DROUGHT EARLY WARNING AND FORECASTING TO STRENGTHEN PREPAREDNESS AND ADAPTATION TO DROUGHTS IN AFRICA

(DEWFORA)

A 7th Framework Programme Collaborative Research Project

Work Package 6

Implementation of improved methodologies

in comparative case studies

DELIVERABLE 6.7 - PERFORMANCE OF THE PROPOSED IMPROVED DROUGHT FORECASTING METHODS APPLIED TO SELECTED RIVER BASINS

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EXECUTIVE SUMMARY

This deliverable presents the compilation of the main improvements developed under the scope of DEWFORA project, mainly regarding drought forecasting tools for three types of drought: meteorological, hydrological and agricultural.

Regarding meteorological drought forecasting, in Eastern Nile, Limpopo, Niger and Oum-er-rbia case studies, an integrated monitoring and forecasting system was developed based on the Standardized Precipitation Index (SPI), multiple globally available precipitation products (Era Interim and CAMSOPI), which are available in near real time, and the ECMWF (European Centre for Medium-Range Weather Forecasts) Seasonal Forecasting System 4 (S4). In the specific case of Eastern Nile the relation between El Niño – Southern Oscillation (ENSO) and drought and flood events was studied, as well as its contribution for seasonal forecasting. On Oum-er-rbia basin, the implementation and skill assessment of medium range to seasonal forecasts was also performed.

In what concerns hydrological drought forecasting, in Eastern Nile a set of three indices has been applied to observed as well as simulated and forecasted flows using the Nile Forecast System (NFS) hydrological and forecasting components respectively. This helped assessing the applicability of these indices and evaluating the NFS in predicting drought. On Limpopo case study, a downscaled and adapted version of "PCR-GLOBWB-Africa" model was developed; and two different approaches were studied for hydrological drought forecasting: a statistical seasonal forecast and a dynamic multi ensemble seasonal forecast. The dynamic forecasting system is based on a distributed hydrological model which was referred above (NFS). On Niger case study, a continuous improvement and development of OPIDIN tool was performed and the eco-hydrological model SWIM (Soil and Water Integrated Model) was selected and tailored to reproduce past drought events with monthly bias corrected reanalysis climate datasets.

For the improvement of agricultural drought forecasting, on Limpopo and Oum-er-rbia case studies, statistical methods were applied in order to develop prediction models for seasonal crop yields.

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List of Abbreviations

ACC - Anomaly Correlation Coefficient

AEJ - African Easterly Jet

ANN - Artificial Neural Networks

BN - Blue Nile

CAMS - Climate Anomaly Monitoring System

CCD - Cold Cloud Duration

CG - Congo

CPC - Climate Prediction Centre

CPT - Climate Predictability Tool

CS - Case Study

DEWFORA - Drought Early Warning and FORecasting to preparedness and adaptation to droughts in Africa

DNH - *Direction Nationale de l´Hydraulique du Mali*

ECMWF - European Centre for Medium-Range Weather Forecasts

ESP - Ensemble Streamflow Predictions

GPCP - Global Precipitation Climatology Project

IND - Inner Niger Delta

ITCZ - Inter Tropical Convergency Zone

LP - Limpopo

NBHIS - Nile Basin Hydrometeorlogical Information System

NFS - Nile Forecast System

NG - Niger

NOAA - National Oceanic and Atmospheric Administration

OLR - Outgoing Longwave Radiation

OPI - OLR Precipitation Index

OR - Oum-er-rbia

PCR - Principal Component Regression

PET - Potential Evapotranspiration

SPI - Standard Precipitation Index

SST - Sea Surface Temperature

S4 - System 4

TEJ - Tropical Easterly Jet

TIR - Thermal Infrared

VarEPS - Variable resolution Ensemble Prediction System

1. Introduction

Drought management depends on the ability to monitor and forecast the time length and geographical extension of droughts. The main objective of this deliverable (D 6.7) is to evaluate the performance of the proposed improved drought forecasting methods applied to selected river basins in Africa.

In this frame, Deliverable 6.7 presents the improvements on drought forecasting, in what concerns the three types of drought: meteorological, hydrological and agricultural. However, it is important to clarify that these three types are not object of study in all case studies. In this context, for each case study, the main improvements on drought forecasting according to their specific objectives are presented.

Figure 1 presents the four river basins included in the case studies, and the blue circle identifies the sub-basins under study.

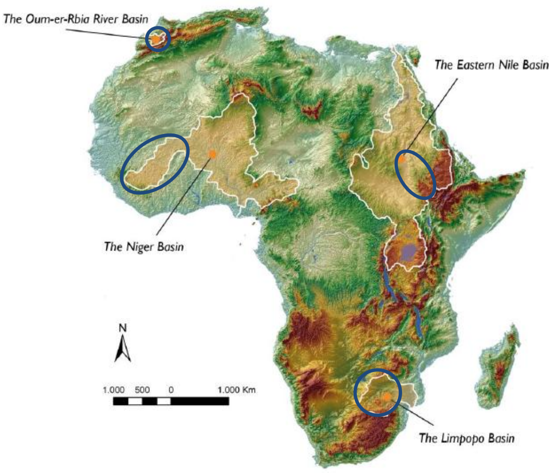

Figure 1. Sub-basins definitions (blue circle) and the full basin (beige). Source: Deliverables 4.3 and 6.1.

2. Drought forecasting improvements due to DEWFORA project

The main developments related to drought forecasting are described in the different deliverables of Work Package 4, for all the case studies. In this specific deliverable the main improvements and results are compiled and synthetized in the following topics and an assessment has been made regarding the added value for drought management in each case study.

2.1. Meteorological drought forecasting

Regarding the study of the application of new meteorological information to improve drought early warning and since this was performed for all case studies, a specific topic was made integrating all case studies and its main conclusions. The remaining studies developed also to improve meteorological forecasting are presented individually for each case study (topic 2.1.2 – Eastern Nile and 2.1.3 – Oum-er-rbia).

2.1.1. Meteorological information to improve drought early warning

Under the scope of DEWFORA project and as reported in Deliverable D4.3, the potential to supplement drought early warning systems with new meteorological information was studied. An integrated monitoring and forecasting system was developed based on the **Standardized Precipitation Index (SPI)**, multiple globally available **precipitation products** (Era Interim and CAMSOPI), which are available in near real time, and the **ECMWF** (European Centre for Medium-Range Weather Forecasts) **Seasonal Forecasting System 4 (S4)**. The capabilities of these drought early warning systems with new characteristics were tested on DEWFORA's case study basins on the African continent: the Blue Nile, Limpopo, Upper Niger and Oum er-rbia. For each one, the main conclusions are presented in the following topics and in topic 2.1.1.1 a global analysis is made.

An integrated monitoring and forecasting drought system was designed for the African case studies, in order to explore the current capability of ECMWF products to provide drought information over the Africa continent. This new approach was done combining globally available precipitation monitoring products, with seasonal forecasts.

The **monitoring** component relies on near real time observation of surface variables such as precipitation. The **forecasting** component relies on seasonal forecast. This has increasing potential as the quality of numerical weather predictions over the monthly to seasonal lead-times steadily improves. One example of such a seasonal forecasting system is the ECMWF seasonal forecasting systems (system-3 and the newly released system-4).

As described in Deliverable D5.3, the ECMWF maintains two currently operational ensemble forecasting systems through its Variable resolution Ensemble Prediction System (VarEPS): (i) weather forecasts out to 32 days and (ii) seasonal forecasting produces forecasts out to 7 months.

(i) For weather forecasting the atmospheric initial state problem is essential, since the time scale for medium-range (up to day 15) and monthly (up to 7 months) weather forecasting is too short, variations in the ocean significantly affect the atmospheric circulation. The ECMWF medium-range weather forecasting system is based on atmospheric-only integrations. The monthly forecasting system comprised the medium-range VarEPS in ocean-atmospheric coupled mode after day 10. The real-time VarEPS/monthly forecasting system is a 51-member ensemble of 32-day integrations.

(ii) Seasonal forecasting is less problematic than monthly forecasting due to the long predictability of the oceanic circulation (of the order of several months) and by the fact that the variability in tropical SSTs has a significant global impact on the atmospheric circulation. Since the oceanic circulation is a major source of predictability in the seasonal scale, the ECMWF seasonal forecasting system is based on coupled ocean-atmosphere integrations. The other hand, the result of seasonal forecasting is a statistical summary of the events that occur in a given time period. Most of the precipitation over the African continent is controlled by the south to north and back displacement of the Inter Tropical Convergency Zone (ITCZ), the intensity of the low level Tropical Easterly Jet (TEJ) and the flow disturbances in the high level African Easterly Jet (AEJ).

Some of the main characteristics in what concerns data and methods used to improve drought early warning, trough meteorological drought forecasting are presented above:

- Standardized Precipitation Index (SPI)

SPI is a commonly used drought index and it is based on the probability of an observed precipitation deficit occurring over a given prior accumulated time period. This time period should be defined according to the application, with typical values of 3, 6 and 12 months. The flexibility of the assessment of different time periods accumulated precipitation allows a range of meteorological, agricultural and hydrological applications. Dependent on each region/application, a detailed study should be carried out to relate the different SPI time scales with the target variable, such as soil moisture available to crops or natural reservoirs.

