DEWFORA

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

DEWFORA

A 7th Framework Programme Collaborative Research Project

Available continental scale hydrological models and their suitability for Africa

WP4-D4.5

August 2011

Coordinator:	Deltares, The Netherlands
Project website:	www.dewfora.net
FP7 Call	ENV-2010-1.3.3.1
Contract no.	265454

COOPERATION

Page intentionally left blank

DOCUMENT INFORMATION

Title	Available continental scale hydrological models and their suitability for Africa
Lead Author	UNESCO-IHE
Contributors	DELTARES, ECMWF
Distribution	<Please select one of three below> PU: Public
Reference	WP4-D4.5

DOCUMENT HISTORY

Date	Revision	Prepared by	Organisation	Approved by	Notes
15-08-2011	1	Trambauer	UNESCO-IHE	Werner	

ACKNOWLEDGEMENT

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement N°265454

Page intentionally left blank

SUMMARY

This report provides a basis for selecting a suitable hydrological model, or combination of models, for drought forecasting in Africa at different temporal and spatial scales, for example weekly forecasts at the resolution at the basin scale or seasonal forecasts at the Pan-African scale. Several global hydrological models are currently available with different levels of complexity and data requirements. However, not all of these models sufficiently represent all the water balance components that are particularly relevant in arid and semi-arid basins in sub-Saharan Africa. The review in this report 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 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 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. Among the sixteen 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.

Page intentionally left blank

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AMS:	American Meteorological Society
AW:	Available Water
CEH:	Centre for Ecology and Hydrology
CV:	Coefficient of Variation
G&A:	Green & Ampt infiltration method
GCM:	General Circulation Model
GHM:	Global Hydrological Model
GRDC:	Global Runoff Data Centre
GW:	Groundwater
GWAVA:	Global Water Availability Assessment method
HTESSEL:	Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land
KWA:	Kinematic Wave Approximation
LaD:	Land Dynamics model
LAI:	Leaf Area Index
LPJ:	Lund-Postdam-Jena model
LSM:	Land Surface Model
Mac-PDM:	Macro-scale-Probability-Distributed Moisture model
MARSIRO:	Minimal Advanced treatments of Surface Interaction and Runoff
MODIS:	Moderate Resolution Imaging Spectroradiometer
P-M:	Penman Monteith
P-T:	Priestley-Tailor
Sat Ex:	Saturation Excess
SCS:	Soil Conservation Service
SMAPI:	Soil Moisture Anomaly Percentage Index
SVE:	Saint-Venant Equation
SWAT:	Soil and Water Assessment Tool
VIC:	Variable Infiltration Capacity
VSC:	Variable Storage Coefficient method
WBM:	Water Balance Model

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. Drought is a normal, recurring feature of climate and 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).

Droughts are often grouped into four types: meteorological, agricultural, hydrological, and socio-economic (AMS, 1997, Mishra and Singh, 2010). Meteorological drought is defined as a lack of precipitation over a region for a period of time. 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. 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 to introduce groundwater drought as a type of drought, which has 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.

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, an ongoing (in the time of writing) severe drought (one in a sixty years drought) is affecting 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, Shanahan et al., 2009, Williams and Funk, 2011, Zeng, 2003). Some authors claim that the intensity and severity of droughts in Africa are increasing, and attribute the cause to anthropogenic factors which 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 characteristic of the monsoon and are linked to natural variations in Atlantic temperatures. 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).

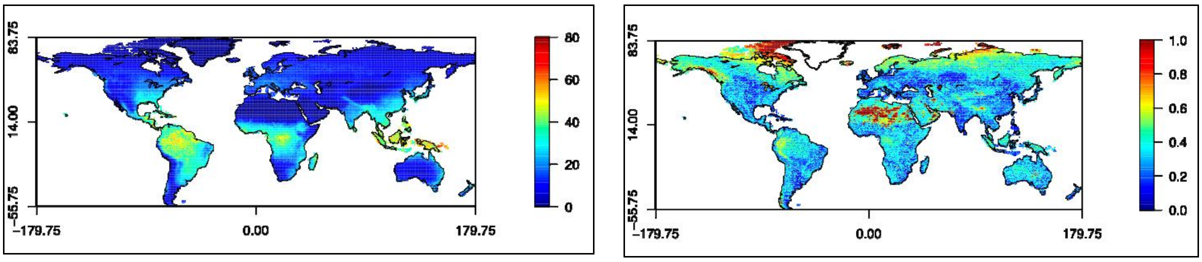
Forecasting of drought assists in mitigating the effects of droughts by warning the jeopardized population about the expected occurrence, severity and duration of the drought. With an early warning, the community can prepare and therefore have a better response and implement mitigation actions. With a view to forecasting hydrological droughts in Africa, a hydrological model should be chosen that can simulate the continental hydrology, but especially ensuring that the hydrological processes that are important to assess droughts are considered. The forecasted meteorology is considered to be an input of the model.

