenarios for the 2050s (EU, 2011) were chosen. These scenarios give differences in the variation of the perturbations and are ranked as low (B1), middle (A1B) and high (A2) scenarios (Nyeko, 2011). Each scenario describes a different demographic, politico-economic, societal and technological future, exploring global energy, industry and other developments and their implications for GHG emissions and other pollutants (EU, 2011). For instance, the A2 scenario implies a differentiated world, with emphasis on regional cultural identities, family values and local traditions. It is accompanied by a continuous and high population growth and less concern for rapid economic development (EU, 2011). Scenario B1 describes a convergent world with a population that peaks in mid-century and declines thereafter, but with a rapid change in economic structures towards a service and information economy, and reductions in material intensity with introduction of clean and resource efficient technologies. In this scenario emphasis is on global solutions to socio-economic and environmental sustainability, including improved equity, but without additional climate initiatives (UNEP, 2005).

The different scenarios are put into GCMs to produce different possible future climate outcomes. It should be noted that scenarios provide alternative views of the future but they are not predictions nor should they be taken as the most likely of the numerous possible futures. By using different scenarios, possible future developments can be explored and strategies to influence the potential developments can be tested (EU, 2011).

Downscaling of Global Climate Model Runs

Assessment of climate change impacts on hydro-meteorological variables, such as rainfall and temperature at regional or local (catchment) scale, requires projected future time series (Fig. 3). The most common source of such future times series are GCM runs. However, direct use of GCM runs may not be appropriate for climate change impacts assessment at local or catchment scale because GCMs have coarser scales than required at catchment level (Nyeko, 2011). Once projected future time series such as rainfall and temperature are derived through downscaling, they can, either be assessed for impacts by comparing them with the observed time series or by using them as inputs into a rainfall-runoff model in order to obtain future stream flows time series or they can be used for assessing climate impact on intensity duration frequency of rainfall (Nyeko, 2011). Projected river flows can be compared with the present day river flows; hence, impacts on river flows can be assessed. **Downscaling** can be dy-

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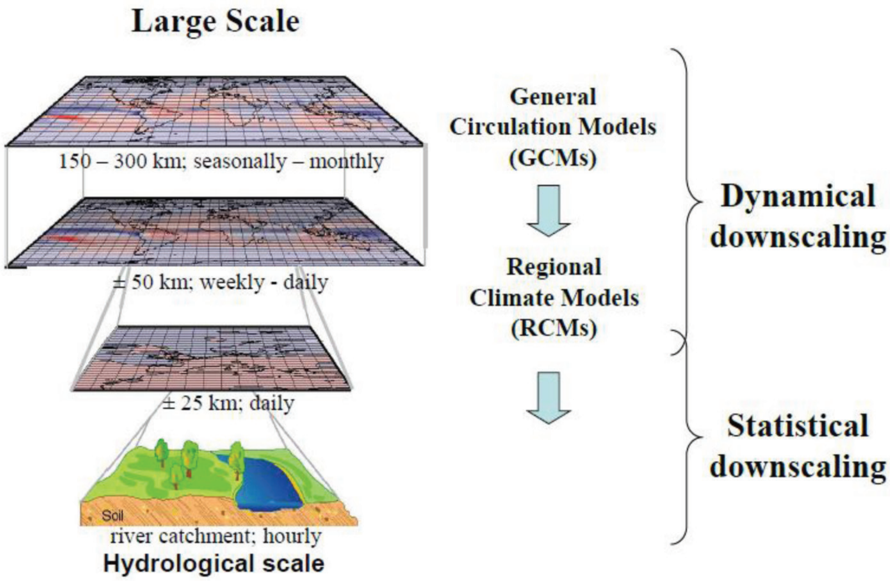

Fig. 3: *downscaling of nested GCM-RCM Simulations (Adapted from Willems, 2011).*

namical, through the use of an RCM with GCM as the boundary condition or through statistical (empirical) methods conditioned on large-scale predictors. Methods are needed to remove bias from GCM outputs and the results should be appropriate for use at local scale (Nyeko, 2011).

Statistical downscaling techniques use an observed relation between large-scale phenomena and local quantities (e.g. daily rainfall or evapotranspiration). The derived relation is subsequently applied to GCM output to obtain local and regional climate change signals. The major disadvantage of this approach is the implicit assumption that the calibrated relationships for present-day climate conditions are applicable to future climate conditions (Ludwig et al., 2009). The other downscaling method is **dynamical downscaling** representing the use of high-resolution regional climate models (RCMs), nested within GCMs. In this case, large-scale phenomena are used from the host GCM; but additional detail is provided e.g. land use, topography, physical features, etc. The additional information can substantially give more credit to local feedback processes such as soil moisture and temperature feedback. A drawback of RCMs and dynamical downscaling is large demand on computer resources and the complexity of operation, requiring highly trained staff (Ludwig et al., 2009).

The change factor downscaling method

The "change factor" or "delta" downscaling technique uses the concept of change factors (multiplicative or additive) extracted from the climate models and applied to observed series. The former has been tested by several researchers (e.g. Diaz- Nieto and Wilby, 2005; Lenderink et al., 2007) (Nyeko, 2011). The traditional delta technique applies the changes to a time series without considering the variability of the time series. The technique assumes that relative changes obtained from the GCMs are more representative than the absolute ones and that biases in the present simulations are similar to the biases in the future simulations. Thus, the temporal structure of the derived time series is maintained. With significant changes in the variability of time series under climate change the delta method may not be suitable (Nyeko, 2011).