- Precipitation data

Monitoring

There are some characteristics of precipitation data that should be considered for drought monitoring using products as SPI, that are:

- the precipitation datasets used for meteorological drought analysis with the SPI should be long enough (at least 30 years, as recommended by Mckee et al. (1993)) and statistically homogeneous.
- the data set needs to be available in near-real time, meaning no more than 1 month delay.

In this study the products used partially fulfil the requirements: globally, at least 30 years of data available in near-real time, but only partially temporally homogeneous. Nevertheless, from dynamical models was used the ECMWF ERA-Interim and from observations the CAMSOPI.

ERA-Interim (ERAI) is the latest global atmospheric reanalysis produced by ECMWF. It covers the period from 1 January 1979 onwards, and continues to be extended forward in near-real time. Gridded data products include a large variety of 3-hourly surface parameters, describing weather, ocean-wave and land-surface conditions, and 6-hourly upper-air parameters covering the troposphere and stratosphere. Some other products have also been produced: vertical integrals of atmospheric fluxes, various synoptic and daily monthly averages, and other derived fields.

The CAMSOPI is a merged dataset produced by the NOAA Climate Prediction Centre (CPC) that combines satellite rainfall estimates from Outgoing Longwave Radiation (OLR) Precipitation Index (OPI) with ground-based rain gauge observations from the Climate Anomaly Monitoring System (CAMS).

In Africa, in-situ observations of precipitation from rain-gauges are spatially and temporally scarce. Thus, for the DEWFORA study the **Global Precipitation Climatology Project (GPCP) version 2.2** monthly precipitation was used which is available since January 1979 to December 2010 on a 2.5°x2.5° lat/lon regular grid.

Seasonal forecast

Seasonal forecasting provides useful information regarding the expected weather evolution in the coming months. The principal aim of seasonal forecasting is to predict the range of values more likely to occur during the next season.

As previously referred, the ECMWF seasonal forecasts, based on an atmosphere-ocean coupled model, were used for drought forecasting in this study, specifically, the recently implemented System 4 (S4).

The seasonal forecast generates 51 ensemble members in real-time, with 30 years (1981-2010, 15 ensemble members) of back integrations (hindcasts). The lead time is 7 months, including the month of issue. Molteni et al. (2011) present an overview of the model biases and forecast scores of S4.

The main results for each case study are presented below.

- **Eastern Nile (sub-basin Blue Nile)**

<u>Models climate</u>

- In the Blue Nile ERAI shows a significant overestimation and CAMSOPI is in good agreement with GPCP annual cycle of precipitation.
- The ERAI overestimation of precipitation is also reflected in higher inter-annual variability.
- S4 forecasts overestimate precipitation in the first forecast month with a reduction of the peak rainfall with lead time, showing the impact of model drift.

<u>Drought monitoring</u>

- The temporal correlation of both ERAI and CAMSOPI compared with GPCP decays with increasing SPI time-scale. GPCP has lower decay time scales and higher variance of white noise while ERAI has the higher time scales and lower white noise variance.

- **Limpopo**

<u>Models climate</u>

- All datasets show a reasonable agreement (ERAI, CAMSOPI and GPCP).

- **Niger**

<u>Models climate</u>

- S4 forecasts overestimate precipitation in the first forecast month with a reduction of the peak rainfall with lead time, showing the impact of model drift.

- The ERAI overestimation of precipitation is also reflected in higher inter-annual variability.

Drought monitoring

- The temporal correlation of both ERAI and CAMSOPI compared with GPCP decays with increasing SPI time-scale. GPCP has lower decay time scales and higher variance of white noise while ERAI has the higher time scales and lower white noise variance.
- In the Niger basin, both ERAI and CAMSOPI show an opposite trend to GPCP, with a wet period until 2000 and severe and long term drought in the last decade.

- **Oum-er-rbia**

Models climate

- All datasets (ERAI, CAMPOSI, GPCP and S4) show a reasonable agreement, with an underestimation of the rainy season and S4 has a reduced drift on both basins.
- The underestimation of precipitation during winter in Oum-er-rbia by all datasets is also associated with lower inter-annual variability. The changes in variability with lead time in S4 are smaller than what was found for the mean annual cycle of precipitation.

2.1.1.1. Global analysis - New meteorological information

Regarding the study of new meteorological information to improve drought early warning and according to the conclusions presented in Deliverable 4.3, significant differences were observed in the quality of the precipitation in individual datasets depending on the corresponding catchments and comparing the seasonal forecasting system and the global precipitation products (ERA Interim and CAMSOPI). Nevertheless, the datasets showed a good match in the South and North West Africa, and a low agreement was verified in Central Africa.

In what concerns seasonal forecasting, the results obtained for the Blue Nile, Limpopo and Upper Niger showed a higher reliability and skill in comparison with the results for Oum-er-rbia. It should be referred, however, that the skill and reliability of forecasts depend on the accumulation period and so, a larger accumulation period corresponds to a higher skill.

In conclusion it was observed that the recent ECMWF seasonal forecasts (system 4) has a higher predictive skill than climatology for most regions; and in regions where no reliable near real-time data is available it is better to use just the seasonal forecast for prediction of droughts.

More specific conclusions about seasonal forecasts are also detailed below:

a) Precipitation

- S4 precipitation forecasts in terms of the Anomaly Correlation Coefficient (ACC) for the ensemble mean in the Blue Nile, Limpopo and Niger basins have a higher predictive skill up to 3 months lead time for the rainy seasons, while in Oum-er-rbia basin S4 does not have a reasonable predictive skill.
- S4 outperforms the climatological forecasts in the basins where the original seasonal forecasts of precipitation have skill, namely on Blue Nile, Limpopo and Niger. In Oum-er-rbia, S4 has a similar skill to climatological forecasts.

b) SPI forecasts

- There is good agreement between the GPCP derived SPI at time-scales higher than 5-6 months, for all calendar months except July, when compared with river discharge anomalies.
- SPI derived from ERAI and CAMSOPI compared with stream-flow shows much lower or no-existent correlations. This reflects the poor intra-seasonal to inter-annual variability of precipitation of the ERAI and CAMSOPI datasets in the Niger region.
- Especially in the Blue Nile Niger basins, CAMSOPI has problems in representing the intra-seasonal to inter-annual variability of precipitation. These problems are present during the monitoring periods and are extended to the forecast period. The quality of monitoring products is very important as they control the skill of the SPI forecasts for accumulation time scales.
- Seasonal forecasts of the 1991/92 drought in the Limpopo basin with different initial forecast dates starting August 1991 to July 1992, comparing the SPI-12 from GPCP (verification), CAMSOPI (monitoring) and the S4 and CLM forecast show that skill improves around Nov–Dec and CLM performs better from Dec onwards.

2.1.2. Eastern Nile

2.1.2.1. The relation between ENSO and drought and floods

El Niño – Southern Oscillation (ENSO) is significantly correlated with rainfall variations over the eastern side of the African continent. The phenomenon plays an important role in medium to long range forecast for the Nile River (Wang and Eltahir, 1999). Monitoring and predicting ENSO can contribute to early warning, and in consequence can lead to disaster risk reduction.

The natural oscillations in the Pacific Ocean originate a significant impact on the patterns of weather and climate around the world. The role of global sea surface temperatures in shaping the potential predictability of rainfall over tropical East Africa in both this observational discharge at the mouth of the upper catchment of the Blue Nile and Global Precipitation Climatology Project (GPCP) dataset, and enabling to inform that ENSO exerts a significant influence to the upper catchment of the Blue Nile has been assessed.

In this context and under the scope of DEWFORA, the connections of ENSO and drought and floods over the upper catchment of the Blue Nile were studied, by using (i) the observational dataset and (ii) a simulation of an ensemble of 9 members describing the regional climate.

(i) Using observational dataset

In fact, the extreme natural events (droughts and floods) are associated with significant anomalies in the Pacific Sea Surface Temperature (SST): El Niño and La Niña events. In DEWFORA study, the river flow and rainfall observations were analyzed, and the impact of El Niño on drought and flood events in the upper catchment of the Blue Nile was evaluated. The suitable seasonal SST conditions over the Pacific Ocean was identified in order to be recommended as input to seasonal forecasting by water resources managers in the region.

Regarding the observed data, discharge measurements between 1965 and 2011 from Eldiem station were used. The gauge station measures both water level and discharge at the outlet of the upper catchment of the Blue Nile. For El Niño, Niño 3.4 index between 1965 and 2011 was downloaded from National Oceanic and Atmospheric Administration (NOAA) website. Data from Niño 3.4 region was analyzed in relation to several observational datasets (GPCP rainfall and discharge flow). The GPCP version 2.2, which is available from January 1979 to December 2010 with a resolution of 2.5°, was selected as a global dataset of monthly precipitation. It should be referred that an El Nino event is identified if 5-month running mean of SST anomalies in the Niño 3.4 region (5°N–5°S, 120°–170°W) exceeds 0.4°C for 6 months or more (Trenberth, 1997).

Through the study referred above it was verified that El Niño years like 1972 and 1987 are associated with low discharge, and La Niña years, for example 1988 are associated with high discharges. This confirms the results of previous studies that El Niño is associated with below average rainfall, and La Niña is associated with above average rainfall.

On this study it was verified that the negative correlation between the SST anomalies in Pacific Ocean in Nino 3.4 region and the discharge anomalies in Eldiem station at the outlet of the upper catchment of the Blue Nile during JJAS is evident. Droughts in the Blue Nile are sensitive to El Niño, with 70% of drought cases when El Niño starts in April-May-June, June-July-August and July-August-September. When El Niño starts in April-May-June, 83 % of the cases resulted in drought. When El Niño ends early (December-January-February, January-February-March, February-March-April and March-April-May), there is almost no effect on the drought in the Blue Nile. When El Niño terminates late in May-June-July (or after that) there is a high possibility of drought occurrence in the Blue Nile.