Hydrological models have become a widely used tool for representing hydrological processes and fluxes. 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 the Land Surface Models (LSMs) and the 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).

Haddeland et al. (2011) compared the simulation results of six LSMs and five GHMs in a consistent way in the scope of the EU-WATCH[1] project. They performed a quantitative comparison of the models, which were run for a baseline of 30 years and for two contrasting forecasted scenarios. They found that the models do not succeed in representing the water balance components in arid and semi-arid basins. The coefficient of variation (CV) of the global evaporation and runoff, respectively, can be observed in Figures 1b and 2b. It is clear that the largest CV's are located in arid and semi-arid areas, which are presented in Figure 3 for comparison. In Figures 1a and 2a, the average evaporation and runoff of the different models are presented, respectively.

---

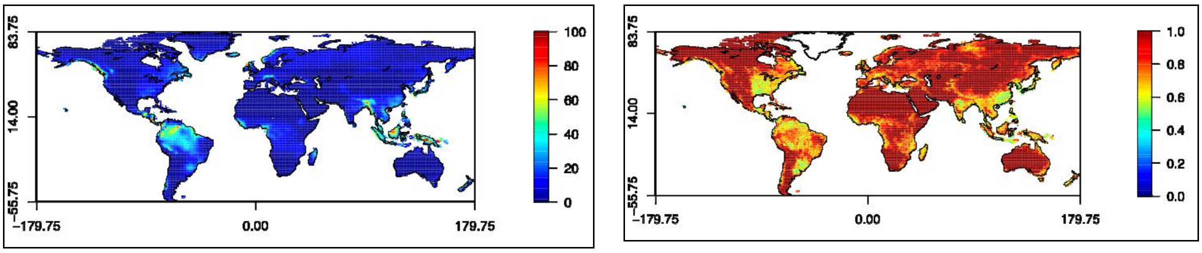
[1] Water and Global Change, funded under the EU FP6 programme



a) Average of models

b) Coefficient of variation

Figure 1 Simulated evaporation with the 11 models (Ludwig et al. (2009))



c) Average of models

d) Coefficient of variation

Figure 2 Simulated runoff with the 11 models (Ludwig et al. (2009))

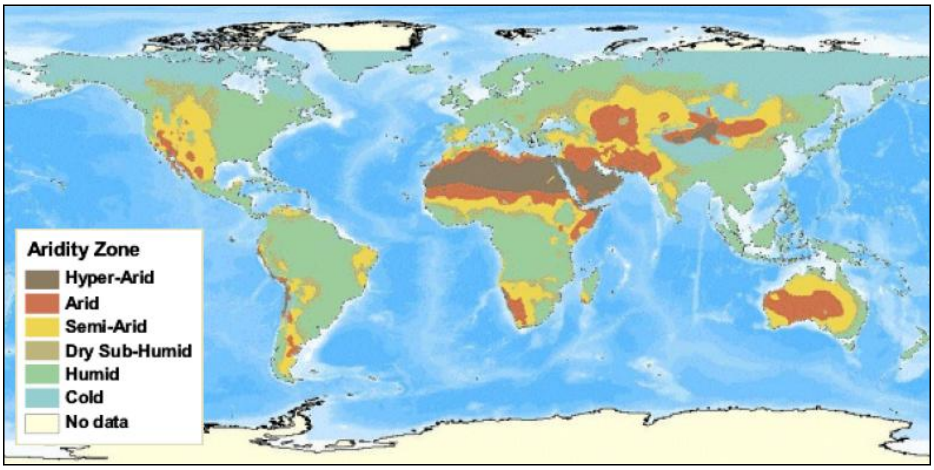


Figure 3 Aridity zones of the world (WRI, 2002)

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 a set of criteria. Drought forecasting as it is considered here 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 report is to provide a framework for selecting models for drought forecasting, conditional on spatial scale, data availability and end-user forecasting requirements.