Tab. 2: *Relative strengths and weaknesses of change factor (CF) and statistical downscaling (SD) methods of climate scenario generation (Wilby R.L and Diaz-Nieto J, 2005)*

Scenario technique	Strengths	Weaknesses
Change factors	Station-scale scenarios Computationally straightforward and quick to apply Local climate change scenario is directly related to changes in the regional climate model output	Depends on realism of the climate model providing the change factors Temporal structure is unchanged for future climate scenarios Step changes in scaling at the monthly interface Restricted to time-slice scenarios
Statistical downscaling	Station-scale scenarios Ensembles of climate scenarios permit uncertainty analyses Delivers transient climate change scenarios at daily time-scale Allows exploration of temporal sequencing of meteorological events	Depends on realism of the climate model providing the forcing Requires high quality observations and climate model output Predictor-predictand relationships are not always stationary Choice of predictor variables and transfer function affects results

Statistical downscaling of GCMs and Time series processing of data

The rainfall data from the three applicable GCMs together with the observations from Kabompo were used to analyse two time periods: recent past (1961-2000) and mid-century (2050s) in terms of climate impact on intensity/duration/rainfall curves (IDFs). Statistical downscaling for daily rainfall time series from GCM runs was done using the change factor (perturbation) approach. The daily rainfall time series for each GCM and respective scenarios were aggregated into monthly averages for the period under consideration. Thus, the time series of each month for all the years under consideration were pooled together before change factors were derived which were then applied on the daily Kabompo historical time series to obtain the future time series (**see equation 4.1 below**). Justification of the principle hinges on the fact that climate change signals can be extracted from the GCM control and scenario runs in an empirical way without explicit assumption of the underlying probability distribution and applied to the observed time series. The modified observed time series become the downscaled GCM results and are eligible for climate change impact assessment at local basin scale (Nyeko, 2011). Additionally, monthly averages were used for calculating the change factors because GCMs in Africa work much better with monthly data and actually most management decisions are based on monthly data (changes occurring for a month are considered extreme). **Table 3** below gives a summary of the obtained monthly change factors.

(I scenario/I control) = change (perturbation) factor 4.1

Where:

- I scenario = Future rainfall (mm/day)
- I control = Historical rainfall (mm/day)

Statistical time series processing

Historical rainfall data and future scenario rainfall were analyzed using Water Engineering Time Series PROcessing tool (WETSPRO) and hydrological extreme value analysis tool (ECQ) to obtain the impact on extreme value distribution and IDF curves. In addition, WETSPRO was used to estimate the distribution of catchment runoff on different components (overland flow, interflow, baseflow) by subflow filtering. Extreme values for historical river flow as well as for historical and future rainfall time series were extracted as peak-over-thresholds (POTs) from "nearly independent" quickflow and slow flow events and then used for extreme value analysis. The independence criterion for POT selection was dependent on base flow. The separated POT values were then used as input in ECQ after ranking them in descending order. The empirical extreme value distribution of each aggregation level was calibrated by setting the number of exceedance of the threshold discharge. For low flows, POT selection was applied after 1/Q transformation of the discharge series, where Q refers to the original discharge time series. The transformation changes low flow minima to maxima and allows for extraction of "nearly independent" low flows. After POT selection, the 1/Q series were transformed back to original flows to determine their percentage change (Willems, 2010). POT selection is an automatic sampling technique which aims at picking all highest independent extreme events recorded (Willems, 2010, Nyeko, 2011). For more theory and application of ECQ and WETSPRO as well as types of extremes one can read Willems, 2010 and Nyeko, 2011.

Aggregation levels and extraction of rainfall and river flow extremes

Aggregation level is the time span over which a representative value of the rainfall or river flow intensity is considered. The choice of aggregation level(s) often depends on the resolution of the data

Tab. 3: *Monthly change factors used on historical Kabompo rainfall data series to obtain the downscaled (future) values. Change factors above 1.000 means there will be an increase while ones below 1.000 means that there will be a decrease.*

MODEL	CGCM 3.1 (T47), R1			CNRM 3.0 CM3			CSIRO MK3.0		
SCENARIO	**A2**	**A1B**	**B1**	**A2**	**A1B**	**B1**	**A2**	**A1B**	**B1**
JANUARY	1.046	1.098	1.040	1.148	1.031	1.029	1.014	0.970	0.897
FEBRUARY	1.059	1.140	1.103	1.087	1.097	1.012	0.979	1.016	0.941
MARCH	1.116	1.163	0.978	1.036	1.017	1.011	1.015	1.011	1.022
APRIL	1.203	1.020	0.681	1.157	0.964	0.955	0.852	0.834	0.995
MAY	1.388	1.052	1.041	1.433	1.128	1.115	0.524	0.550	0.921
JUNE	0.734	0.834	0.458	1.349	1.254	0.232	0.454	0.325	0.446
JULY	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AUGUST	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SEPTEMBER	1.046	0.566	0.641	0.721	0.432	0.347	0.758	0.569	0.363
OCTOBER	1.139	1.041	0.845	0.700	0.687	0.574	0.934	1.089	0.746
NOVEMBER	1.163	1.034	1.029	1.024	0.883	0.924	0.886	0.981	0.814
DECEMBER	1.257	1.062	1.067	0.925	1.027	1.017	0.972	0.947	0.941

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to be considered, response time of the system, intended application and a common practice (Nyeko, 2011; Willems, 2010). In this study, aggregation levels of 1, 2, 3, 5, 7, 10, 30 and 90 days were used. These are common aggregation levels used in practical engineering applications (Nyeko, 2011). Except for the daily time series, the series for the other aggregation levels were obtained by a moving average technique (Willems, 2010). Using this technique, the series for a desired aggregation level were derived by taking the average of the original time series values over the desired aggregation levels span sequentially. E.g, if xi, …, x_n, is the daily series for rainfall or river flows , for i = 1, 2, ..., n and l = 2, 3,…L, where n and L are the total number of days in N years and the total number of aggregation levels respectively, e.g. the time series for aggregation level, l = 2, is $(x_1+x_2)/l$, $(x_2+x_3)/l$, $(x_3,+x_4)/l$,…, $(x_{n-1}+x_n))/l$. In the same way, the series of all other aggregation levels were obtained (Nyeko, 2011; Willems, 2010).