When La Nina started in April-May-June, June-July-August and July-August-September, in 50 % of the cases there was a flood or extreme flood. An active event El Nino / La Nina during the season for development of the monsoon over Ethiopia (May to September) is necessary, for this teleconnection have an impact.

In conclusion, in 50 % of the cases that El Niño was followed by La Niña there were extreme floods in the Blue Nile. The important conclusion is that June-July-August-September rainfall in the upper catchment of the Blue Nile is highly sensitive to the SST in the early season of April-May-June in Nino 3.4. The facts could be studied in order to be used in the seasonal forecasting of the Blue Nile.

(ii) Using a simulation of an ensemble of 9 members

Eltahir (1996) found that 25% of the natural variability in the annual flow of the Nile is associated with El-Niño oscillations and proposed to use this observed correlation to improve the predictability of the Nile floods. Wang and Eltahir (1999) recommended an empirical methodology for medium and long-range (~6 months) forecasting of the Nile floods using ENSO information.

In DEWFORA study observational data sets were analyzed, and the hypothesis whether a connection can be formed between droughts/ floods and Sea Surface Temperature in the Pacific Ocean by using a physically based model of the climate system (the Regional Climate Model (RegCM4.1.1)) was evaluated. It was simulated an ensemble of 9 members describing the regional climate to study the impact of El Niño on the drought and floods in the upper catchment of the Blue Nile.

RegCM4.1 is a hydrostatic, sigma-p vertical coordinate model with multiple physics options. The initial and lateral boundary conditions for the RegCM4.1 simulations were obtained from the ERA-Interim (ERAI) 1.5° × 1.5° gridded reanalysis which is the third generation ECMWF reanalysis products. RegCM4.1 was forced with sea surface temperatures (SSTs) 1° resolution, and a weekly temporal resolution, obtained from the NOAA Optimum Interpolation (OI) SST dataset (Reynolds et al., 2007).

The results from this study could be divided in two parts:

- The difference between La Niña and El Niño years in the model and in the GPCP observational data set

This analysis intends to assess if the model (RegCM4.1) was able to capture the difference between La Niña and El Niño years. These model results agree with the previous analysis, confirming that El Niño years are associated with the below normal rainfall and La Niña years are associated with the above normal rainfall in the upper catchment of the Blue Nile. So, the model can capture the impact of El Niño/ La Niña.

- Correlation between rainfall anomalies over Ethiopian Highlands and SST anomalies over the Pacific Ocean in Nino 3.4 region for 9 members

Regarding the correlation between the rainfall anomalies during June-July-August-September and the SST anomalies during (January-February-March, February-March-April, March-April-May, April-May-June, May-June-July and June-July-August), the model results show the highest correlation during April-May-June. These results support the use Nino3.4 in April-May-June for a seasonal forecasting of drought in the upper catchment of the Blue Nile.

In conclusion, in this study the impact of ENSO on the upper catchment of the Blue Nile was investigated. Series of 9 long simulations were made for a domain covering the entire globe between 43°S and 43°N, with only upper and lower boundary conditions from the ERA-Interim reanalysis.

The RegCM4.1 is firstly evaluated against observations and the reanalysis. It is shown that the model performs reasonably well in reproducing the observed climatology of temperature, precipitation, outgoing long wave radiation and large scale atmospheric circulation features. For example, the model captures well the rain belt, as well as the peaks in Ethiopian Highlands, Guinea Highlands, and Cameroon Highlands. In general, the temperature biases are approximately between -2° C and 2° C. In addition, the lower level and large-scale circulation features affecting the monsoon (Tropical Easterly Jet - TEJ, African Easterly Jet - AEJ) are realistically captured. The model (9 average members) was able to reproduce the negative correlation and showed the highest correlation also during April-May-June (62%). So, this season (April-May-June) could be used in the seasonal forecasting of the Blue Nile.

2.1.3. Oum-er-rbia

2.1.3.1. Assessment of medium range to seasonal forecasts

On Oum-er-rbia case study an analysis of the implementation and skill assessment of medium range to seasonal forecasts was performed. The main objective was to assess the skill of medium range weather forecasts in the Oum-Er Rbia basin and their potential use for the mitigation of intra-annual dry-spell episodes. This analysis focused on rainfed areas and cereal crops given their predominance and socio-economic importance around the basin and throughout all the country.

Once the drought is declared, the Moroccan government implements different actions; farmers and herders, at their side, handle drought through many strategies: seed supply, application of measures for livestock, measures for water supply and drought insurance. A prolonged drought spell can damage cereal crop production in rainfed areas, and in this situation, medium range precipitation forecasts could provide an early warning system allowing the farmers to prepare supplementary irrigation (SI). SI means the addition of small amounts of water to essentially rainfed crops during times when rainfall fails to provide sufficient moisture for normal plant growth, in order to improve and stabilize yields. In addition, 15 day forecasts can be used for soil labours and sowing, planning of fertilizers and harvesting dates. If drought events are predicted, farmers can delay the crop installation.

In fact, seasonal or medium range weather forecasts can provide an indication of the occurrence, duration and severity of dry periods and thus reduce impacts of drought events through the application of adequate mitigation measures and early warnings systems which allow, for example, the farmers to prepare temporary irrigation systems in order to minimize the drought impacts in rain fed areas.

For this study, different types of data were used: daily rainfall (observed and forecasted) and seven days accumulated precipitation data (observed and forecasted). Daily rainfall data on an 18 years long period for the Oulad Gnaou and Khmiss Mettouh stations was collected, and the also the precipitation forecasted rainfall with a lead time of 15 days. The second phase was designed after the analysis of the preliminary verification of daily forecasts. The analysis was performed on 7 days accumulated forecasts; in order to assess the performance of the forecasts to identify end-season dry spells and the data analysis was restricted from mid-February to mid-April since it corresponds to the cereal’s grain formation and filling period.

The methods used were based on the comparison of: daily observed and forecasted rainfall and also of 7 days accumulated observed and forecasted rainfall. Regarding the results of medium range forecast of daily rainfall can be concluded that:

- The forecasts do not enable to detect rainy days 15 days ahead. In fact, none of the forecasts was able to predict either the occurrence of rain or the amount of rain. Even when the rainy episodes are forecasted (around 6 days), the amount of rainfall is very often underestimated, especially for important rainfalls.
- The forecasts seem good to predict dry periods.

The main conclusions from the first sets of analysis were that both daily and medium range forecasts are not able to forecast rain but seem to have better skill in forecasting dry periods. Consequently, in a second step, analysis on probabilistic forecasts of 7 days accumulated rainfall was conducted in order to confirm this trend and assess, thanks to the Brier score, their skill for forecasting dry periods.

Regarding the comparison of the probabilistic forecasts and the observed 7 days accumulated precipitations for two stations (Oulad Gnaou and Khmiss Metthouh), using 3 years data (2008, 2010 and 2012) over a period of two months (15 February -15 April) as above referred, the results focus on the Brier Score for each of the 3 categories tested: dry (below normal), normal and wet (above normal) conditions. Overall, Brier score results indicate that the drier periods seem to perform better on average, although there is a significant variation between years. The most interesting results correspond to the skill in predicting dry conditions. Thus, the results confirm the hypothesis presented after the analysis of the daily forecast and show that, the medium range rainfall forecast can be used to predict dry spells, under the conditions of Oum-er-rbia basin. Indeed, some significant potential exist both for early warning and mitigation operations; this is particularly true for herders which cannot afford major food purchases to save their cattle, but also for crop imports, subsidies, and some agricultural practices. An efficient drought early warning system would allow farmers to evaluate more accurately their production options and insurance companies anticipate payments to farmers.

Regarding the relation between medium-range forecast and the early warning improvements, it could be mentioned that a reliable prediction of a drought period 15 days before a drought event will allow a shorter collaborative process between several administration which are involved in drought management plan in Morocco and decision makers to set an early drought warning and to take, consequently, the more appropriate decisions, as well as the agricultural producers that need to decide what type, where and how many surfaces of crops will be planted, and/or how many cattle will be sold or bought.

2.2. Hydrological drought forecasting

As described in D 5.3 and D 4.8, hydrological forecasting usually requires a hydrological model to transform the meteorological forecast into hydrological predictions. Hydrological models are usually used to simulate the effects of periods of precipitation shortfall on water resources (surface or subsurface discharges, groundwater, soil moisture, etc.). The results of such hydrological models can be used to compute spatially distributed drought indicators for different time lengths. Hydrological predictions are generally carried out by forcing hydrological models with ensembles of atmospheric forecasts produced by climate models.

2.2.1. Eastern Nile

Under the scope of DEWFORA, in terms of hydrological drought, a set of three indices has been applied to observed as well as simulated and forecasted flows using the Nile Forecast System (NFS) hydrological and forecasting components respectively. This helped assessing the applicability of these indices and evaluating the NFS in predicting drought.

- **NFS Hydrological Component and Forecasting**

The Nile Forecast System (NFS) is a near real-time distributed hydro-meteorological forecast system designed for forecasting Nile flows at designated key points along the Nile. The basis of the NFS is a conceptual distributed hydrological model of the Nile system including soil moisture accounting, hill slope and river routing, lakes, wetlands, and man-made reservoirs within the basin. The main inputs to this model are the rainfall and potential evapotranspiration.

