Flow Forecasting and Skill Assessment in the Blue Nile Basin

Gehad H. Nassar[1], Doaa M. Amin[2], Shokry M. Abdelaziz[3]and Tahani F. Youssef[3]

[1]Nile Forecast Center (NFC), Planning Sector, Ministry of Water Resources and Irrigation (MWRI), (Email: ge.had87@hotmail.com),
[2]Nile Basin Department, Water Resources Research Institute (WRRI), National Water Research Center (NWRC),
[3]Civil Engineering Department, Faculty of Engineering, Elmataria- Helwan University

Abstract

The long term (seasonal) flow forecast provides an opportunity to improve the planning and management of water resource and hydropower especially for countries-like Egypt- that facing water scarcity. The main purpose of this study is to assess two different forecast methods; the Extended Stream Flow Prediction (ESP) and the European Center for Medium range Weather Forecasting (ECMWF S4) for forecasting the stream flow in the Blue Nile Basin in order to show the strength and weakness in both methods in providing skillful seasonal streamflow forecast that support the early warning system for flood and drought mitigation and adaptation. For both methods, the Nile Forecast System (NFS) hydrological models were used.
The results show that both methods are highly correlated with the observed flow in the Blue Nile Basin. The ECMWF showed high efficiency in forecasting peak flow, especially at Diem station, and its overall performance in Diem station was better than for Khartoum. The performance of the ESP forecasted flow showed high efficiency when starting forecast in September for both stations, while it is underestimated when starting forecast in May.

Keywords: Flow forecasting methods; Extended stream flow prediction; Seasonal forecast; ECMWF

1. INTRODUCTION

Early warning of flood or drought provides an opportunity for adaptation and mitigation, especially in a region like the Blue Nile Basin which provides Egypt with the largest part of the flow. The forecasting systems with good certainty can provide the necessary information to support the early warning system. Forecasting the flow in the Blue Nile will help Egypt to manage the flow to meet Egypt's annual- as well as over year needs. In addition, development in the Nile basin countries affects the hydrology of the Nile. The scientific understanding of the Nile was limited due to insufficient basin-wide hydrological, meteorological, climatic related data and information. Good flow forecast techniques with accepted certainty to determine the data and information about the Nile, helps giving an overview of the hydrological condition in the Upper Nile.
In this study, two methods are used with different procedures for forecasting the flow in the Blue Nile Basin. The 1st method is the ESP method which depends on the historical rainfall data; the size of the ensemble is restricted to the number of historical years of metrological data available in the NFS database. In addition, the initial conditions at each starting date of the forecast plays an important role in the ESP technique. The ESP predicts future streamflow from the current initial conditions in the hydrological model with historical meteorological data. While the 2nd one is the ECMWF (System 4 - S4) issued 51 ensemble members with seven months lead time. Weather forecasting models are set up at global scale in different meteorological centers, producing deterministic and ensemble products. The 51 ensembles produce weather parameters which determine the evapotranspiration and rainfall. The seasonal forecasted rainfall and evapotranspiration will be the input for the simulation runs of the NFS hydrological Models for each ensemble to produce forecasted streamflow ensembles.
ESP is used in several research studies; where Najafi et al., (2012) found that the mean or median of the ensemble runoff volume is commonly reported as the single (possibly best) prediction, the initial condition affects the forecast resulting from the ESP (Li et al., 2009, and Wood and Lettenmaier, 2008). Wood et al., (2005) found that ESP flow forecast is not affected by El Niño Southern Oscillation (ENSO).
The ECMWF seasonal forecast method is skillfully detected the hazardous events in large river basins (Alfieri et al., 2013). Block and Rajagopalan, (2007) found that ECMWF forecast ensembles have very high skills during extreme wet and dry years for the upper Blue Nile basin. Molteni et al., (2011) approved that ECMWF seasonal forecast represents large-scale rainfall anomalies which are closer to

their observed counterparts in terms of amplitude and spatial pattern for Africa and South America. Trambauer et al.,(2015) found that the skill of ESP forecast is lower than that of ECMWF seasonal forecast and deteriorates rapidly with lead time in the Limpopo River basin.

