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A review of continental scale hydrological models and their suitability for drought forecasting in (sub-Saharan) Africa

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ABSTRACT

The aim of this review is to provide a basis for selecting a suitable hydrological model, or combination of models, for hydrological drought forecasting in Africa at different temporal and spatial scales; for example short and medium range (1–10 days or monthly) forecasts at medium to large river basin scales or seasonal forecasts at the Pan-African scale. Several global hydrological models are currently available with different levels of complexity and data requirements. However, most of these models are likely to fail to properly represent the water balance components that are particularly relevant in arid and semi-arid basins in sub-Saharan Africa. This review critically looks at weaknesses and strengths in the representation of different hydrological processes and fluxes of each model. The major criteria used for assessing the suitability of the models are (1) the representation of the processes that are most relevant for simulating drought conditions, such as interception, evaporation, surface water-groundwater interactions in wetland areas and flood plains and soil moisture dynamics; (2) the capability of the model to be downscaled from a continental scale to a large river basin scale model; and (3) the applicability of the model to be used operationally for drought early warning, given the data availability of the region. This review provides a framework for selecting models for hydrological drought forecasting, conditional on spatial scale, data availability and end-user forecast requirements. Among 16 well known hydrological and land surface models selected for this review, PCR-GLOBWB, GWAVA, HTESSEL, LISFLOOD and SWAT show higher potential and suitability for hydrological drought forecasting in Africa based on the criteria used in this evaluation.

1. Introduction

According to the American Meteorological Society (1997), droughts originate from a deficiency of precipitation resulting in water shortage for some activity or for some group, and its severity may be aggravated by other meteorological elements. They state that drought is a normal, recurring feature of climate, and that it occurs in virtually all climatic regimes. While aridity is a permanent feature of a regional climate, drought is a temporary aberration. Drought should be considered relative to some long-term average condition of balance between precipitation and evaporation in a particular area, a condition often perceived as "normal" (AMS, 1997; Peters, 2003).

Droughts are often grouped into four types: meteorological, agricultural, hydrological, and socio-economic (AMS, 1997; Tallaksen and Van Lanen, 2004; Mishra and Singh, 2010). Meteorological drought is defined by AMS (1997) as a lack of precipitation over a region for a period of time. They indicate that agricultural drought links the various characteristics of meteorological drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evaporation and soil–water deficits that can lead to crop failure. Hydrological droughts are concerned with the effects of periods of precipitation shortfall on surface or subsurface discharges and water resources, rather than with precipitation shortfalls directly. Hydrological droughts are typically out of phase, lagging behind the occurrence of meteorological and agricultural droughts (AMS, 1997). They also have a much larger inertia than meteorological drought, which can basically end overnight. Socio-economic drought associates the supply and demand of some economic good with elements of meteorological, agricultural, and hydrological drought (AMS, 1997). Mishra and Singh (2010) suggest the introduction of groundwater drought as a type of drought, which has hitherto not been included in the classification of droughts. They state that a groundwater drought occurs when first groundwater recharge and later groundwater levels and groundwater discharges decrease significantly. Only major meteorological droughts will result in groundwater

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droughts and the lag between them can be of months or even years, much larger than the lag between meteorological and streamflow droughts (Tallaksen and Van Lanen, 2004). The spatial scale of groundwater droughts can be very variable depending on the aquifer size, recharge and discharge locations, etc. Peters (2003) concludes from her study in groundwater droughts that while short droughts will generally be more severe near the streams and dampened further away, long periods of below average recharge will have more effect near the groundwater divide.

Droughts differ in three essential characteristics – intensity, duration, and spatial coverage – and are among the most complex and least understood of all natural hazards, affecting more people than any other hazard (AMS, 1997). Africa has been severely affected in the past by intense droughts resulting in the death of hundreds of thousands of people and contributing to food insecure conditions in several African countries. In fact, a recent severe drought in 2011 (1:60 years drought) affected millions of people in the Horn of Africa. Several studies have been carried out with a view to understanding the causes of these droughts, especially in the Sahel region (Giannini et al., 2003; Zeng, 2003; Shanahan et al., 2009; Williams and Funk, 2011). Some authors claim that the intensity and severity of droughts in Africa are increasing, and attribute the cause to anthropogenic factors that lead to reduced precipitation, such as greenhouse gas and aerosols emissions (Ramanathan et al., 2001; Williams and Funk, 2011). Others claim that intervals of severe droughts lasting for decades to centuries are characteristics of the monsoon and are linked to natural variations in Atlantic temperatures (Shanahan et al., 2009). Thus, the severe droughts in recent decades are not anomalous in the context of the past three millennia, indicating that the monsoon is capable of longer and more severe future droughts (Shanahan et al., 2009).