Satellite remote sensing technology was used in estimating rainfall over the basin, taking into account the scarcity and discontinuity of rainfall records within the basin, and the lack of direct monitoring control over rain gauges. Thus, the system grid was designed to match that of the satellite rainfall. In addition, the system includes a large database of rain gauge data, as part of the Nile Basin Hydrometeorological Information System (NBHIS) which also holds flow records at all key river gauges.

Regarding the satellite remote sensing technology, geostationary satellite imagery is received using a dish antenna on the roof of the ministry building. This imagery is used to generate daily high resolution (20 km) gridded estimates of rainfall over the basin, that is then blended with gauge-only rainfall analyses. The combined daily rainfall product is used to drive a gridded distributed hydrological model of the basin.

The NFS is composed of 6 main functions, also described in Figure 2:

1. Rainfall Estimation
2. Hydrological Simulation
3. River Flow Forecasting
4. Assimilation
5. Data Collection and Management (NBHIS)
6. GIS Functions

This model, when used for forecasting as intended, a short NFS simulation (a few weeks) is performed using observed rainfall (merged satellite and gauge estimates) to define the model status (soil moisture storage, reach storage) on the current date. Subsequently, an ensemble of historical rainfall (for as many years as available) for the 3 months ahead the current date is applied to the model to simulate the Extended (and more recently Ensemble) Streamflow Predictions (ESP).

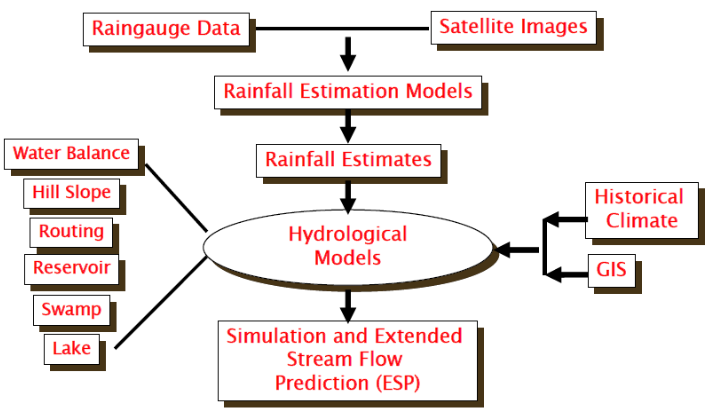

Figure 2. The structure of the Nile Forecast System.

Satellite Precipitation Estimation

Regarding the meteorological issue, and just to better understand the process, the NFS 5.1 satellite rainfall-estimation system is based on the principle of Cold Cloud Duration (CCD). This technique assumes that high cloud tops (which show cold in infra-red imagery) are frequently associated with strongly precipitating cumulonimbus systems. A probably precipitating cloud is identified from Thermal Infrared (TIR) imagery using a brightness temperature threshold.

Description of the regional hydrological model

The hydrological component of the NFS is defined on the quasi-rectangular grid of the METEOSAT. Each grid cell (pixel) imitates a small basin with generalized hill slopes and stream channels. Input to each grid cell is precipitation and potential evaporation/evapotranspiration.

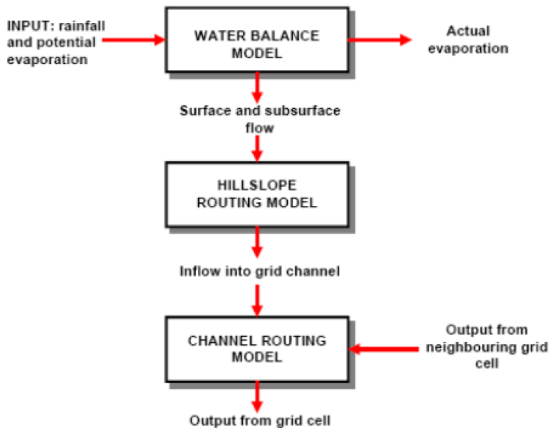

Figure 3. Hydrological models at the Pixel Scale.

The results of the work developed under the DEWFORA project for the Eastern Nile case study, which main objective is to improve the hydrological drought forecasting in this region, can be divided in two parts: the first, using the rainfall forecast, corrected by the bias correction method, and the Potential Evapotranspiration (PET) calculated from the outputs of the seasonal forecast for all ensembles; and the second, using the same rainfall forecast and the Nile forecast System (NFS) PET. Atbara Station, Diem and Khartoum were the three sub-basins studied.

Regarding the PET calculations it was verified that the range of the forecasted PET is close to the NFS_PET except for October and November which are far from the overestimated NFS_PET evaluations. This is clear in the Atbara basin, and in the Khartoum basin, although the differences decrease in this last case. In the Diem basin the NFS_PET estimations are within the range of the 51 ensembles seasonal forecasts. Regarding the Atbara and Khartoum sub basins it is expected that the differences in PET in October and November will affect simulation flow in these two months.

In what concerns runoff simulations, for each sub basin, two situations were considered: I) using the forecasted PET and II) using NFS_PET. On this study and according to the information present in Deliverable 4.8, it is found that when using the NFS_PET the simulated runoff range is reduced.

The results show that, in case of using NFS_PET in Atbara basin, the NFS runoff simulation is close to the average simulated flow of the 51 ensembles, which does not occur when using the forecasted PET. In fact, in this last case, the NFS runoff becomes closer of the lower limit of the range of the 51 ensembles' results. The results in the Blue Nile basins (Diem basin and Khartoum basin) show some changes in the range of the 51 ensembles when comparing the NFS runoff simulation for both cases, especially in October and November. For the other months it can be verified that the NFS simulation is closer to the average range of the 51 when using the forecasted PET.

According to the main results it can be concluded that, although in both cases a reduction in October and November runoff simulations is expected, due to the raise of PET in these months, the differences in rainfall in October and November do affect the results and raise the flow simulations range.

- **Indices used**

The first of the three indices corresponds to the drought classification of the Ministry of Water Resources and Irrigation (MWRI) of Egypt which was developed by the Nile Yield Committee in 2010 based on different ranges of natural flow of the Nile at Aswan. The classification has been extended to other important stations on the Blue Nile and the Atbara by considering the average irrigation abstractions in Sudan and the contribution of those basins to the flow at Dongola. The classification has been applied to observed and forecasted flow records for the Blue Nile at Khartoum and Diem and for the Atbara river at its mouth near Atbara town. The results show that the MWRI classification has been successfully adjusted for the application to the selected sub-basins. However, the small flow range of the Atbara has resulted in small bounds for the categories which make difficult to get the right drought characterization. The results show a general agreement of drought classification between observed and forecasted flows for the Blue Nile but with some discrepancies for some years. The results for the Atbara river have more discrepancies indicating that the hydrological model or forecasting parameters of the Atbara basin need to be revisited.

The second index used is the Surface Water Supply Index (SWSI) which combines hydrological and climatic features in a single index and allows for the consideration of reservoir storage. The revised SWSI is computed using expected streamflow and initial reservoir storage only, which is more advantageous than the original formulation which required weights for the different hydrologic components (snowpack, precipitation, streamflow, and reservoir storage).

The revised SWSI has been calculated for the Blue Nile and Atbara Basins using forecasted streamflows starting on the period May 1992 - October 2011 by using the median ESP (Ensemble Streamflow Prediction) forecast. The forecasted flow was accumulated from the first of May until the end of October for each year (to get the flow forecast over the season). The period May-October denotes the rainy season for the Eastern Nile basins. This flow forecast is added to the actual storage in reservoirs at the end of April for both the Atbara and Blue Nile basins.

The results have not reflected the actual situation of the flood season for some years for both sub-basins but the results for the Atbara are worse than those of the Blue Nile because of the reduced forecast quality for that basin compared to the Blue Nile. Flow forecast values need to be corrected to enhance the results of the SWSI values. In addition, longer records need to be used because SWSI values are a function of the probability of non-exceedance which is obtained based on the rank of the year.

The third index used is the Standardized Discharge Index (SDI) which is very similar to SPI but uses the streamflow instead of precipitation. The SDI has been calculated using the observed discharge time series, NFS simulated flow, and the median of ESP forecasted flow. The simulated and forecasted SDI at Atbara, in many years did not have the same direction of the observed SDI, indicating that the hydrological model of Atbara should be calibrated and it is clear that the bad simulation of Atbara could be the reason for the poor results of the ESP used to calculate SWSI above. The results of the Blue Nile at Diem and Khartoum show that the observed SDI, Simulated and forecasted SDI have the same sign for most years.

2.2.2. Limpopo

Under the scope of DEWFORA project and regarding Limpopo case study, two different approaches were studied for hydrological drought forecasting: a **statistical seasonal forecast** and a **dynamic multi ensemble seasonal forecast**. The dynamic forecasting system is based on a distributed hydrological model developed within DEWFORA for the seasonal prediction of hydrological droughts for the semi-arid Limpopo river basin in Southern Africa - PCR-GLOBWB model, which is a downscaled and adapted version of the "PCR-GLOBWB-Africa" model.

The **statistical forecasting approach** followed here employs two different methods: multiple linear models and Artificial Neural Networks (ANN). All these methods are able to relate multiple predictors (input) to one predictand (output). Thus, to apply them, the first step is to identify potential predictors for drought in the Limpopo basin, the second is to choose the best predictors, and third, the models are set up with these predictors and drought forecasting performance is, finally, compared. The statistical models are set up for a three month lead time forecasting, based on teleconnected ocean regions. Multiple linear models and an artificial neural network model are compared for all stations.