With this purpose, a variety of global hydrological models available were studied and a brief description of these is given in section 2. In section 3 the criteria to assess the suitability of the models for drought forecasting are defined, and section 4 presents the results of assessing the selected models with the defined criteria. Finally, some conclusions and final remarks are presented.

2. DESCRIPTION OF THE REVIEWED MODELS

From the numerous available hydrological models, a first selection of models was prepared to include in this review. Hydrological models can be classified using different criteria, such as (Melone et al., 2005): (i) according to the nature of basic algorithms (empirical, conceptual or process-based), (ii) whether a stochastic or deterministic approach is taken to input or parameter specification, (iii) whether the spatial representation is lumped or (semi-) distributed, and (iv) according to the process modelled (event-driven models, continuous-process models, or models capable of simulating both short-term events and continuous simulations).

For the particular purpose of this study, a combination of conceptual and process-based (semi-)distributed hydrological models with deterministic inputs that represent continuous-process models are evaluated. The hydrological models should be suitable to evaluate the spatial and temporal occurrence of droughts based on a defined indicator. Continental and river basin-scale approaches need to be studied, and, as a result, the global macroscale model should be such that it can be downscaled to a river basin scale. Sixteen different models which are widely used or are reported to be used in important applications are chosen and a brief description of each is presented in sections 2.1 and 2.2.

The macroscale models considered include five LSMs: Variable Infiltration Capacity (VIC, Liang, et al. (1994)), Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO, Takata, et al.(2003)), Land Dynamics Model (LaD, Milly and Shmakin (2002)), ORCHIDEE (Ngo-Duc et al., 2005) and Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land (HTESSEL, Balsamo et al. (2009)); and eleven GHMs (or large scale hydrological models in some cases): WaterGAP (Döll et al., 2003), PCR-GLOBWB (van Beek and Bierkens, 2009), Macro-scale-Probability-Distributed Moisture Model (Mac-PDM, Gosling and Arnell (2010)), Water Balance Model (WBM, Vörösmarty, et al. (1989)), Lund-Postdam-Jena model (LPJ, Gerten, et al.(2004)), Soil and Water Assessment tool (SWAT, Schuol and Abbaspour (2006)), SWIM (Krysanova et al., 1998), HBV (Lindström et al., 1997), Global Water Availability Assessment method (GWAVA, Meigh, et al.(1999)), WASMOD-M (Widén-Nilsson et al., 2007) and LISFLOOD (De Roo et al., 2000, JRC, 2011) (see Table 1).

Table 1 Macroscale models considered in this review

LSM	GHM
VIC	WaterGAP
MATSIRO	PCR-GLOBWB
LaD	Mac-PDM
ORCHIDEE	WBM
HTESSEL	LPJ
	SWAT

LSM	GHM
	SWIM
	HBV
	GWAVA
	WASMOD-M
	LISFLOOD

2.1 LAND SURFACE MODELS

VIC is a hybrid of physically based and conceptual components. It uses physically based formulations for the calculation of the sensible and latent heat fluxes, but uses a conceptual baseflow model to simulate runoff generation from the deepest soil layer, and a conceptual scheme to represent the spatial variability in infiltration capacity and hence production of runoff (Nijssen et al., 2001a). It runs at a daily time step and is a gridded model with a spatial resolution from 2˚x 2˚ up to 1/16˚ x 1/16˚, but generally applied at a 0.5˚ x 0.5˚ resolution in the global scale, and it allows for subdivision of the grid cells into a number of elevation bands permitting sub-grid variability in both precipitation and temperature (Nijssen et al., 2001b). The model partitions the grid cell into multiple land surface cover types, where for each land cover type the fraction of roots in the upper and lower zone is specified. The soil is represented with two or three layers. The meteorological inputs for the model are daily precipitation and temperature. The less well-known variables (vapour pressure, incoming shortwave radiation, and long-wave radiation) are calculated as a function of daily precipitation and daily minimum and maximum temperature (Nijssen et al., 2001b).Total evaporation consists of three components; canopy evaporation, evaporation from bare soils, and transpiration (Liang et al., 1994). Total daily runoff and evaporation are simulated for each grid cell independently. The runoff from each of the individual cells is then combined using a routing scheme (only for the stream), to produce daily and then accumulated monthly flows at selected calibration points. The routing model allows for the explicit representation of reservoirs. This modelling approach has three elements: snow, land surface hydrology and routing models (Nijssen et al., 1997). Nijssen et al. (1997) applied the model in two large basins in USA. Difficulties in reproducing observed stream flow in the arid basins were attributed to groundwater-surface water interactions which are not modelled by VIC (it does not include a mechanism to account for deep groundwater recharge and drainage to streams). The model does not have an explicit mechanism to produce infiltration excess flow and it does not represent capillary rise in the soil zone. Moreover, the processes responsible for channel losses are not represented by the routing model. This can be an important deficiency of the model in river basins like the Niger, where according to Nijssen et al. (2001a), the annually averaged flow decreases from about 1,540 m^3/s to 1,140 m^3/s between Kolikoro (Mali) and Gaya (Niger) even thought the catchment area at the upper point is about 10 times smaller than that at the downstream point. This difference in discharge could be also explained from high evaporation given that the Inner Niger Delta lies between these two points.