After the series for each aggregation level were obtained the POT series for each of the aggregation levels were extracted using WETSPRO. POT selection was firstly done on observed rainfall series to obtain observed POT series then POT values for each model and scenario were obtained to give model down scaled extremes. During the extraction of model POT series, the same threshold values for each aggregation level used for extracting observed POT series were applied for extracting model POTs so that both observed and model extremes were given equal weighting (Nyeko, 2011). The impact of climate change on intensity-duration-frequency curves (IDFs) was assessed by comparing the IDFs constructed using observed extremes with IDFs constructed using perturbed extremes for each scenario and model.

Effect of climate change on water engineering and related designs

In this era of climate change many types of development activities will, by their very nature, need to consider the expected climate regime. This is the most obvious link between development and climate change/variability. For example, road construction projects need to use expected rainfall data when making drainage systems, bridges need to be constructed according to expected water levels, and building construction projects need to consider relative humidity, rainfall, wind conditions and storms, etc. That is, any changes to the climate will imply, first, a changed risk situation (such as increased risk of damage to infrastructure if the frequency of storms increases or inundation of buildings and excessive flooding of agricultural fields (CICERO, 2003). Many river basins will likely experience shifts in extreme rainfall magnitude, frequency and distribution at the local level leading to the need for new water management measures plus changes in water engineering design practices.

Developing IDF relationships in a changing climate

Intensity/duration/frequency (IDF) curves and flow duration frequency (QDF) curves are traditionally developed using historical rainfall time series data and river flow data time series respectively. The IDF curves are made up of parameter/aggregation-level relationships together with the analytical description of the extreme value distribution. Extreme series of rainfall or river flow data are fitted to theoretical probability distributions from where rainfall or flow intensities corresponding to given durations and return periods are derived (Willems, 2010, Nyeko, 2011). Traditional hydrological practice assumes that historical extremes can be used to characterize future extreme regimes i.e. assuming stationarity of historical rainfall time series data. Changing climatic conditions that may bring shifts in the magnitude and frequency of extreme rainfall may render this assumption invalid.

CCIs on the water cycle may lead to highly significant shifts in extreme rainfall magnitude, frequency and distribution. There is therefore need to develop new strategies and regulations at local basins level and accordingly improve RBMP. For instance, designs and upgrading of urban water management infrastructure e.g. sewers, storm water detention ponds, gutters, drain ditches, etc. mainly rely on the use of local rainfall IDF curves (Nyeko, 2011). Hence there is need for taking into account potential CCIs when developing IDF curves.

Change in IDF curves

The impact of climate change on IDF curves was assessed by comparing the current and the projected IDF curves. Using aggregation levels of 1, 2, 3, 5, 7, 10, 30 and 90 days, the theoretical extreme quantiles for return periods 2, 5, 10, 20, 50 and 100 years were estimated based on calibrated distributions. Calibration of the empirical IDF relationships was done using equation 4.2(a) below by plotting β, xt or t against aggregation level D. Thereafter, calibrated IDF relations were derived using equation 4.2 (b).

$$\theta(D) = cD^{\frac{H}{a}}\left(1+W\left(\frac{A}{D^{\frac{1}{z}}}\right)^{a}\right)^{-\beta} \qquad 4.2\text{ (a)}$$

$$x = X_t\left(D\right)+\beta\left(D\right)\left(\ln\left(T\right)-\ln\left(\frac{n}{t\left(D\right)}\right)\right) \qquad 4.2\text{ (b)}$$

In formula 4.2a, A is the catchment area being considered for the rainfall or upstream catchment in case of river flows, D is the aggregation level and θ is one of the parameters β, xt or t, whereas H, a, and z are scaling exponents being Hurst-exponent (H), temporal scaling exponent (a) and dynamic scaling exponent (z), and these need calibration together with parameters c and w. The formula is based on scaling properties for rainfall or flow intensities and assumes that the same extreme value distribution is valid for different aggregation levels after application of scaling factors to rainfall or flow values. It is important to note that scaling factors are different for different aggregation levels (Willems, 2010).

After calibrating the empirical IDF relationships based on historical rainfall extremes for Kabompo the quantiles for each model and scenario were estimated. Thereafter, impact of climate change on the IDF curves was assessed by comparing historical theoretical extreme quantiles with the model quantiles. It is important to note that the used return periods correspond to acceptable risk levels and are values commonly used by many engineers worldwide to specify return periods for extremes for water engineering designs (Nyeko, 2011).

The change in IDF curves i.e. the extent to which the IDF relation is shifted was measured by perturbation of theoretical quantiles for each corresponding aggregation level (i.e. ratio of observed quantiles to that of the model with similar aggregation level). Additionally, the plots of observed and the model extreme quantiles versus aggregation levels, for each return period, were constructed for visual satisfaction (Nyeko, 2011). This was done for each model and scenario and charts containing observed IDF curves for a given return period and the IDF curves for each model and scenarios were obtained. From the tables of average change per scenario and constructed charts, it was possible to make conclusions on potential shifts on current IDF curves due to climate change impact i.e. by average change and visualization (Nyeko, 2011).