2. STUDY AREA

The Blue Nile basin (about 32–40° East, and 8–16° North) rises on the Ethiopian plateau and is concentrated at elevations of 2000-3000 m. The Blue Nile is one of the most important tributaries of the Nile as it contributes about 50BCM/year of the River Nile in average; which is about 60% of the annual Nile discharge at Dongola (Sutcliffe and Parks, 1999). The area of the Blue Nile basin is 325000 Km^2 and outlets at Khartoum station.

Fig. (1): Blue Nile Basin Map, ***(Nile Basin water resources Atlas, 2016)***

Two main tributaries join the Blue Nile also rising from Ethiopia, which are Rahd & Dinder north of Roseires. From the Sudanese-Ethiopian border, the Blue Nile flows north from humid to semi-arid conditions. The rainfall season starts in May till the end of November. Most of the rainfall is from June to September with a peak in July or August. The average annual rainfall over the Blue Nile basin above Roseires is about 1600 mm. It increases from about 1000 mm near the Sudan border to about 1400-1800 mm over parts of the upper basin (Gamachu, 1977), at the Blue Nile below Lake Tana, and reaches above1800 mm in the south within the Didessa basin. The average annual potential evapotranspiration over the Blue Nile basin is 1,703 mm.

In this study, the forecasted flow will be compared to the observed flow at 2 main locations along the Blue Nile: The 1^{st} is the Diem station which is located at the Ethiopian-Sudanese borders at which the upper Blue Nile basin flow passes through it, and the 2^{nd} is the Khartoum station which is the outlet of the Blue Nile Basin that is located at Khartoum City in Sudan. **Fig. (1)** Shows the Blue Nile Basin.

3. METHODOLOGY

3.1. The Nile Forecasting System (NFS)

The NFS is a distributed based modeling system that is driven by satellite images from MSG satellite, for rainfall estimation and hydrological forecasting. The real time estimated rainfall is merged with the observed rainfall over the basin to enhance the rainfall product to feed the NFS hydrological models. NFS provides medium-range hydrological forecasts with a lead time up to three months.

3.1.1. Hydrological models

Rainfall to runoff for each grid cell is simulated using: a) a water balance model, b) a hill-slope routing model, and c) a channel routing model, respectively in addition to other specific models for some specific regions over the Nile basin.
Once a week observed flows at some key points (e.g. Diem) are assimilated to update the model state, it implies that the rainfall estimates are adjusted for the last 4 weeks to minimize the difference between the simulated and the observed flows (Elshamy, 2006).
The last evaluation of the NFS was in 2011. The evaluated criteria were Root Mean Squared Error (RMSE), the Mean Absolute Error (MAE), the percentage of them , and the Nash-Sutcliffe (coefficient of Efficiency (R^2)). The evaluation showed that the NFS performance is generally satisfactory for the Blue Nile; **Table (1)** shows the evaluation results.

Table (1): Summary of Statistics for Key Locations Along The Eastern Nile,
(NFS Evaluation Report, 2011).

Station	R^2	MAE (BCM)	MAE %	RMSE (BCM)	RMSE %	Mean Annual Volume (BCM)	
						Obs	NFS
Diem	0.92	0.77	1.52	1.38	2.72	50.74	50.80
Khartoum	0.88	1.01	2.25	1.70	3.80	44.80	42.23