The main intention in this study was to identify teleconnected ocean regions which show potential to predict drought in the Limpopo basin. Thus, a thorough analysis of potential predictors for hydrological drought was conducted. From an extensive list of teleconnected ocean regions, skilful predictors were selected for multiple linear models.

For the first step, in order to identify potential predictors, a number of climate and circulation anomaly were compiled and teleconnected sea surface regions were selected (based on work presented in Deliverable D4.6, in which the relationship between drought variability and sea surface temperature was analysed). In order to obtain time series of SST anomalies, the regions that showed high correlations were selected and the spatial fields were averaged. With the correlation analysis, regions which show a general relationship with precipitation (but are not specific to drought) were highlighted.

For prediction, some climate indexes were selected, such as: Sea Surface Temperature (SST), Darwin Sea Level Pressure (SLP), number of indices related to the El Nino/southern oscillation (ENSO), Northern Atlantic Oscillation (NAO), Indian Ocean Dipole Mode Index (DMI), among others.

The analysis was focused on the rainy season and droughts were defined as moments in time, where the all Limpopo SPI was below a threshold of -0.8, which equals the 21 % lowest periods.

The runoff data (preditand) pre-processing covered three steps: first, a quality control was performed; second, completeness was checked, and, third, priorities were assigned to the station. Then, the Standardized Runoff Index was calculated for the runoff time series. In this study, four stations were chosen: Botswana, Loskop Noord, Combomume and Chókwè, which are the biggest catchments.

The multiple linear models definition is a stepwise selection of predictors from the set of potential predictors, to simulate the predictand (runoff), until no potential predictor leads to an improvement of the model.

However, since multiple linear models and linear discriminant analysis have one major shortcoming, which is their limitation to model non-linear processes, and the atmospheric processes are very likely to be non-linear, the application of artificial neural networks for the prediction of rainfall, can give better results, since ANN are capable of representing more complex non-linear relationships between variables.

The application of the artificial neural networks, which were trained with the genetic algorithm (ANN-GA), used as input layer the predictors chosen from the multiple linear models.

The artificial neural network model shows far better performance in fitting the calibration data. However, by cross-validation it is shown that the multiple linear models are more robust and hence more suitable for prediction. The artificial networks probably suffer from overfitting for a small dataset as the available for the analysed stations.

Nevertheless, the prediction skill of multiple linear models is still low. The best results are achieved for the station at Combomume in Mozambique which drains a large catchment of the upper Limpopo. The early warnings for Combomume were the most skillfull ones from all the stations.

The **dynamic multi ensemble seasonal forecast** for the Limpopo river basin is based on a process-based distributed hydrological model forced with ECMWF seasonal forecasts (global atmospheric model ECMWF-System 4). This system seeks to provide operational guidance to farmers and water managers within the basin at the seasonal time scale by predicting the availability of water for irrigation and water supply, which are the most important water uses in the basin. Regarding the regional hydrological model, for the Limpopo river basin case study, a downscaled version of the global PCR-GLOBWB hydrological model is used.

PCR-GLOBWB is a grid-based model of global terrestrial hydrology that was developed in Utrecht University, Netherlands. The model was set up for the Limpopo basin with a spatial resolution of 0.05 x 0.05° and the simulation is carried out for the past 32 year-period on a daily time step. The model includes water storages and flow components, such as surface, sub-surface and groundwater flows, soil moistures availability, canopy interception and snow storage. In order to account for the highly modified hydrology in the Limpopo river basin the new developments includes an irrigation scheme.

The hydrological model results include: actual evaporation, soil moisture, surface and subsurface runoff, river discharge, root stress, water storage in the three layers, and other hydrological parameters. In the end, the model results could be verified using runoff data available from the basin and the model is also tested for identifying historic droughts in the basin and to estimate hydrological drought related indices. It is also important to note that the final objective of this model is hydrological drought forecasting using forecasted meteorological forcing. On DEWFORA project, as mentioned above, was made a downscaled version of the global PCR-GLOBWB hydrological model. The main objective was to model streamflow and hydrological drought indicators for selected river reaches in the Limpopo River basin, for the period 1979-2010 using a distributed physically based model. A thorough description of the model set up for the Limpopo river basin is referred on Deliverable 4.7.

The approach followed in this forecasting system is summarized in Figure 4. It starts with obtaining the meteorological seasonal forecast from ECMWF, together with some necessary "pre-processing" of the data. The hydrological model (embedded in the Delft-FEWS forecasting shell) then simulates the forecasted seasonal hydrology obtaining predicted streamflows and other hydrological variables.

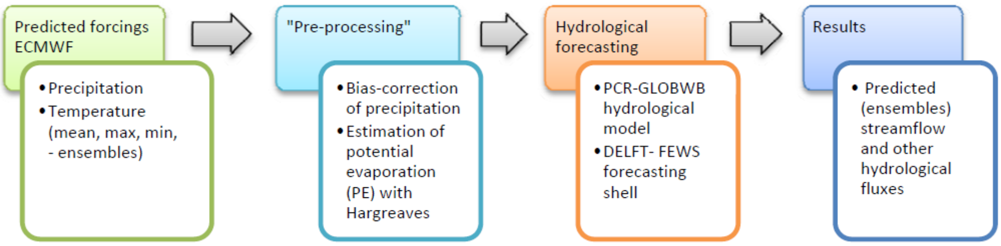

Figure 4. Approach followed in PCR-GLOBWB hydrological model for the Limpopo river basin.

The dynamic multi ensemble seasonal forecast for the Limpopo river basin forced with ECMWF S4 seasonal forecasts show higher skill in predicting low flows and high flows than in predicting near normal conditions. The predictive skills of these forecasts, which worsen with lead time, are higher than using the climatology. The evaluation of the forecasts for some selected seasons when a drought or flood actually occurred suggests that the hydrological forecast using ECMWF S4 seasonal meteorological forecast is improved and offers a clearer signal compared to the use of the ensemble streamflow prediction (ESP)[1]. These selected seasons suggest that seasonal forecasts based on numerical weather prediction models can offer better seasonal hydrological forecasts than ESP.

[1] ESP is used as reference forecast (forecasted runoff anomaly). The ESP predicts future streamflow from the current initial conditions (warm state) in the hydrological model with historical meteorological data (observed meteorology from the last 30 years).

2.2.3. Niger

2.2.3.1. OPIDIN

The Inner Niger Delta (IND) is a flood-dependent ecosystem and economy, and so, changes in its dynamics (level and discharge) have significant social, economic and environmental consequences, e.g., the rice production in the agriculture sector. In fact, the life of (rural) people in the IND is governed by flooding. Predicting the flood becomes also gradually more important, given the changes to be expected in the Inner Niger Delta due to the ongoing climate change. A seasonal forecast of the flood extent is therefore key information which can support stakeholders to anticipate their economic activities for the coming season and possibly reduce their livelihood risks in the delta.

In this context, OPIDIN (*Outil de Prédiction de l´inondation dans le Delta Intérieur du Niger*) was developed in the IND to predict the height and the timing of flood peak and to function as an early warning system and a decision support tool for the people, being either fishermen or farmers, to achieve food security. Projecting the timing of annual deflood permits to support the decision of local stakeholders and authorities to select the appropriate date regulating each year the access of rich and highly nutritive pastureland from the floodplain to the livestock. The flood prediction function of OPIDIN can enable various stakeholders in the IND to plan their livelihood activities and to support investments.

The OPIDIN is a tool product of simple statistical relationship based on historical water height time series monitored at different gauged stations by DNH (*Direction Nationale de l´Hydraulique du Mali*) along the Inner Niger Delta.

The initial version of OPIDIN is based on the two gauge stations Mopti and Akka. OPIDIN prediction is based on a single water level measure in one station; the prediction is then subject to uncertainty from local disturbances or local punctual peaks in the water levels. The statistical method in OPIDIN is based on the correlation of one water level measurement upstream at a single date to a specific occurrence of a given water height in the downstream time series. Therefore, the prediction is based only on few numbers of correlations equal to the number of years in the upstream and downstream time series. Moreover, the transformations (by linearization or other technics) of the statistical correlation partly truncate the correlation. As the statistical correlation do not account for time of concentration according to water levels, the prediction is also subject to large uncertainty concerning the variability of the flood onset and the inner flood cycle.

After the prediction being produced, the main problem is to convert technical information into really meaningful and practical information for people. So far, the solution adopted in OPIDIN is to categorize the flooding prediction into a five-point early warning scale (very high, high, normal, low and very low) and use systematically five classes in the transfer of information.

In this case study, DEWFORA project aimed to support the continuous improvement and the development of OPIDIN tool. In collaboration with AFROMAISON fp7 project, workshops were organized with key regional and local stakeholders of the OPIDIN stakeholder platform. According to the Deliverable 4.8, DEWFORA developed extended methods to improve the skill assessment of the initial version of OPIDIN tool.

OPIDIN demonstrates less skill to predict extremes and tends then to overestimate (for dry episodes) or underestimate (wet periods) flood peak water level. It presents better skill in capturing extreme events for shorter lead times. Moreover, the tool shows to better capture the flood peak water level than the flood peak timing.

2.2.3.2. SWIM

For the Niger case study, the eco-hydrological model SWIM (Soil and Water Integrated Model) was selected and tailored to reproduce past drought events with monthly bias corrected reanalysis climate datasets.