The VIC model has been applied for identifying regional-scale droughts and associated severity, aerial and temporal extent under historic and projected future climate in Illinois and Indiana, USA (Mishra et al., 2010). Mishra, et al.(2010) used observations of streamflow from USGS gauging stations and soil moisture from the Illinois Climate Network (ICN) to calibrate the model. Results demonstrated that the major historical drought events were successfully identified and reconstructed using the model simulations. In addition, Lin (2010) reports that VIC simulated soil moisture values are used to calculate the Soil Moisture Anomaly Percentage Index (SMAPI) as an indicator for measuring the severity of agricultural and hydrological droughts. A real time drought monitoring and forecasting system for the Canadian Prairies, Lin (2010) uses the VIC model to simulate daily soil moisture values starting from 1 January 1950 and is continually running through present with a forecast lead time up to 35 days.

MATSIRO has been developed for climate studies at the global and regional scales. Takata et al. (2003) present the MATSIRO model as a bucket-type hydrology model and a multilayer snow scheme, which is intended to represent all the important processes for water and energy exchange between the land and atmosphere. It runs at a daily time step and has a spatial resolution from a fraction of a degree to several degrees latitude by longitude (Hirabayashi et al., 2005) but is generally applied at a 1˚ x 1˚ resolution when applied globally. The forcing data includes wind velocity, temperature, humidity, pressure, incoming radiation and precipitation in a 6 hourly time step. MATSIRO consists of two parts; in one of which the parameters are determined and the surface fluxes are calculated, and in the other, the ground processes are treated. Parameters are not considered for the groundwater part (Takata et al., 2003). The fluxes are calculated from the energy balance at the ground and canopy surfaces in snow-free and snow-covered portions considering a sub-grid snow distribution. The interception evaporation from canopy and the transpiration on the basis of photosynthesis are treated. A simplified TOPMODEL is used to calculate runoff. Four types of runoff are considered in MATSIRO: the base flow, the saturation excess runoff, the infiltration excess runoff and the overflow of the uppermost soil layer. The snow model has a variable number of layers from one to three, which is determined uniquely from the snow water equivalent (SWE, computed from a water balance) assuming that the snow density has a constant value of 300 kg/m^3. The snow temperature is calculated by a thermal conduction equation. The soil model has five layers in this version, and the soil temperature, the soil moisture, and the amount of frozen moisture are calculated (Takata et al., 2003). It was validated both at the global scale and at the local scale and it reproduced well the observed seasonal cycles of the energy and water balance (Takata et al., 2003). Hirabayashi et al.

(2005) describe the derivation of 100-year daily estimations of terrestrial land surface water fluxes using MATSIRO. In their research they estimated the correlation coefficients between simulated and observed time series of annual runoff at locations where discharge records were available for more than 10 years. High correlations were obtained in most basins including the Sahel but correlations resulted low in dry areas and in cool-temperate zones. They believe that the poor correlations in dry areas may be due to the fact that MATSIRO's runoff generation processes are based on TOPMODEL which was originally developed to simulate catchment runoff under humid conditions. Another possible reason of low correlations in dry areas is the human effect, given that the percentage of total river water usage may be higher in dry regions (Hirabayashi et al., 2005).