3.1.2. Hydrological forecasting

NFS uses the US National Weather Service Extended Streamflow Prediction (ESP) procedure to forecast the flow at some main locations along the Nile. ESP was originally developed by the United States National Weather Service (Day, 1985). The ESP predicts future streamflow from the current initial conditions (soil moisture, river, and reservoir conditions). The hydrologic models are used to first simulate real-time flow conditions up to the date of the forecast with historical meteorological data. These data are used to run the hydrological models forward in simulation model with each historical annual rainfall being treated as an equally likely scenario for future rainfall. This procedure yields a Monte Carlo evaluation of the possible range of future streamflow, conditional upon current hydrological model states (Bellerby, 2009).The size of the ensemble is restricted to the number of historical years of metrological data available. The forecast streamflow distribution is established by a ranking process as follows: the year with the maximum simulation is ranked as number one; the probability of flow above certain value is calculated by dividing its rank by the number of years in the ensemble (plus one). As a result, the lowest simulation has the highest probability of occurring (Singh, 2016).
Bias and RMSE were calculated between the mean of the ESP ensembles forecast and observed flow as well as climatology and observed flow. Both statistics indicate that the mean of the ensemble forecast is better than climatology (Singh, 2016).

3.2. ECMWF (system 4- S4)

In the latest version of the European Centre for Medium Range Weather Forecasts (ECMWF), the atmospheric resolution is about 79 km with 91vertical levels, and is fully coupled with an ocean model with a horizontal resolution of 1°. S4 has been in operational use since November 2011, issuing 51 ensemble members. The ensemble is constructed by combining the 5-member ensemble ocean analysis with SST perturbations and the activation of stochastic physics. The forecasts have an initial date at 1st of each month, and was run for 7 months (Molteni et al. 2011).

3.3. Approach

First, the NFS had been run in a simulation mode creating the initial condition (warm state) for each day the forecast will start at it. Second, NFS had been run with the ESP component using the historical meteorological data and the initial condition for the beginning of each month; (i.e. May to Sep.) and forecast the flow up to 3 months ahead in monthly time step for each year from 2005 to 2011. Third, Bias correction method was applied to the seasonal forecast. The method to bias correct precipitation is based on monthly means, by applying a multiplicative correction factor. The correction factor was calculated by comparing the mean climate of the forecasts and an observed mean climatology of the real time rainfall data in NFS (for each calendar month), (Amin and Kotb, 2015). Forth, NFS hydrological models were forced with the forecasted meteorological outputs of the 51ensembles of the ECMWF producing 51 forecasted flow ensemble. Finally, different statistical criteria were applied to evaluate the outputs of the two methods regarding the observed flow, from the NFS database, for the two stations Diem and Khartoum.

4. RESULTS AND DISCUSSIONS

The most frequently used Nash-Sutcliffe efficiency and the coefficient of determination are very sensitive to peak flows in comparison to different efficiency criteria for hydrological model assessment mentioned by Krause, (2005). So, Nash-Sutcliffe efficiency was used in this study to determine the efficiency of the forecast for both methods. RMSE is a good measure of accuracy, it measures the average magnitude of the error. The MAE measures the average magnitude of the errors in a set of forecasts, without considering their direction. The MAE and the RMSE can be used together to detect the variation in the errors in a set of forecasts.

The ESP was run for 3 months with one month time step starting at the 1st of May up to 3 months, and ending in September which cover forecast from September to the end of November, for each year of the 7 years (2005-2011). **Tables (2, 3)** show the statistical Criteria for the 2 stations Diem and Khartoum respectively which were calculated for the time series of the 7 years, for each starting date of the forecast. The results of the forecasted flow using ESP method show high correlation with the observed for the two locations. The least efficiency, for both stations, was shown when starting the forecast at 1st of May, because ESP is affected by the initial conditions at the date of starting forecast which is changed due to the starting of rainfall season. R^2 values are low at Diem when starting forecast in July and August which are the peak of the rainfall, but they are higher in case of Khartoum which show that ESP method has different performance depending on the location. The highest error is shown when starting forecast at July and August for Diem station. For both stations, the highest efficiency with the least error at September are shown.