SWIM is a daily continuous-time, semi distributed catchment model for the coupled hydrological / vegetation / water quality modelling in mesoscale watersheds. The model is set-up and calibrated to represent region specific processes, stocks and fluxes by using regional ground-truth and remote sensing data. The model enables to consider various water storages and flow components such as soil moisture availability, surface, sub-surface and groundwater flows. It simulates crop and vegetation growth, nutrients dynamics (nitrogen and phosphorous), hydrological and erosion processes at the river basin scale.

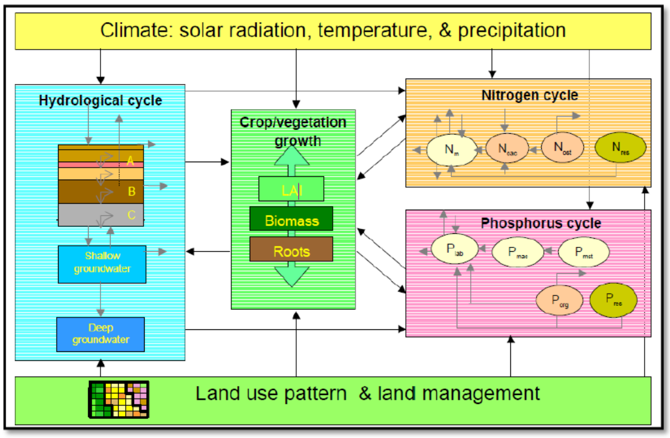

Figure 5. Simulation process diagram for the SWIM model.

Further developments integrate now reservoir management, wetlands and inundation plain dynamics to account for specific hydrological patterns encountered in the Niger case study. The advancements of the calibration and validation processes for two model setups were investigated: the first version called *Upper Niger model* and the second model set-up version called *Niger River model*. The model will be then employed to simulate short to mid-term hydrological forecast (through ECMWF and CCAM weather forecast products) and long term hydrological projections (through CCAM model, which is used to simulate long term climate projections) in order to assess drought persistence and risk under a range of upstream water resources management.

The results of the calibration and validation processes of the model SWIM present satisfactory results to further extend analyses of drought variability and impact in the Niger case study. The final objective of the study was to translate modelling results into explicit indices measuring the socioeconomic vulnerability and the potential adaptive capacities of specific water uses in the Inner Niger Delta. Current efforts to setup a model to analyse the entire Niger River are initiated and under process but the main interest for DEWFORA project remain to deliver appropriate answers at the local scale with a focus on the Inner Niger Delta actors.

It is important to highlight that in this study, many factors were not considered yet. For instance, the existing Talo dam, the Markala barrage, and the planned dam in Djenné at the River Bani were not yet included in the model. The impacts of the extension of irrigation areas in the Upper Niger catchment, which is expected to have impacts on the hydrology, still need to be integrated as well. Moreover, social and environmental consequences of the investigated adaptive measure, proposed by the stakeholder platform and Wetlands International, need to be now considered. There is a need for more detailed studies with specific focuses and for more process-based and integrated assessments of the highly complex socio-ecological system of the Inner Niger Delta and the Upper Niger Basin as a whole.

2.3. Agricultural drought forecasting

2.3.1. Limpopo

Under the scope of DEWFORA project, and regarding agricultural drought forecasting, statistical methods were applied in order to develop prediction models for seasonal crop yields, over Limpopo (southern Africa) and Oum-er-Rbia (Morocco) river basins, according to the Deliverable D4.10.

The crops of these two basins are strongly rain-fed. To develop the referred models it was assumed that the global model's output, previously used to predict rainfall over a certain area, can be used in a statistical forecast system to predict a rain-fed commodity such as crops. These models were tested over a 26-year period to determine their deterministic skill levels, as well as over a 16-year retro-active forecast period to test their probabilistic skill capabilities.

To post-process ECMWF S4 data to crop yields was used a method called model output statistics (MOS). The corresponding equations are based on the Principal Component Regression (PCR) option of the Climate Predictability Tool (CPT) of the International Research Institute for Climate and Society. Prior to the PCR application, yield values are transformed into approximate normal distributions, Figure 6.

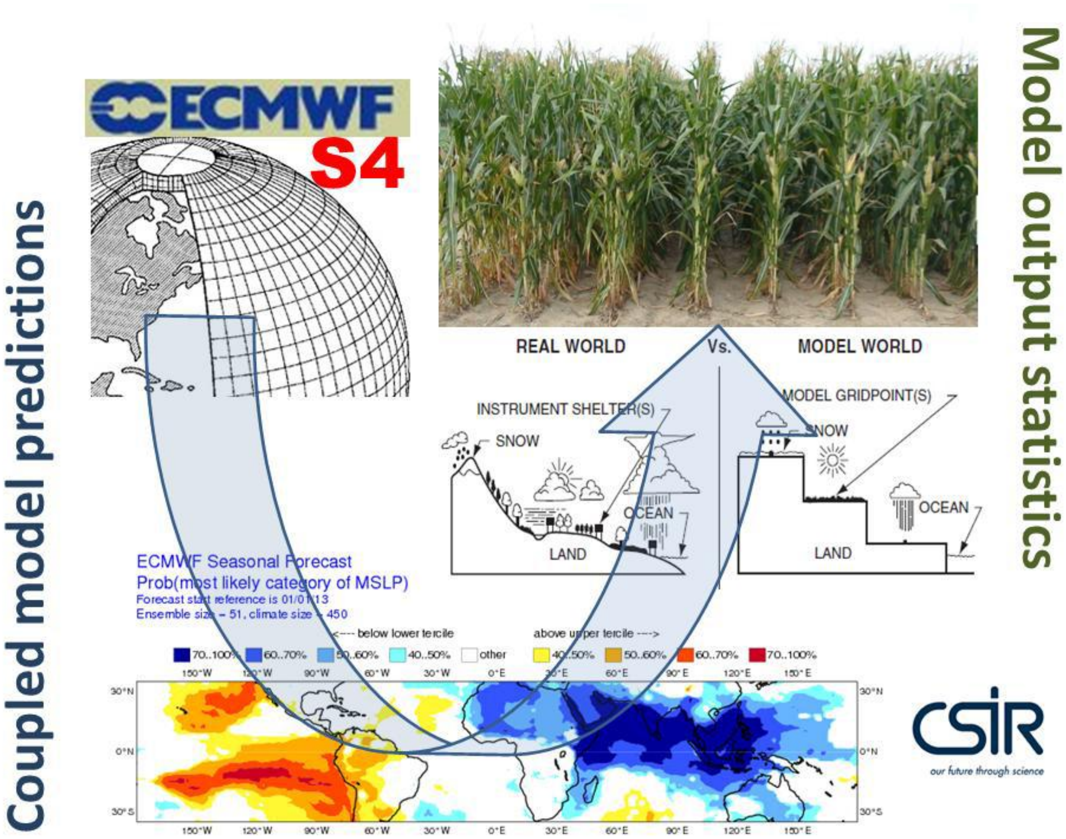

Figure 6. Schematic representation of the procedure to produce crop yield forecasts, based on the output generated by the ECMWF S4 coupled model.

The low-level circulation data for the three-month season prior to the period of harvesting is used, and it is assumed that the seasonal averaged low-level circulation is associated with the rainfall over the region of interest and hence related to the production of dry land crops.

In resume, the general procedure involves the prediction of seasonal circulation fields by the ECMWF S4 coupled model, which is subsequently used as predictors in a MOS system that has seasonal crop yields as the predictand. Regarding the verification, the MOS equations' ability to skilfully produce downscaled forecasts is tested both deterministically and probabilistically.

Regarding the data, the global model data sets used in the downscaling work are from the ECMWF System 4 (S4); and crop yield data for the Limpopo basin are yellow and white maize obtained from the South African National Department of Agriculture, Directorate: Statistics and Economic Analysis.

The work presented some deterministic (over 26 years) and probabilistic (over 16 years) skill estimates of statistical downscaling models for crop yields. Forecast lead-times of up to 4 months were considered and it was found that the low-level circulation data of the ECMWF S4 can be successfully downscaled statistically for certain dry-land crop production areas. The main conclusion of this work is that the ECMWF S4 global coupled model can potentially provide the required output for the commodity-orientated forecast system for application in agriculture, especially for dry land farmers.

2.3.2. Oum-er-Rbia

As referred in the previous topic, in order to develop prediction models for seasonal crop yields, the same methods were applied for both basins: Limpopo and Oum-er-rbia. In this context, the main characteristics of the method and the main conclusions correspond to those described above, and in this specific case: forecasts with lead-times of up to four months (but mainly up to two months) using ECMWF S4 hindcasts were analysed showing that low-level circulation data can be successfully downscaled for predicting durum wheat yield for the mountain and coastal areas, but very low predictability is seen over the plains of the basin.

3. Performance Assessment on Droughts Monitoring and Forecasting after DEWFORA project

Following the conclusion of DEWFORA's contribution for each case study and under the frame of the activities foreseen in T6.6 of WP6, a final Questionnaire (Questionnare 2) was sent to case study partners, envisaging the characterization of the main improvements (developed under the scope of DEWFORA project) in processes of drought monitoring and in DEWFORA case studies. The brief Questionnaire 2 focuses on the following topics:

Performance assessment of Drought monitoring: Compilation of the specific questions regarding the characterization of the improvements on monitoring and assessment processes.