LaD is a simple model of large-scale land continental water and energy balances developed by Milly and Shmakin (2002) which may be run either in stand-alone mode or coupled to an atmospheric model. It is generally applied at a 1° x 1˚ resolution grid globally (but it can be applied at smaller resolutions). Input data include incoming short-wave and long-wave radiation, total precipitation, surface pressure, and near-surface atmospheric temperature, humidity and wind speed. The energy, soil water, and snowpack equations are solved in an hourly time step and the groundwater equation in a daily time step. LaD partitions precipitation into evaporation, runoff, and soil storage, and partitions net radiation into sensible heat flux, latent heat flux, and ground heat storage. The model includes groundwater storage processes, varying land characteristics such as vegetation root depth, vegetation roughness length, and soil and vegetation albedo, but does not include precipitation interception process (Xia, 2007). Runoff is generated when root-zone soil water storage exceeds a water holding capacity, which depends on the soil and vegetation type. All runoff passes through a groundwater reservoir of specified residence time, and a river discharge is calculated by summing all grid cells of a basin according to a river routing network (Xia, 2007). Xia (2007) calibrated the LaD model at nine basins in the north-eastern United States and analyzed the impacts of model parameter errors on the calibration of the LaD model. Milly and Shmakin (2002) evaluated the model and found that few basins resulted in a major positive runoff bias that could not be explained by precipitation errors. They include, among others, the Niger River basin in the Sahel region. All of these basins are in a region where climatic aridity is strongly seasonal. The model ignores the possibility of evaporation from interception water and (except for desert) the direct evaporation from the soil. This can also lead to positive biases in runoff in arid areas (Milly and Shmakin, 2002).

ORCHIDEE solves both the energy balance (on a 1˚ x 1˚ grid boxes, which is the scale of the forcing used) and the hydrological balance (on a smaller scale) in a time step of 30 min. The meteorological forcing includes 3 hourly precipitation data, temperature, short and long-wave radiation, specific humidity, pressure and wind speed. River flows are computed through basins defined at a 0.5˚ x 0.5˚ scale. Partitioning between surface infiltration and runoff is computed through a time-splitting procedure. Vegetation types are grouped into 3 classes (bare soil, trees and grass/crop). Transpiration and interception losses are computed separately for each vegetation type, but the induced throughfall and root uptake are aggregated per vegetation class. Therefore, in each grid box, the hydrological balance is computed for three tiles corresponding to the 3 different vegetation classes. Depending on the slope of the land surface, the surface runoff may re-infiltrate, especially through small pond systems. The saturated conductivity varies with depth in accordance to the compactness of the soil and it is also modified in the root zone for each vegetation type (d'Orgeval et al., 2008). Ngo-Duc, et al. (2005) indicate that the soil hydrology consists of two moisture layers with varying depth, but with a constant total soil depth of 2 m. The soil has a maximum water content per unit of soil volume. Runoff occurs when the soil is saturated and it is the only runoff mechanism in the model. d'Orgeval, et al. (2008) introduces the routing module as surface, subsurface runoff and river fluxes routed through three different reservoirs in each basin of each grid box. A floodplain module is included to deal with swamps and floodplains. An optional pond module is added in order to provide a first-order simulation for small ponds that re-evaporate and re-infiltrate surface runoff over flat areas. ORCHIDEE accurately simulates most of the largest rivers, which means that the Precipitation-Soil Moisture and the Soil Moisture-Evaporation links are reasonably well represented at the regional scale. d'Orgeval, et al. (2008) applied the model to an area divided in 4 regions covering different geographic characteristics (rainforest, composition of humid mountains and dry plains, semi-arid and desert) in which the sensitivity to infiltration processes was analysed. In the semi-humid basins, ORCHIDEE overestimates river discharges by 20-50%, and in intermediate basins it underestimates it by 30-60%. In the semi-arid basins ORCHIDEE overestimates river discharges. Surface infiltration has a stronger impact on semi-arid regions, whereas the root zone and deep-soil infiltration resulted in having a stronger impact for semi-humid regions (d'Orgeval et al., 2008).