Observed changes in IDF curves

Figure 4 shows the IDF curves for the observed and that for the model runs for 100 years and 20years return periods under the different scenarios for 2050s (mid-century) while **Table 4** gives a summary of the IDF change factors for T=100 and T = 20. On one hand, the figure shows that the shift in the observed IDF curve is upwards for the CGCM 3.1 (T47), R1 and CNRM 3.0 CM3 models. On the other hand, the CSIRO MK3.0 model reveals an IDF relation very close to the current IDF with a slight shift downwards. This clearly shows that different model and scenario combinations yield different pictures of the future. Hence using more models and more gauging stations could help give a much better picture of the climate impact on IDFs. Despite the uncertainty involved it can be seen that the current IDF curves may not remain the same depending on the evolution of the future climate. In addition, the differences in the shift of the IDF curves among the scenarios for a given GCM are not substantial. It was also observed that the different return periods give the same result in the shift of the IDF curves (e.g. 100 year and 20 year return period in this case gave same IDF shift patterns).

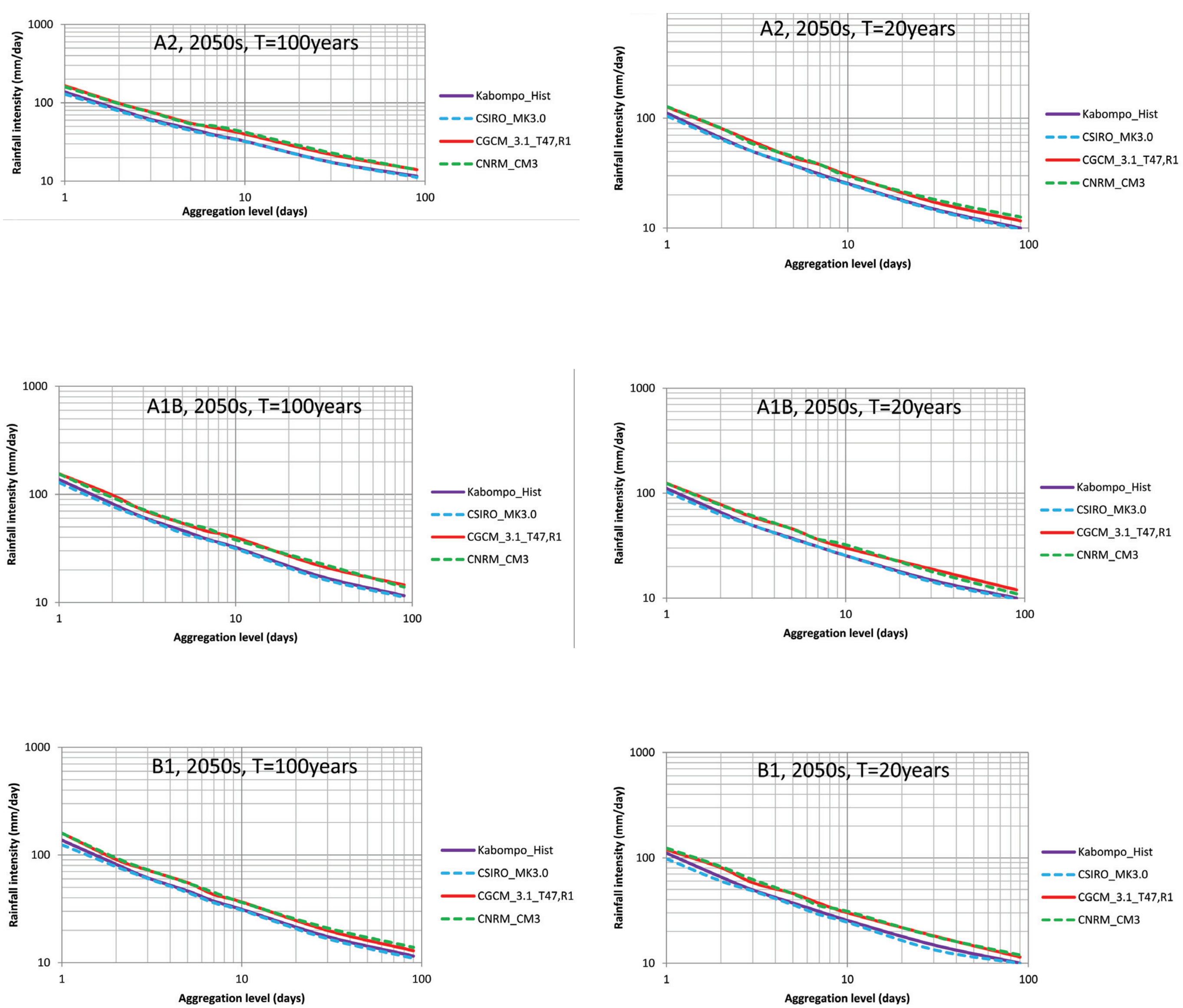

Fig. 4: *IDF curves for 100 and 20 years return period for the current (1990-2003) and different GCM runs under A2, A1B and B1 scenarios for the 2050s for Kabompo catchment (showing an upward shift for CGCM and CNRM).*

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Tab. 4: *Change in IDF curves for each model and scenario for the 100 and 20 years return period (a) and (b) respectively. Change factors above 1.000 means upward shift while ones below 1.000 means downward shift.*