Performance assessment of Drought forecasting: Compilation of the specific questions regarding the characterization of the improvements on forecasting processes.

Other comments: Identification of additional improvements achieved under DEWFORA and further developments that could be recommended for the future in the case study region.

The responses of each case study partner are presented in the following tables. The lack of response is indicates with "-", and "N/A" represents the following situations: the question is *not applicable* or the information is *not available*.

Performance assessment of Drought Monitoring

1. Drought monitoring indicator

a) Which improvements in drought monitoring evaluation were developed under the scope of DEWFORA project?	
Limpopo	Spatial improvement of drought monitoring using SPI
Niger	-
Eastern Nile	Preparing the input data of the case study (Blue Nile and Atbara) to be used with the SPI Indicator, and applying the SPI on the climate change different scenarios.
Oum-er-Rbia	No major achievements were realized during the scope of the Dewfora project. Efforts were focused on drought forecasting and drought vulnerability mapping.
b) Is there any additional index/indicator being used?	
Limpopo	Vegetation Condition Index and Normalised Difference Vegetation Index
Niger	The main indices used in DEWFORA project are: Meteorological indices - rainfall Anomaly Index, Standardized Precipitation Index; Hydrological indices - Discharge/ Water Level Anomaly Index, % from the flow/ water level duration curve, mean annual minimum flow/water level, Base flow/water level indices, Standardized Discharge/water level index; Agricultural indices - hydrological requisite and fodder production indices for the main vegetation formation
Eastern Nile	The drought classification of the Ministry of Water Resources and Irrigation (MWRI) of Egypt, Surface Water Supply Index (SWSI) and The Streamflow Drought Index (SDI)

Oum-er-Rbia	No.

Regarding drought monitoring, it is possible to verify that specific studies based on SPI were developed and additionally some new drought indices are being used (with exception of Oum-er-Rbia Case Study). In Limpopo case study, the indices presented are focused on agricultural component, in the Eastern Nile on hydrological component, and in Niger case study, indices for each category (meteorological, hydrological and agricultural) are presented. In the specific case of Niger case study it was referred that in Questionnaire 1 the indices mentioned represented a large literature and project application review, so, in this questionnaire, they presented the main indices used in DEWFORA project.

2. Impact of climate change

a) Is there any additional information regarding the impact of climate change, according to DEWFORA developments?	
Limpopo	-
Niger	For the Niger case study 20 different gridded datasets for past and present precipitation analysis were used. Considering climate change projections, 19 GCMs from the Coupled Model Intercomparison Project (CMIP) phase 5, 5 bias corrected ESMs from the Inter-Sectoral Impact Model Intercomparison Project as well as first RCMs results delivered by the COordinated Regional climate Downscaling EXperiment (CORDEX) were the object of investigation. The 5 ESMs from the Inter-Sectoral Impact Model Intercomparison Project were also used with SWIM model application to compare the hydrological impact of climate change and variability to upstream river management planning.
Eastern Nile	The SPI has been a very sufficient way to characterize meteorological drought across different catchments and at different time scales for the different climate change scenarios. It normalizes the rainfall distribution and it is less sensitive to systematic biases in the data.
Oum-er-Rbia	No
b) What regions are more vulnerable?	
Limpopo	**-**
Niger	The most vulnerable regions in the Upper Niger Basin are mainly located in the Sahelian fringe of the River Basin (Mali, Niger).
Eastern Nile	Atbara region is more vulnerable than the Blue Nile region.
Oum-er-Rbia	N/A

The main developments on the study of climate change impacts were provided to Niger and Eastern Nile case studies. In fact, these two case studies were selected to assess whether and how climate change impacts on the effectiveness of the supportive framework for drought early warning, for example identifying which are the more vulnerable regions and recommend adaptation measures.

3. Risk/Vulnerability mapping

a) Is there any additional risk mapping developed under the scope of DEWFORA?	
Limpopo	-
Niger	In the frame of DEWFORA, a large work to associate flood pattern to vegetation formation was initiated. The associated indices of fodder production given for each vegetation formation can support further regional vulnerability assessment of the livestock sector.
Eastern Nile	No
Oum-er-Rbia	A drought vulnerability map at the rural commune level was developed. It is based on a composite drought vulnerability index integrating 4 different components: (i) the renewable natural capacity, (ii) the economic capacity, (iii) human and civic resources, and (iv) infrastructure and technology. This map represents the first drought vulnerability map at the commune level ever realized at the basin level or even at the country level and represents therefore a major achievement.
b) If yes, how useful are they?	
Limpopo	-
Niger	-
Eastern Nile	N/A
Oum-er-Rbia	In Morocco, 50% of the population lives in rural areas and they are mostly small subsistent farmers whose production remains almost entirely on rainfall. They are therefore very sensitive to drought episodes that may dramatically affect their incomes. Drought vulnerability assessment and mapping at the rural community level represents therefore for decision makers a decision tools allowing to develop efficient mitigation actions, tailored to the needs and specificities of each rural community.
c) What regions are more vulnerable?	
Limpopo	-
Niger	-
Eastern Nile	N/A
Oum-er-Rbia	The drought vulnerability map that were derived from the computation of the DVI shows that except the provinces of Azilal, Khenifra, Settat and El Kelaa, most of the other parts of the Oum er Rbia basin are highly vulnerable to drought.

Regarding the vulnerability assessment, the main developments were observed in Oum-er-Rbia case study. For Niger case study it was referred in Questionnaire 1 that there are two types of maps: global risk maps provided by several global drought early warning systems that provide alerts for governmental and NGO's decision level, but are not sufficiently detailed to support local stakeholders decision making; and, local drought risk maps developed by local communities, but only in the frame of specific projects, and not regularly, reason why they are not useful for stakeholders needs. On this questionnaire it is possible to verify that some improvements were initiated for this case study, based on the livestock sector.

Performance assessment of Drought Forecasting

1- Meteorological drought forecasting

a) What are the main improvements regarding meteorological drought forecasting, attending to the characteristics detailed on *Questionnaire 1*?	
Limpopo	Better spatial precision on SPI maps helps as a decision making tool.
Niger	The ECMWF seasonal forecast (System 4) was used with SWIM model to test an experimental hydrological drought forecast.
Eastern Nile	The ECMWF meteorological seasonal forecast data has been applied through the Nile Forecasting System (NFS) for drought forecasting.
Oum-er-Rbia	**(i) Medium range forecasts of precipitations**: the objective was to assess the skills of medium range weather forecasts and their potential use for the planning of the sowing period, the scheduling of large scale irrigation, the management of intra-annual dry-spell episodes. This was achieved by comparing daily recorded rainfall data from 4 meteorological stations of the basin to precipitation data from the ECMWF ensemble prediction system with 15 days lead time. **(ii) Seasonal forecast of the standardised precipitation index**: forecasted SPI were developed by ECMWF partners in WP4 using ERAI and GPCC. Unfortunately, the skill of these seasonal forecasts of SPI was not assessed.
b) Are there some additional improvements that should be recommended on meteorological drought forecasting?	
Limpopo	The use of remote sensing could be useful as the rainfall stations are declining. Rapidly and also topographical attributes with soil conditions
Niger	The ECMWF seasonal forecast (System 4) has still some difficulties to capture and represent well the effects of the West African Monsoon causing some detrimental bias in the forecast of the rainfall.
Eastern Nile	Correct the forecasted rainfall using a semi observed data.
Oum-er-Rbia	Seasonal forecasts of the SPI could be a very useful tool for providing seasonal outlooks of crop production. The preliminary work achieved by ECMWF partners should be completed by the assessment of the skills of these forecasts.

Regarding meteorological drought forecasting, it is possible to observe different developments for all case studies and they included the improvement of SPI precision, the use of new meteorological seasonal forecasting data and medium range and seasonal forecasting studies.

2- Hydrological drought forecasting

a) What are the main improvements regarding the hydrological drought forecasting, attending to the characteristics detailed on *Questionnaire 1*?	
Limpopo	**(i)** It was conducted a statistical analysis of the complex relationship of drought in the Limpopo basin with climate anomalies, for example El-Nino. **(ii)** A downscaled and adapted version of the "PCR-GLOBWB-Africa" model was developed for the seasonal prediction of hydrological droughts for the semi-arid Limpopo river basin. **(iii)** In order to provide the necessary information for decision makers regarding seasonal hydrological forecast for the Limpopo river basin, two different approaches for

	hydrological drought forecasting was presented namely: a statistical seasonal forecast, and a dynamic multi ensemble seasonal forecast.
Niger	The investigations encompass two modeling applications: **(i)** SWIM, a comprehensive GIS-based tool for hydrological and water quality modeling in mesoscale watersheds and **(ii)** OPIDIN a peak and flood propagation statistical prediction model. In SWIM, the improvements come from the calibration of the whole Niger river basin and the integration of climate change projections and seasonal forecast products with more detailed upstream river management including dams and water transfer into irrigation schemes. Also, DEWFORA project supported drought vulnerability assessment of different economic sectors at the scale of the Inner Niger Delta by improving the refinement of the simulated flood propagation in the flood plains and by associating flood characteristics to the development and constraints of different economic sectors. In OPIDIN, the statistical prediction tool was extended to 9 gauging stations. The statistical regressions integrate now the effects of the Sélingué dam. The skill assessment of the forecast tool was deepened and a confidence interval was created. Finally, a large work was launched to convert forecast information into a meaningful application for stakeholders with the publication of an inundation atlas, weekly bulletin and a web platform all disseminated with the support of the OPIDIN stakeholder platform.
Eastern Nile	Appling hydrological drought indicators on the flow forecasted by ESP, the results show that SWSI cannot be used with data time series less than 30 years. Using the rainfall and PET elements from ECMWF to forecast the flow for seven months ahead.
Oum-er-Rbia	No
b) Are there some additional improvements that should be recommended on hydrological drought forecasting?	
Limpopo	-
Niger	Still some efforts can be done to better formalize the interactions between the flood propagation dynamics, the food security and the biodiversity maintenance in the Inner Niger Delta. The application of ECMWF forecast with SWIM can be also further improved using a calibration based on ERA Interim or Watch Forcing Data ERA Interim products instead of Watch Forcing Data ERA40 in order to avoid some detrimental jump in climate time series.
Eastern Nile	Correct the PET elements using a semi observed data (cru data).
Oum-er-Rbia	It seems that that the work done on the seasonal forecasts for the prediction of cereal yields could be repeated with river inflows in order to predict hydrological drought. This may represent a way of improving hydrological drought forecasting in the basin.