HTESSEL computes the land surface response to atmospheric forcing, and estimates the surface water and energy fluxes and the temporal evolution of soil temperature, moisture content and snowpack conditions. It has a flexible spatial resolution, depending on the input resolution, and it has been applied globally with a resolution of 0.5°. The model runs with a time step of one hour forced with sub-daily (6 hourly or less) near surface meteorology (air temperature, wind speed, specific humidity and surface pressure) and surface fluxes (solid and liquid precipitation and downward solar and thermal radiation). At the interface to the atmosphere each grid box is divided into fractions (tiles), with up to six fractions over land (bare ground, low and high vegetation, intercepted water, shaded and exposed snow). Vegetation types and cover fractions are derived from an external climate database, based on the Global Land Cover Characteristic (Loveland et al., 2000). The grid box surface fluxes are calculated separately for each tile, leading to a separate solution of the surface energy balance equation and the skin temperature. The latter represents the interface between the soil and the atmosphere. The surface albedo is similar for all land tiles within a grid box except for those covered with snow. Below the surface, the vertical transfer of water and energy is performed using four vertical layers to represent soil temperature and moisture. Soil heat transfer follows a Fourier law of diffusion, modified to take into account soil water freezing/melting (Viterbo et al., 1999). Water movement in the soil is determined by Darcy's Law, and surface runoff accounts for the subgrid variability of orography (Balsamo et al., 2009). In the case of a partially (or fully) frozen soil, water transport is limited, leading to a redirection of most of the rainfall and snow melt to surface runoff when the uppermost soil layer is frozen. The snow scheme (Dutra et al., 2010) represents an additional layer on top of the soil, with an independent prognostic thermal and mass content. The snowpack is represented snow temperature, snow mass, snow density, snow albedo, and a treatment for snow liquid water in the snowpack. HTESSEL is part of the integrated forecast system at ECMWF with operational applications ranging from the short-range to monthly and seasonal weather forecasts. A detailed description of HTESSEL can be found online. The most recent version of the land surface model is the CY36R4. It includes also the MODIS-Leaf Area Index monthly climatology by Boussetta et al. (2011), and a bare-ground evaporation revision, using lower limit to residual soil moisture instead of wilting point (Balsamo G. et al., 2011). Recently, a river routing scheme, including floodplains inundations dynamics (CaMa-Flood, Yamazaki et al. (2011)), has been integrated in the system. The verification of the model's hydrology for large domains is a complex task. This is due to both the lack of direct observations and to a composite effect of shortcomings in land surface parameterizations, which produce errors not easily traced to a single process (Balsamo et al., 2009). Wipfler et al. (2011) state that the HTESSEL performs weaker in dryer areas.

2.2 GLOBAL HYDROLOGICAL MODELS

WaterGAP comprises two main components: a Global Hydrology Model (including surface runoff, groundwater recharge and river discharge) and a Global Water Use Model (including withdrawal and consumptive water use; domestic, industry, irrigation and livestock) (Lehner et al., 2006). It has a spatial resolution of 0.5° x 0.5° and covers the global land area. The land cover of the land areas is assumed to be homogeneous within each grid cell. The climate input includes monthly values of precipitation, temperature, number of wet days per month, cloudiness and average daily sunshine hours. Calculations are performed with a temporal resolution of one day for which synthetic daily values are generated. Within each grid cell, the vertical water balance for open water bodies and for the land area are completed separately. A global data set of wetlands, lakes and reservoirs was generated based on digital maps (Döll et al., 2003). Döll et al. (2003) describe the vertical water balance of the land areas by a canopy water balance and a soil water balance. For the canopy water balance, daily values of leaf area index (LAI) are modelled as a function of land cover, leaf mass and daily climate. In the soil water balance, capillary rise from the groundwater is not taken into account as they state that no information on the position of the groundwater table is available at the global scale. The transport between cells is assumed to occur only as surface water flows and not as groundwater flows. In the WaterGAP Global Hydrology Model (WGHM), natural cell discharge is reduced, with a daily time step, by the consumptive water use in a grid cell as calculated by the Global Water Use Model of WaterGAP 2 (Döll et al., 2003). For the tuning of the model, Döll et al. (2003) used observed discharge data. Only the vertical water balance for the land area is tuned by adjusting one model parameter, the runoff coefficient γ. WGHM has been tuned for 724 drainage basins worldwide, but resulting discharges where overestimated in some basins. These are often located in arid and semi-arid areas, for which the model formulation of WGHM is likely to be inadequate.