Table 19 (a)	A2 2050s (T = 100 years)			A1B 2050s (T = 100 years)			B1 2050s (T = 100 years)		
Aggregation level (days)	CSIRO	CGCM	CNRM	CSIRO	CGCM	CNRM	CSIRO	CGCM	CNRM
1	0.940	1.202	1.165	0.934	1.129	1.123	0.906	1.160	1.157
2	0.956	1.199	1.187	0.943	1.202	1.141	0.950	1.109	1.144
3	0.970	1.246	1.238	0.985	1.163	1.183	0.987	1.181	1.188
5	0.954	1.186	1.165	0.942	1.164	1.177	0.967	1.192	1.186
7	0.975	1.236	1.307	0.983	1.183	1.257	0.964	1.153	1.205
10	0.991	1.236	1.300	0.973	1.236	1.175	0.982	1.170	1.161
30	0.992	1.253	1.314	0.956	1.250	1.315	0.955	1.141	1.200
90	0.970	1.214	1.206	0.969	1.257	1.202	0.953	1.121	1.205
Average Change	**0.968**	**1.222**	**1.235**	**0.961**	**1.198**	**1.197**	**0.958**	**1.153**	**1.181**

Table 19 (b)	A2 2050s (T = 20 years)			A1B 2050s (T = 20 years)			B1 2050s (T = 20 years)		
Aggregation level (days)	CSIRO	CGCM	CNRM	CSIRO	CGCM	CNRM	CSIRO	CGCM	CNRM
1	0.940	1.138	1.148	0.927	1.121	1.115	0.883	1.079	1.117
2	0.970	1.225	1.228	0.948	1.187	1.171	0.914	1.225	1.255
3	1.000	1.230	1.175	1.001	1.198	1.231	0.977	1.172	1.253
5	0.995	1.174	1.207	0.985	1.234	1.227	0.961	1.230	1.225
7	0.968	1.220	1.228	0.999	1.170	1.181	0.933	1.196	1.135
10	0.986	1.192	1.160	1.003	1.183	1.267	0.961	1.182	1.220
30	0.982	1.157	1.224	0.963	1.275	1.209	0.902	1.219	1.209
90	0.971	1.165	1.261	0.975	1.200	1.101	0.992	1.143	1.194
Average Change	**0.977**	**1.188**	**1.204**	**0.975**	**1.196**	**1.188**	**0.940**	**1.181**	**1.201**

Flood and Drought Frequency analysis

On one hand flood frequency is the average interval between floods that have a flow of at least that flow or is the probable frequency of occurrence of a given flood. On the other hand, drought frequency is the average interval between droughts with a flow of less or equal to that flow or is the probable frequency of occurrence of a given low flow or less. Rivers experience floods when flows exceed the capacity of river channels. In stochastic hydrology, floods are defined as high flows with very low exceedance probabilities or very high return periods while droughts are defined as low flows with very low exceedance probabilities or very high return periods (Nyeko, 2011).

Statistical properties of river flow and system state variables can be expressed in the most efficient way using amplitude/duration/frequency relationships. These describe the relationship between the amplitude (i.e. flow in QDF relations) and the frequency of exceedance for different time intervals for given aggregation levels. QDF relations are tools for estimating the severity of flood or drought events as an integrated function of return period and flow duration. That is, Flood and drought frequency analysis hinges on extreme value distribution and respective QDF relations. The QDF relations represent a probabilistic picture of the flood regime for a river in both flow and time dimensions. From a single QDF curve, a synthetic hydrograph could be derived containing the flows of each aggregation level possessing the same return period (Willems, 2011).

Flood and drought frequency can be summarized in the form of QDF and more advanced, in the form of composite hydrographs. This type of hydrograph is constructed in such a way that the average flow equals a specific return period for all durations that are considered centrally in the hydrograph (Willems, 2011). In this study, only the QDFs where constructed from extreme peak flows (for flood frequency) and extreme low flows (for drought frequency). Analysis of flood and drought frequency is very important in a changing climate in order to support water management and decision making.

Based on 11 years historical river flows (2000-2011) for Kabompo catchment, flood and drought frequency distributions were derived for aggregation levels of 1, 2, 3, 5, 7, 10, 30 and 90 days and the theoretical extreme quantiles for return periods 2, 5, 10, 20, 50 and 100 years were estimated using calibrated distributions. Calibration of the empirical QDF relationships was done using equation 4.2 but in this case q was added to 4.2a. Where q is threshold discharge and can be considered equal to the mean discharge value and is obtained based on the complete discharge series (Willems, 2010). Analysis of the tail for extreme value distribution showed that the tail is normal for high flows (Q) as well as for the 1/Q transformed low flows.

Extreme value distribution

The tail of each of the extreme values was analysed for both flood and drought frequency. The distribution can have one of the three tails, the heavy tail, normal or light tail. Parameter values for each distribution (with a right tail) were obtained and then used for analysis. Consequently, a graph giving relationship between discharge and return period was plotted for each case (Willems, 2010, Willems 2011). The selected return periods were used to calculate discharges for each aggregation level. The formulae below were used for calculating return periods and discharges during the construction of the empirical QDF curves.

$$T = \frac{n}{t}\left[\frac{1}{\left[\exp\left(\frac{x - x_t}{\beta}\right)\right]}\right] \quad \text{and}$$

$$x = x_t - \left[LN\left(\frac{n}{T \cdot t}\right) \cdot \beta\right] \qquad 6.3$$

Where:
x = flow for corresponding return period (m³/s)
x_t = optimal threshold flow (m³/s); where: t=rank number of threshold level
β = slope of exponential distribution
n = total number of simulated rainfall-runoff series (years)
T = return period (years)

Fitting of extreme value distribution for the extreme river flows was done using 1day aggregation level as an example of how flood frequency analysis can be used in decision support and in designing solutions for floods (**figure 5**). That is, peak flows were plotted against empirical return periods. For the same reason, a graph for design discharge versus different return periods was also constructed (**figure 6**). The plot of design discharge versus return period is a summary of the flow statistics. Since the data series was 11 years extreme value fitting was made for the 11 year period then extrapolation was made to higher return periods (Willems, 2010). NB: Every solution to risk reduction or adaptation in a changing climate goes with a cost and depends on desired level of protection and available resources.