Different improvements on hydrological drought forecasting were provided for all cases studied and are focused on the development of downscaled models adapted to the basin level, improvements on some models already in use, and various studies based on statistical or dynamic multi ensemble seasonal forecasting.

3- Agricultural drought forecasting

a) What are the main improvements regarding the agricultural drought forecasting, attending to the characteristics detailed on *Questionnaire 1*?	
Limpopo	Statistical methods were applied in order to develop prediction models for seasonal

	crop yields
Niger	N/A
Eastern Nile	No
Oum-er-Rbia	Seasonal forecasts were used to predict cereal yields. This statistical-dynamical approach represents more a new approach for forecasting agricultural drought impacts rather than the agricultural drought phenomena in itself. The main assumption was that if a global model is able to represent seasonal rainfall, the same model output can be used in a statistical forecast system to predict rain fed commodities such crops.
b) Are there some additional improvements that should be recommended on agricultural drought forecasting?	
Limpopo	-
Niger	N/A
Eastern Nile	No
Oum-er-Rbia	Not foreseen at the moment since the previous point is in fact more related to meteorological drought forecasts than agricultural drought forecasts.

Agricultural drought forecasting improvement was focused on Limpopo and Oum-er-Rbia case studied as established in the main objectives of DEWFORA project. In both cases, statistical methods were applied in order to develop prediction models for seasonal crop yields. This was based on the assumption that the outputs of the models (used to predict rainfall) can be used also to predict a rain-fed commodity.

Other comments

a) Besides the above detailed topics, how do you describe DEWFORA's contribution to the improvement of Drought capabilities in your region?	
Limpopo	-
Niger	The originality of DEWFORA project was to investigate with different modeling application and products regional drought hazard using different scope. Seasonal meteorological forecast, past climate products and climate change projections were analyzed. SWIM was used to assess climate change and variability impact under upstream water resources management in the Inner Niger Delta and an experimental coupling with ECMWF seasonal forecast product was tested. Finally, the improvements of OPIDIN tool allow generating tailored information for stakeholder using the specific characteristics of the Inner Niger Delta case study.
Eastern Nile	Under the DEWFORA project new techniques have been improved to evaluate drought forecasting.
Oum-er-Rbia	The studies were focused mainly on drought forecasting and vulnerability mapping and represent a very important improvement. Indeed, the forecasts of forthcoming drought periods during the growing season may help to issue drought early warnings and trigger mitigations actions such as the implementation of supplementary irrigation (in case of dry spells during the season).
b) What additional improvements can you suggest for the future?	
Limpopo	-

Niger	The suggested improvements would be to better associate the different applications to support implemented stakeholder and early warning platform. ECMWF seasonal forecast could supply OPIDIN with local rainfall forecast which would further complete flood forecast information. When satisfactory results of the coupling between SWIM and ECMWF forecast are delivered, OPIDIN can use this information incorporating seasonal climate variability and upstream management planning.
Eastern Nile	- Using other indices for more evaluation of the different tools of drought forecasting. - Study the impact of climate change by using new emission scenarios.
Oum-er-Rbia	The used methodology to assess drought vulnerability represents a good approach for drought vulnerability assessment. Nevertheless, it can and should be improved by: drought vulnerability validation, the choice of more pertinent and appropriate indicators, the integration of other indicators and qualitative studies. The medium range forecasts of precipitation failed to forecast the occurrence of the rain. Thus, Oum-er-Rbia case study partners suggest ways of improving the skills of these forecasts especially regarding drought onset, frequency and intensity that would allow farmers to make better choices. Moreover, for an actual increasing of both rainfed and irrigated farming resilience, the integration of seasonal forecast appears to be essential. Such scale of forecast may allow: a better planification of irrigation water allocation and scheduling; governments and relief agencies to position themselves for more effective and cost-efficient drought interventions; producers to more accurately evaluate their production options and insurance their payment rat and herders could better sale their livestock.

According to the responses collected through the Questionnaire 2 it was verified that DEWFORA project provided different improvements on drought management, namely regarding vulnerability assessment and drought monitoring and forecasting. In each case study, these improvements can contribute to the drought early warnings and the definition of adaptation and mitigation measures. All the efforts/studies contribute to reduce vulnerability and strengthen preparedness to droughts in Africa, and the responses of case study partners regarding the DEWFORA contribution to the improvement of drought capabilities seems to be positive.

4. Main findings and conclusions

Drought is one of the greatest natural hazards which affect many sectors and systems with major impacts on agriculture, water resources and natural ecosystems. These impacts depend on the duration, severity and spatial extent of the precipitation deficit. Drought conditions are much more difficult to identify than other natural hazards because drought is commonly the result of a number of factors that are only apparent after a long period of precipitation deficit. In this context the improvement of drought forecasting tools are essential to prevent its effects.

On DEWFORA project one of the main objectives was to prototype operational forecasting by bringing advances through the development of prototype systems and piloting methods in operational drought monitoring and forecasting agencies. To fulfil this objective various studies were performed aiming to test the available tools and provide improved ones for forecasting droughts and hence water availability in different regions, correspondent to each case study: Eastern Nile, Limpopo, Niger and Oum-er-rbia.

The main improvements focused on meteorological, hydrological and agricultural drought forecasting. On **Eastern Nile case study** statistical seasonal forecasting (e.g. based on ENSO) were conducted in the Blue Nile and Atbara Basins. A new system was obtained, combining globally available precipitation monitoring products, with seasonal forecasts. This last study was applied to all the case studies. On hydrological forecasting it was used methods to produce a seasonal drought warning, applying indices to observed as well as simulated and forecasted flows using the Nile Forecast System (NFS) hydrological and forecasting components. On **Limpopo case study** a downscaled version of the hydrological "PCR-GLOBWB-Africa" model was set up for this specific basin. At the same topic (hydrological forecasting) statistical and dynamic seasonal forecasting were conducted. Regarding agricultural forecasting, on Limpopo and Oum-er-rbia case studies statistical-dynamical approach was applied in order to develop prediction models for seasonal estimate crop yields. On **Niger case study** the OPIDIN tool was continuously improved and developed; and the eco-hydrological model SWIM (Soil and Water Integrated Model) was selected and tailored to reproduce past drought events with monthly bias corrected reanalysis climate datasets. On **Oum-er-rbia case study** the main improvements focused on meteorological and agricultural drought as referred above. Nonetheless, more detailed information which results from DEWFORA project is presented in deliverable D6.2, specifically for each case study.

Despite the new approaches and the improvements proposed in DEWFORA projects, a continuous work will be crucial to increase knowledge in this issue and the consequent drought preparedness and adaptation that will contribute to increased resilience and improved effectiveness of drought mitigation measures. In many cases it was verified that due to the low forecasting performance some approaches presented can only serve well for specialists and technical, and are not suited for operational early warning. For this reason, more work/research must be performed in order to provided more reliable information and with an appropriate format to better understanding of the population in general.

On Oum-er-rbia, e.g., regarding agricultural forecasting, a potential for making yield predictions over the mountains and over the coastal areas was detected using both deterministic and stochastic approaches. Particularly, with a two months lead-time, high and low yield are well discriminated for both areas. On the other hand a very low predictability was identified over the plains of the basin. This is another example to prove that the increased knowledge shouldn't stop. In fact, the continuity of this work is fundamental to reduce vulnerability and strengthen preparedness to droughts in Africa. At this stage and taking into account the responses of case study partners to the Questionnaire 2, the DEWFORA contribution was positive/ useful to the improvement of drought capabilities in different regions and a good incentive to better prepare African countries to drought impacts.

5. References

Eltahir, E.A.B., 1996. El Niño and the natural variability in the flow of the Nile River. Water Resources Research, 32(1): 131-137.

Mckee, T. B., N. J. Doesken, and J. Kleist, 1993: The relationship of drought frequency and duration to time scales. Eight Conference on Applied Climatology.

Molteni, F., and Coauthors, 2011: The new ECMWF seasonal forecast system (System 4), ECMWF Tech. Memo., 656, 49 pp.

Reynolds, R.W. et al., 2007. Daily high-resolution-blended analyses for sea surface temperature.

Wang, G. and Eltahir, E.A.B., 1999. Use of ENSO information in medium-and long-range forecasting of the Nile floods. Journal of Climate, 12(6): 1726-1737.

(Trenberth, 1997).