The results of the ECMWF method were monthly forecasted flow from May to November every year of the study period which lasted from 2005 to 2011. **Tables (4, 5)** show the statistical criteria of ECMWF at the two locations; Diem and Khartoum, respectively. ECMWF showed high correlation with observed streamflow for all the study period 2005-2011. R^2 values are 0.833 and 0.673 for Diem and Khartoum respectively, ECMWF shows higher efficiency in forecasting the flow at Diem than Khartoum. The error at Khartoum is higher than that at Diem.
The comparison graphs between the two forecasted methods, referring to the observed flow data, represent three months accumulation flow with one month time step from May to November. Figures (2) and (3) show the flow forecasted using ECMWF average ensemble, the 50% probability of exceeded flow forecasted using ESP, NFS simulated flow and Observed flow for Diem and Khartoum, respectively.

Table (2): Statistical Criteria for Diem Station Calculated for The ESP Forecasted Flow at Which The Forecast Started at The Beginning of Each Month Up to 3 Months for 7 Years Time Series.

Statistical Criteria	Three months forecast				
	May-July	June-Aug	July-Sep	Aug-Oct	Sep-Nov
Corr.	0.903	0.923	0.803	0.920	0.953
R^2	0.304	0.763	0.394	0.495	0.799
RMSE(BCM)	2.934	2.908	3.161	3.608	1.968
MAE(BCM)	2.183	2.399	2.595	2.946	1.739

Table (3): Statistical Criteria for Khartoum Station Calculated for the ESP Forecasted Flow at Which The Forecast Started at The Beginning of Each Month Up to 3 Months for 7 Years Time Series.

Statistical Criteria	Three months forecast				
	May-July	June-Aug	July-Sep	Aug-Oct	Sep-Nov
Corr.	0.818	0.945	0.877	0.907	0.967
R^2	0.241	0.762	0.754	0.765	0.914
RMSE(BCM)	2.336	3.228	2.757	2.835	1.704
MAE(BCM)	1.530	2.349	2.071	2.270	1.270

At Diem station, both methods were highly correlated with the observed. **Fig. (2)** Shows that for both methods the forecasted flow differs in capturing the value of the observed especially the peak values. The values from the ECMWF forecasted flow is the closest in most of the months for all years, but ESP showed better values than ECMWF almost in September for all years; at which the rainfall rates starts to decrease and the soil is saturated and the warm state was perfectly simulated. Also ESP showed better performance than ECMWF in some specific months, as in 2005 where the forecasted quantity for the period from June to August starting the forecast in June is closer than that of the ECMWF. This means that the ESP method succeeded to forecast the quantity of this period quite well. ESP in all years underestimated the flow when forecast started in May. That is because ESP depends mainly on the initial conditions at the beginning of the forecast which is almost dry soil at the beginning of the flood season in May, thus the unsaturated soil conditions strongly affect the ESP forecasting results. The ECMWF having high efficiency in forecasting the peak flow; i.e. July and August; and that was illustrated from the values of R^2. ESP results showed low efficiency in forecasting peak flow for most of the years except for 2006 & 2010 which showed better efficiency in July & August.