For the purpose of forecasting hydrological droughts in Africa, a hydrological model should be chosen that can simulate continental hydrology, but ensuring that the hydrological processes that are important to assess droughts are considered. Various hydrological models exist at different spatial and temporal scales with diverse levels of complexity and data requirements. At the global scale a distinction can be made between Land Surface Models (LSMs) and Global Hydrological Models (GHMs). Whereas the LSMs describe the vertical exchange of heat and water, the GHMs are more focused on water resources and lateral transfer of water (Haddeland et al., 2011). By comparing simulation results of six LSMs and five GHMs in a consistent way, Haddeland et al. (2011) found that the models do not succeed in representing the water balance components in arid and semi-arid basins. Similar results were also found in other models that were not included in this comparison (Milly and Shmakin, 2002). Therefore, the selection of a suitable hydrological model, or a combination of models, for a given objective (e.g. drought forecasting in Africa) should be carried out by assessing various models using set criteria. Drought forecasting is aimed both at the continental scale and at the river basin or regional scale. Moreover, the forecasting is intended for different temporal scales: medium-range (weekly), monthly-range (1 month) and long seasonal range (up to six months). The aim of this review is to provide a framework for selecting models for drought forecasting, conditional on spatial scale, data availability and end-user forecasting requirements.

2. Development of the model selection framework

Five selection criteria were set for assessing the suitability of the process driven hydrological models for drought forecasting at a continental scale in Africa. The criteria are described below. These are listed in the order of importance considered in this evaluation.

2.1. Represented processes and fluxes

First, the strengths and weaknesses in the representation of different hydrological processes and fluxes of the global hydrological models in question should be assessed. Ideally, a complete hydrological model would represent the following water balance components and fluxes: gross precipitation (snow, rain), interception storage, evaporation, throughfall, transpiration, snow pack storage, snowmelt, surface storage (microdepressions, lake and reservoir storage), overland flow, soil storage, recharge to shallow aquifer, capillary rise, intermediate flow, baseflow, leakage to deep aquifer, deep aquifer storage, streamflow, groundwater flow. However, there should be a compromise between model complexity and efficiency. It is important to consider the purpose of the modelling and bear in mind that a more complex model will not necessarily lead to better results. For example in drought forecasting, including the complexity of snow–water–ice dynamics will most surely not lead to better results. Representation of groundwater may, however, be of great importance.

2.2. Model applicability to African climatic conditions and physiographic settings

Very much linked to the previous criterion, the processes that are most relevant for simulating drought conditions in African climatic conditions and physiographic settings need to be represented. This means that processes usually considered, such as interception, evaporation, surface water-groundwater interaction and soil moisture should be included in the model while others such as glacial representation or overland fast flow are of less importance. Moreover, some extra processes or fluxes that are in general not included in the modelling framework due to its high complexity or because they are not considered important in average conditions in some regions such as channel losses, evaporation from rivers, wetlands representations, are key components for simulating droughts in specific African climatic conditions and physiographic settings.

2.3. Data requirements and resolution of the model (spatial and temporal resolution)

The first two criteria deal with the evaluation of the represented processes and fluxes of the models. However, including all the processes mentioned may not result in a better performance of the model if the necessary data are not available. Input data can be scarce in some regions of Africa and therefore there should be a trade-off between the data availability and process representation for drought forecasting. Some models can be very detailed and complex. However, if the necessary input data are not available then the model cannot be run in practice and extra efforts should be made to estimate the input data. This could result in a performance that is worse than that of a simpler model. For example, a detailed representation of groundwater flows and tables would be very relevant for drought forecasting in some regions of Africa, but the lack of information on the hydrogeology and groundwater tables in these regions makes this detail representation pointless, and a simpler representation is preferred. With regards to the choice of the model grid size, there is a compromise between that need to represent spatial variability and the availability of suitable data (CEH, 2011). Most of the input data for a continental model are at a very coarse scale, and downscaling the input data to finer scales to run the model in a fine grid size leads to extra work and may not result in a higher performance. The same may be the case with the temporal resolution. Some models may have an hourly temporal resolution, but if the input meteorological data is available only at a daily resolution for example, then the use of