Designs of hydraulic structures e.g. culverts, weirs, bridges, dykes, etc. largely depend on QDF curves. For instance, a culvert could be designed to be able to convey a flood of a given flow without surcharging for a given return period. Thus, in flood or drought frequency analysis the goal is to estimate peak flow (flood) or low flow (drought) magnitudes corresponding to any required mean reoccurrence interval (Nyeko, 2011). The concept is to fit to a historical flood or drought record on an extreme value distribution, which is then used to make deductions about the probability of occurrence of floods and droughts. The assumption that statistical properties of historical flood or drought data are representative of what could happen in the future; could not be true due to CCIs (Nyeko, 2011), however, analyses like this one are very important for water management in a changing climate.

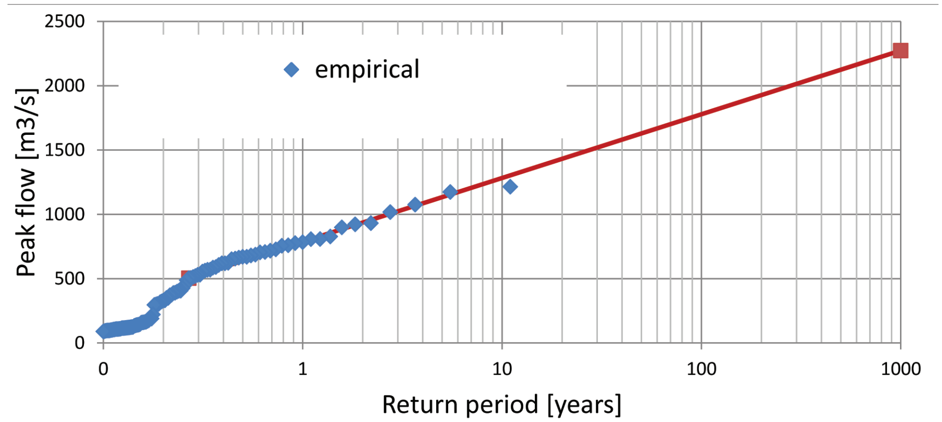

Fig. 5: *Return period plot for Extreme value distribution of high river flow values.*

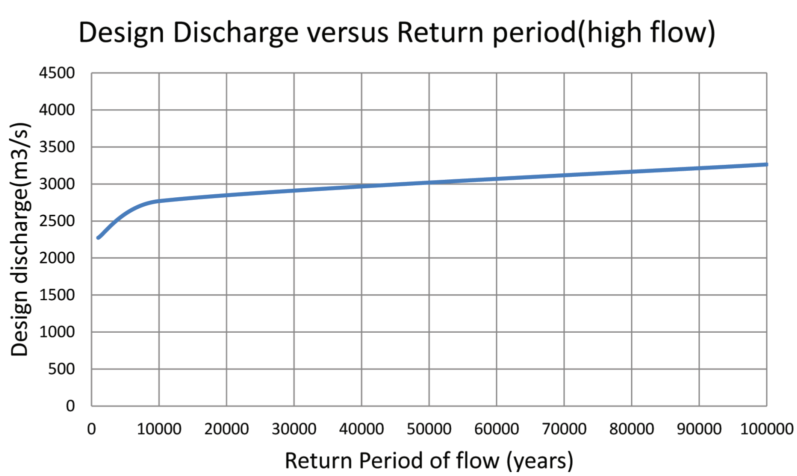

Fig. 6: *A plot of design discharge versus return period for design purposes.*

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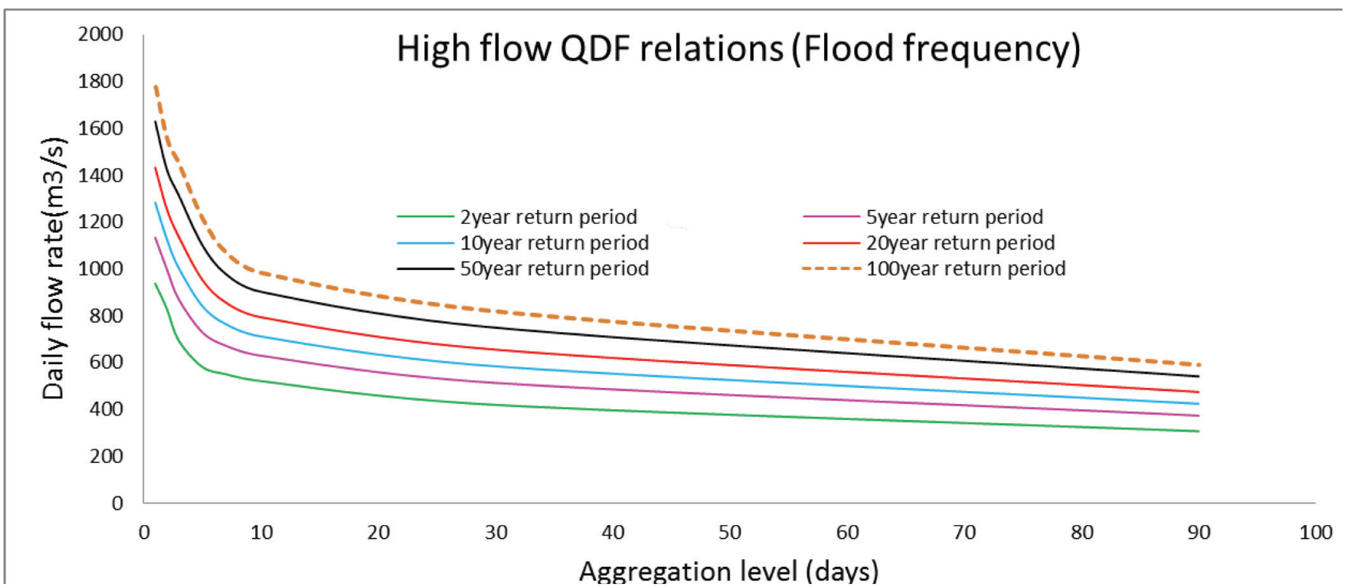
Flood and drought frequency analysis