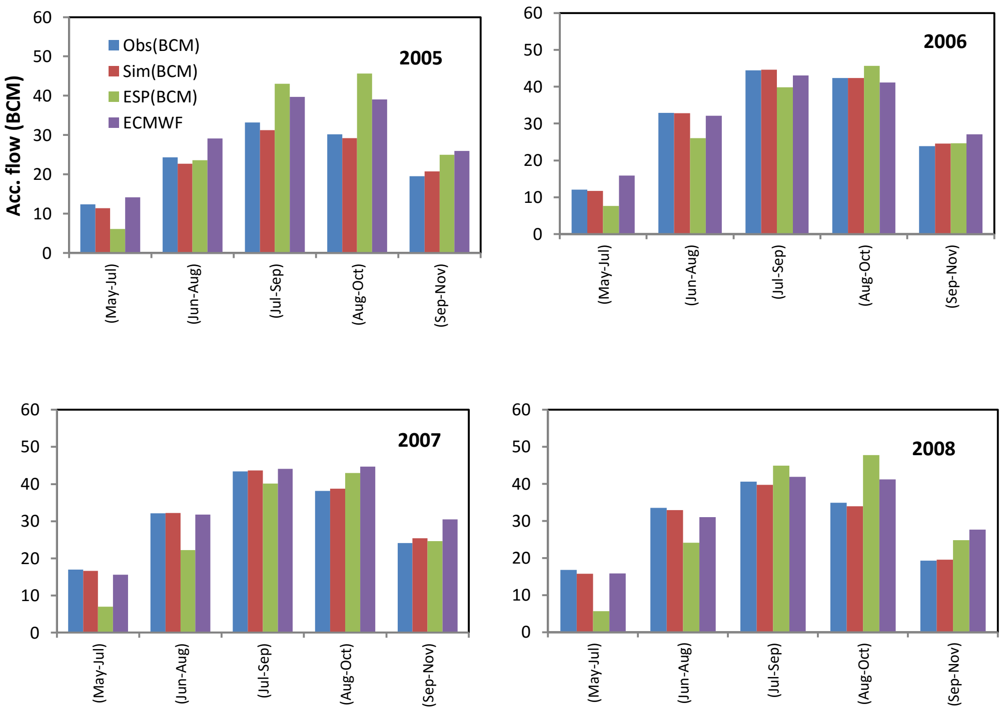
Table (4): Statistical Criteria for Diem Station Calculated for The ECMWF Forecasted Flow, at Which The Forecast Started at May to November Each Year and for Duration of 7 Years.

Statistical Criteria	Seven months forecast
	May-Nov.
Corr.	0.936
R^2	0.833
RMSE(BCM)	2.286
MAE(BCM)	1.670

At Khartoum station, the same as Diem station, **Fig. (3)** Shows that both methods are highly correlated with observed for all years. For most of the years ESP underestimated the flow when starting the forecast at May & June but the quantity for the 3 months (May-July and June-August) was closer than that of the ECMWF except for years 2007, 2008 and 2010 at which the ECMWF had better forecast than ESP. The forecast which stared at September was more skillful in ESP than ECMWF and that was due to the same reasons for Diem. Efficiency of the ESP to forecast high flow in July and August was high in most of the years except for 2005, and for forecast started at July 2007. In addition, there is a deviation between the observed and the NFS simulation at Khartoum station, especially in 2007, 2010 and 2011, due to the lake of data that simulate the losses and abstraction accurately in the model. RMSE and MAE of ECMWF were higher in Khartoum station than that in Diem.

Table (5): Statistical Criteria for Khartoum Station Calculated for The ECMWF Forecasted Flow, at Which The Forecast Started at May to November Each Year and for Duration of 7 Years.

Statistical Criteria	Seven months forecast
	May-Nov.
Corr.	0.908
R^2	0.673
RMSE(BCM)	3.565
MAE(BCM)	2.681