Döll et al. (2003) conclude in their study that reliable results can be obtained for basins of more than 20,000 km^2. However, semi-arid and arid basins are modelled less satisfactorily than humid basins. Furthermore, highly developed basins with large artificial storages, basin transfers and irrigation schemes, or basins where discharge is controlled by man-made reservoirs cannot be simulated well. Future model improvements include more realistic snow modelling, refined modelling of groundwater recharge and the simulation of river channel losses, also the inclusion of river velocity as an additional tuning parameter. Lehner, et al. (2006) evaluated WaterGAP concerning its capability to assess droughts in Europe. Overall, WaterGAP demonstrated a reasonable performance in simulating timing and magnitude of average monthly and low-flow values in Europe. However, significant errors occur for certain stations and conditions.

PCR-GLOBWB is a grid-based model (coded in a dynamic modelling language that is part of the GIS PCRaster) of global terrestrial hydrology. It is essentially a leaky bucket type of model applied on a cell-by-cell basis. The model calculates for each grid cell (0.5° x 0.5°) and for each time step (daily) the water storage in two vertically stacked soil layers (max. depth 0.3 and 1.2m) and in an underlying groundwater layer (of infinite capacity), as well as the water exchange between the layers and between the top layer and the atmosphere. The model also calculates canopy interception and snow storage. The input data includes precipitation, actual or potential evaporation, snow and ice dynamics. The meteorological forcing is supplied at a daily time step and assumed constant over a grid cell. Sub-grid variability is taken into account by considering separately tall and short vegetation, open water and different soil types. Canopy interception store is finite and subject to open water evaporation. The total specific runoff of a cell consists of saturation excess surface runoff, melt water that does not infiltrate, runoff from the second soil reservoir and groundwater runoff from the lowest reservoir. Groundwater reservoir characteristic response time is parameterized based on a world map of lithology. River discharge is calculated by accumulating and routing specific runoff along the drainage network taken from DDM30 and includes dynamic storage effects and evaporative losses from the GLWD[2] inventory of lakes, wetlands and plain (van Beek and Bierkens, 2009). The model includes new schemes of sub-grid surface runoff, interflow and baseflow and incorporates explicit routing of surface water flow using the kinematic wave approximation. Also, it contains a routine for lateral transport of latent heat from which the water temperature and river ice thickness can be calculated (Sperna Weiland et al., 2010). Candogan Yossef et al. (2011) assessed the model skill to reproduce floods and droughts events. For this simulated discharge values were compared with observed monthly streamflow records for a selection of 20 large river basins that represent all continents and a wide range of climatic zones. They observed that the system has a markedly higher skill in forecasting floods compared to droughts, but the prospects for forecasting hydrological extremes are positive. Sperna Weiland, et al. (2010) studied the usefulness of data from General Circulation Models (GCMs) for hydrological studies, with focus on discharge variability and extremes. The hydrological model PCR-GLOBWB was used to simulate the discharge with a GCM ensemble mean as forcing data. The resulting discharges were compared with the Global Runoff Data Center (GRDC) discharge data. Even after bias-correction, the method performed less well in arid and mountainous areas.

Mac-PDM was first developed in 1999 and later further revised and improved. It is usually run at 0.5° x 0.5° spatial resolution, but it has been run at resolutions ranging from 10 x10 min to 2° x 2° (Gosling and Arnell, 2010). This model extends the well known basin-scale PDM (Probability Distributed Moisture Model) of Moore (1985). It can be forced with daily or monthly input climate data, including precipitation, number of wet days (if forcing with monthly data), temperature, relative humidity or vapour pressure, net radiation and wind speed. The model assumes that the input precipitation is distributed equally across the cell and that precipitation falls as snow if temperature is below a defined threshold. The land cover is divided into 13 classes and the vegetation cover is taken from a global land cover data set. For the purpose of the calculation of evaporation and interception, the model distinguishes between the grass land cover class and a 'not grass' land cover class. Potential evaporation is calculated using the Penman-Monteith method. Water that reaches the ground becomes 'quickflow' if the soil is saturated and infiltrates if the soil is unsaturated. The model