Figure 7 gives QDF relationships for flood and drought frequency respectively. In water engineering practice the aggregation levels strongly depend on the application such as design of flood control reservoirs; rainwater harvesting structures, water quality control; drinking water supply and Irrigation purposes (Willems, 2011). That is, from the relation plotted, decisions can be made for drought and flood preparedness. The graphs give flow information as a function of durations and probability of occurrence. The plots are very important in flood and drought frequency analysis (i.e. from these graphs one can deduce the highest and lowest expected flow for each aggregation level and return period) (Willems, 2011).

In the case of flood frequency (**figure 7**), it can be seen that for a given aggregation level, the highest flow corresponds to the highest return period (≈1778 m^3/s for T=100). Additionally for flood frequency, the flow decreases with increasing aggregation level for the same return period. The drought frequency graph shows that for a given aggregation level the lowest possible flows correspond to the highest return period. The drought QDF relations gave lowest flows in the lowest aggregation level (≈36m^3/s for T=100). Statistical processing of hydrological data is an important process that should be frequently implemented in a changing climate because it is helpful in decision making and in RBMP.

In this study river flows were used and are assumed to be approximately representative of catchment runoff. Due to potential flooding or water scarcity in a changing climate, how often floods or droughts of a given magnitude occur is important. It should be noted that for decision making the indicator variable for floods is water level-which is highly dependent on available river flow and channel cross section-and for droughts it is low flows or groundwater table. Additionally, a 100 year return period is good enough for checking what could happen in the future to water systems (Willems, 2011).



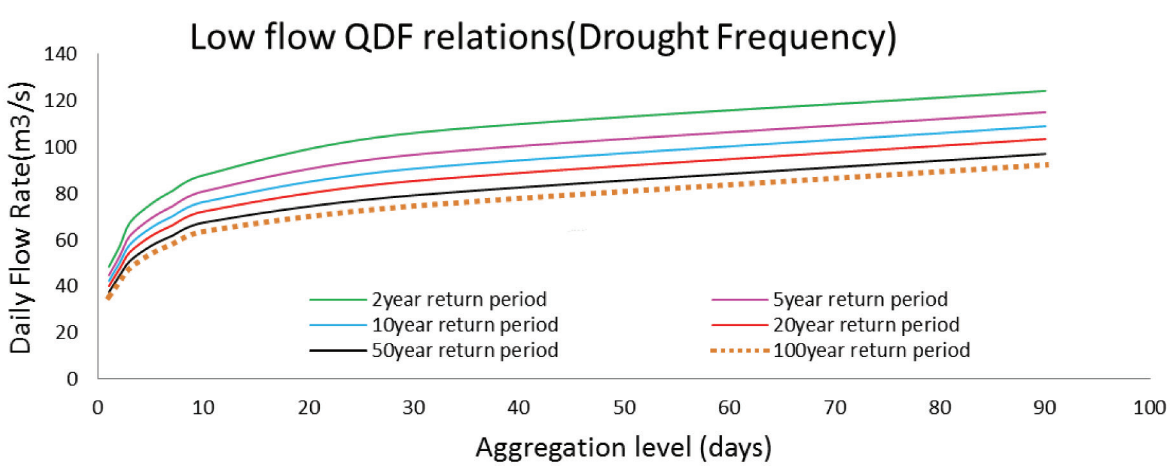


Fig. 7: *Kabompo River Flood and Drought QDF curves (respectively) for the period 2000-2011 for different return periods.*

Tab. 5: *Calibrated flood and drought frequency QDF relationships with Return periods in green, Aggregation levels in purple and river flows in blue (to the nearest whole number).*

	Flood frequency QDF relationship						Drought frequency QDF relationship					
*Aggregation level (days)↓	**2**	**5**	**10**	**20**	**50**	**100**	**2**	**5**	**10**	**20**	**50**	**100**
1	936	1134	1283	1432	1629	1778	48	45	42	40	37	36
2	828	998	1126	1254	1423	1551	57	53	50	47	44	42
3	693	870	1004	1138	1314	1448	67	62	58	55	51	48
5	582	730	842	954	1103	1215	75	69	65	62	57	55
7	550	672	764	856	978	1071	81	74	70	66	62	59
10	520	629	711	793	902	984	88	81	76	72	67	64
30	419	513	584	655	749	820	106	97	91	85	79	75
90	306	373	423	474	541	591	124	115	109	103	97	93