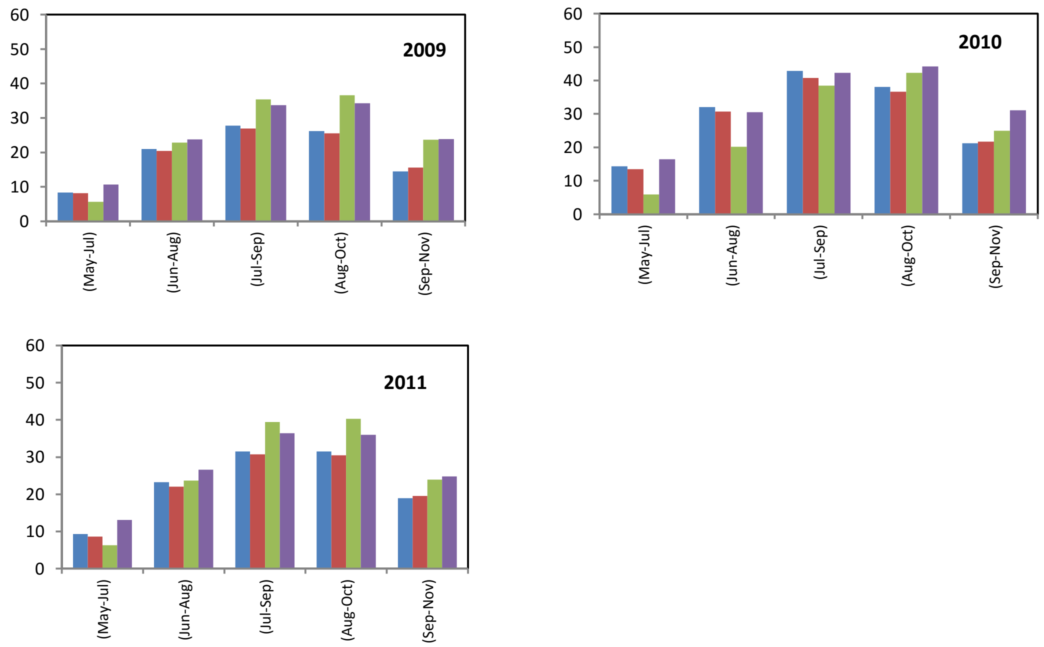
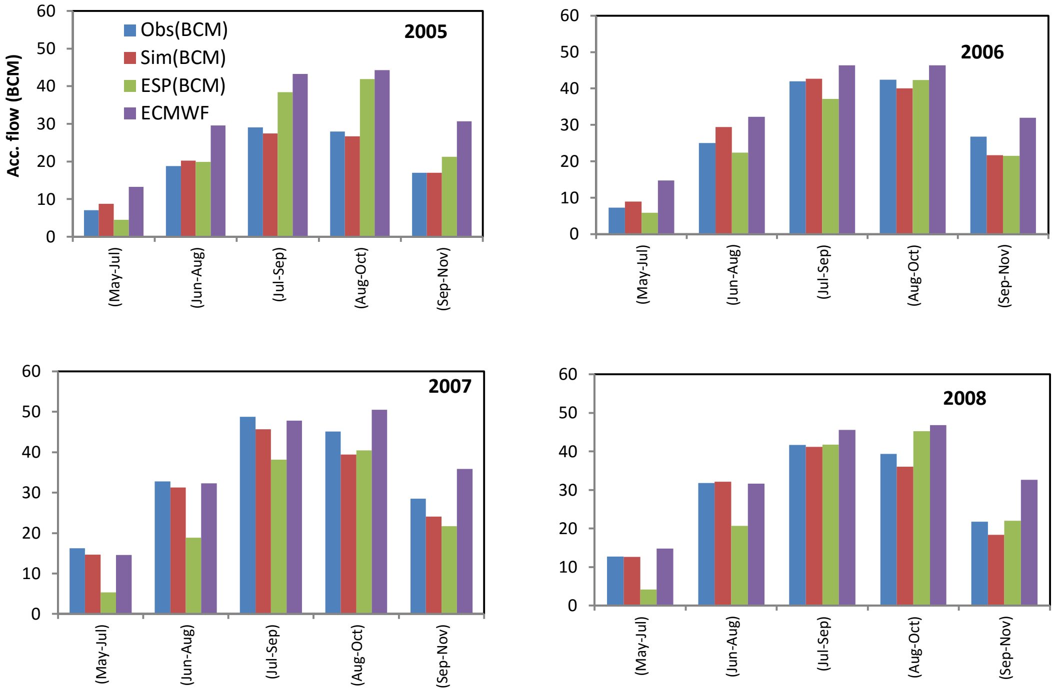


Fig. (2): Three Months Accumulated Flow at The Start of Each ESP Forecast Verses ECMWF, Simulated Flow from NFS and Observed Flow for Diem Station



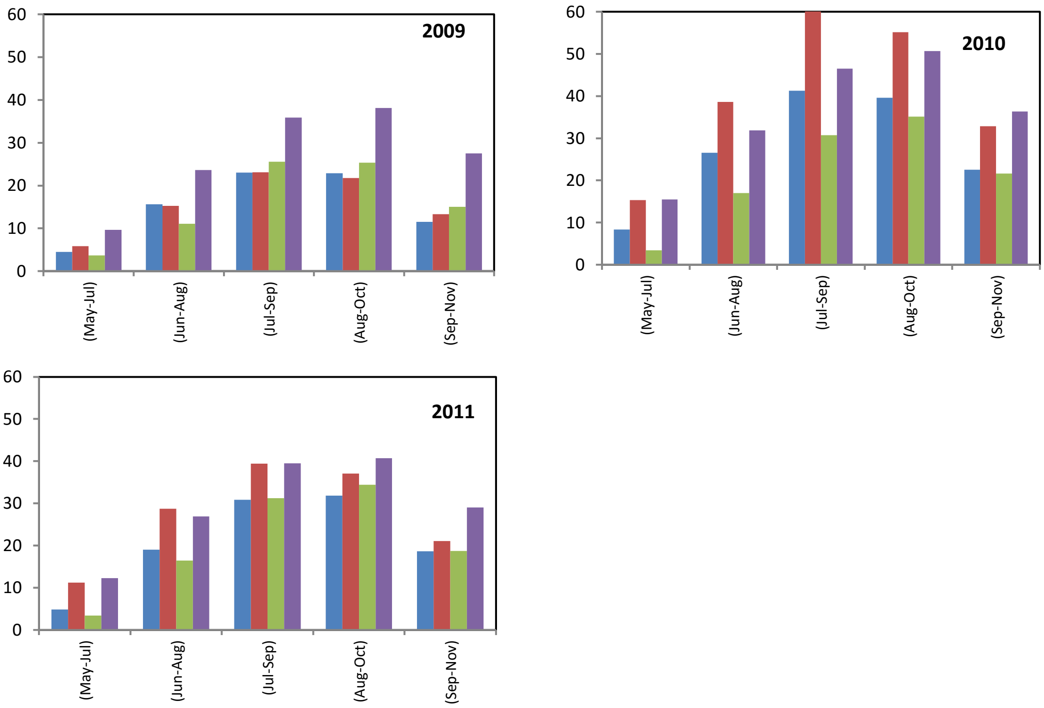


Fig. (3): Three Months Accumulated Flow at The Start of Each ESP Forecast Verses ECMWF, Simulated Flow from NFS and Observed Flow for Khartoum Station

5. CONCLUSIONS & FUTURE WORK

Bias correction method is a good way to enhance the quality of the weather parameters for ECMWF. The ECMWF showed high efficiency in forecasting peak flow, and the overall performance of the ECMWF forecasted flow for Diem station was better than for Khartoum station which might have been affected by the modeling of the basin especially, the Sudan abstractions and losses in the area between Diem & Khartoum which are not precisely presented in the NFS hydrological models, in addition to the uncertainty in forecasting, the weather parameters. Forecasted flow using ESP showed better performance in Khartoum station than that for Diem station. For ESP, always the forecasted flow was underestimated when starting forecast at May due to the effect of the initial conditions at the 1st of May which can't be simulated accurately at the beginning of the rainfall season especially for rainfall rates which were around the average rainfall. The results from comparing S4 and ESP in seasonal streamflow forecasting at Limpopo river basin showed that the skill of FS_ESP is lower than that of FS_S4 in almost every case (Trambauer et al., 2015) which goes in line with the results of this study at Diem station which showed that the S4 is more skillful than ESP in most of the months in all years, especially for peak.

The work will be continued in order to present more detailed analysis for both methods. As the 50% probability of exceed was used in this study for the ESP, future work will be done on the 10% and 90 % probability as well, and applying the probability analysis on the results from the ECMWF forecasted data in order to get 10%, 50%, 90% probabilities of exceed. The comparison will be done between the different percentages of the forecasted probability and the output for each percentile from forecasted method with its equivalent in the other method. It is recommended to increase the number of historical years of the metrological data available, so as to increase the size of the ensembles. In addition, comparing forecasted flow from ECMWF for larger number of years in order to have flood, drought and average year to assess the ability of this method to capture different phenomena in the Blue Nile.

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