Conclusion and applications

Amplitude/duration/frequency relationships (IDFs or QDFs) are utilized for many purposes in water engineering. IDF-relationships are used to calculate return periods of historical rainfall events, to construct design storms for hydrological modelling applications, to calibrate stochastic rainfall models (e.g. stochastic rainfall generator), etc. while QDF-relationships can be used to construct rainfall-runoff design hydrographs for river flood (Willems, 2010). It is hence vital to determine how frequent an extreme event of a given magnitude occurs that can be related to different water resources issues. That is, given the importance of these applications it is imperative in a changing climate to check for possible impact of climate change on IDFs or QDFs while allowing for all possible scenarios (low, mean and high) during their development. Since statistical downscaling requires a lot of time, only three GCMs and three scenarios were used for this study in order to give an idea on impact of climate change on IDFs and subsequently on water engineering and related designs. The results for CGCM 3.1 (T47), R1 and CNRM 3.0 CM3 models reveal an upward shift in IDFs while CSIRO MK3.0 gave a very minimal difference with the current IDF curves with a slight downward shift. For a better understanding and strong conclusions it is better to use longer time series, more gauging stations, more GCMs, and more scenarios as well as use of several downscaling techniques to minimize the uncertainty. Use of many GCMs and scenarios gives a better understanding of the range of possible future impact.

The main objective of flood and drought frequency analysis was to calculate high and low flow discharge-duration-frequency (QDF) relationships for the river flow time series that could be used for decision making in water management. Flood and drought frequency analysis is very vital for strengthening adaptation strategies to CCIs particularly if QDFs for both the historical and future data are constructed and the change subsequently assessed. In a changing climate, statistical properties of floods and droughts are likely to change due to change in the flood or drought frequency. Hence, if projected climate model data for the future is available, it is important to check whether the hypothesis of non-stationarity in flood or drought frequency is valid whilst using long enough data series to minimize bias towards wet or dry extremes (which could happen when one uses very short time series) (Nyeko, 2011). That is, QDF predictions are usually dependent on the period and data quality used for analysis.

Recommendations and potential areas of research

1. National water engineering designs need to be considering impacts of climate change.
2. Development of a perturbation or downscaling tool for each agro-ecological zone.
3. Assessing impacts of climate change on river flows, rainfall intensity and temperatures in all subcatchments to obtain a national picture of potential impacts of climate change on water resources.
4. Prioritizing and improving measurement and analysis of hydro-meteorological data.
5. Assessing climate change impacts on decadal basis e.g.2050a (2046-2055) and 2050b (2056-2065) then for the whole 2050 period (2046-2065) could be necessary to obtain a bigger picture of the future.
6. Need to study monthly rainfall and temperature trends in addition to annual trends. Though increasing precipitation could increase water availability to society and ecosystems, increase in temperature intensifies evapotranspiration nearly everywhere thereby reducing water availability. These two effects interact differently in different places and can produce a net increase or decrease in water availability (EU, 2011). Hence changes in temperature need also to be studied for better RBMP.

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REFERENCES

CEC (Copperbelt Energy Corporation Plc.), 2011. Proposed Kabompo gorge hydroelectric scheme, environmental impact statement, Volume 1: main report, DH Engineering Consultants, Lusaka, Zambia.

EU (European Union), 2011. Briefing water scarcity, jointly produced by Institute for European Environmental policy and United Nations Environment Program (address: Research4policy@unep.org).

Ludwig, F., Kabat, P., van Schaik, H., and van der Valk M., 2009. Climate change adaptation in the water sector, published by Earthscan publishers, London, UK.

MEWD (Ministry of Energy and water development), 2010. Zambia national water policy, Lusaka, Zambia.

MTENR (Ministry of Tourism, Environment and Natural Resources), 2008. Report on adverse impacts of climate change and development challenges: integrating adaptation in policy and development in Zambia, Lusaka, Zambia.

Nyeko, O.P., 2011. Climate change impacts on hydrological extremes and water resources in Lake Victoria catchments, upper Nile basin, PhD thesis dissertation, Katholieke Universiteit Leuven-Faculteite Ingenieursweten-schappen, Arenberg Doctoraatsschool, Leuven, Belgium.

Quevauviller, P., 2011. Water sustainability and climate change in the EU and global context-policy and research responses, published by the royal society of chemistry. Available@: www.rsc.org.

Shongwe, E. M., Van Oldenborgh, J.G., and van den Hurk, B.J.J.M., 2009. Projected changes in mean and extreme precipitation in Africa under global warming. Part I: Southern Africa, Royal Netherlands Meteorological Institute, De Bilt, Netherlands, published by American Meteorological Society.

Taye M. T., Ntegeka. V, Ogiramoi N. P., and Willems .P, 2011. Assessment of climate change impact on hydrological extremes in two source regions of the Nile River Basin, Katholieke Universiteit Leuven, Hydraulics Division, Kasteelpark Arenberg 40, 3001 Leuven, Belgium.

Troeh, F.R., Hobbs, J. A., Donahue, R.L., 2004. Soil and water conservation for productivity and environmental protection, 4th edition, published by Pearson Prentice Hall, New Jersey, USA.

UNEP (United Nations Environment Programme), 2005. Vital climate change Graphics, February 2005, UNEP/GRID-Arendal publication. Available@: www.grida.no/climate.

USCLAR (United States CLimate Action Report), 2010. United States Department of State, 5th edition, Washington: Global Publishing Services, January 2010, Washington, DC, USA.

Wilby, R.L., and Diaz-Nieto, J., 2005. A comparison of statistical downscaling and climate change factor methods: Impacts on low flows in river Thames, United Kingdom, Springer publishers.

Willems, P., 2010. Statistics for water engineering, 1st year Master of Water Resources Engineering, Course text, K.U. Leuven, Leuven, Belgium.

Willems, P., 2011. Systems approach in water engineering, 2nd year Master of Water Resources Engineering, Course text, K.U. Leuven, Leuven, Belgium.

Woodward, J., 2009. Eye Witness water, published by DK publishers, New York, USA