---

[2] Global Lakes and Wetlands Database (Lehner and Döll, 2004)

assumes that all runoff generated within the grid cell reaches the cell outlet; it does not include transmission loss along the river network or evaporation of infiltrated overland flow, and does not include human intervention. The model does not route water from one grid cell to another (Gosling and Arnell, 2010). The performance of Mac-PDM.09 was evaluated by validating simulated runoff against observed runoff for 50 catchments. Because the simulated catchments are not routed, Glosling and Arnell (2010) results showed that generally, with the larger catchments, the runoff peak is simulated a month in advance. Another result from the analysis is that the coefficient of variation of annual runoff increases with aridity, for example, the highest values are simulated over the Sahel region, amongst others. The seasonal cycle plots confirm that Mac-PDM.09 tends to overestimate runoff in very dry catchments (e.g. Niger, Murray, and Red catchments).

WBM simulates spatially and temporally varying components of the hydrological cycle and multi constituent water quality variables. Capabilities include prediction of river discharge, water temperature, dissolved nitrogen, the impacts of irrigation, and the distortion of hydrographs through the operation of reservoirs. Other important features include freeze-thaw dynamics, snowmelt runoff, surface runoff due to impervious surfaces, and a series of physically based evaporation functions dependent on air temperature, vapour pressure, wind speed and solar radiation (University of New Hampshire, 2009). The WBM simulates grid cell level hydrology associated with long-term climate. Inputs to the WBM include global or continental scale data sets covering precipitation, temperature, potential evaporation, vegetation, soils and elevation, and in more complex configurations it requires also vapour pressure, solar radiation, wind, daily minimum and maximum temperature. The WBM then predicts soil moisture, evaporation and runoff for each 0.5˚ x 0.5˚ grid cell in the simulated region. The model is deterministic and employs a monthly time step (in its older version). The WBM calculates soil moisture to a maximum defined by the field capacity of a particular soil. It makes no prediction of the degree of waterlogging beyond this capacity. When field capacity is attained, excess water is transferred to subsurface runoff pools for rain and snowmelt. From these storage pools, runoff is generated as a linear function of the existing pool size. Moreover, there is no contribution to the runoff storage pools when a moisture deficit exists in relation to field capacity; any available water recharges the soil. WBM, coupled with a water transport model (WTM) can characterize water dynamics over large areas of landscape with high spatial and temporal resolution, that can be used to study the impact of land use and climate change on surface hydrology (Vörösmarty et al., 1989). The latest version WBMplus extends WBM by explicitly accounting for the effects of irrigation and reservoirs, implementing an improved snow melt routine, a daily time step and a Muskingum-Cunge flood routing scheme. Monthly precipitation input needs to be downscaled to daily values. This new version computes water release from large reservoirs as a function of inflow to the reservoir, mean annual inflow, current storage, and maximum capacity (University of New Hampshire, 2009). Groundwater is represented by a simple runoff retention pool that delays runoff before it enters the river channel; WBMplus does not account for the dynamics of horizontal groundwater flow or deep groundwater (Wisser et al., 2010). Fekete et al. (2004) used the WBM to assess the uncertainties of six different monthly precipitation datasets and their impact on the terrestrial water balance. They observed the apparent insensitivity of WBM in the arid regions to precipitation (no runoff is produced regardless of the amount of precipitation). They indicate that WBM performs most poorly in extremely dry regions where rapid rain events may have the ability to produce substantial runoff despite the overall water stress.

LPJ is a dynamic global vegetation model that simulates the coupled terrestrial carbon and water cycle, and thus is well suited for investigating biosphere-hydrosphere interactions over large domains. It combines process-based representations of terrestrial vegetation dynamics and land-atmosphere carbon and water exchanges in a modular framework. The simulations are driven by gridded monthly fields (in general a 0.5° resolution is adopted but it can work at different resolutions) of air temperature, precipitation, number of wet days, cloud cover, and by texture of soil types. Non-gridded model inputs include annual CO_2 concentrations. Daily air temperature and cloud cover are disaggregated by linear interpolation of the monthly values. The cloud cover data are scaled to generate daily fields of sunshine hours. Daily precipitation is disaggregated using a stochastic weather generator (Gerten et al., 2004, Rost et al., 2008). Gerten, et al. (2004) compared the result of this model with three global hydrological models (WBM, Macro-PDM and WaterGAP). Their result showed that the general quality of the LPJ simulation agrees well with that of the global hydrological models. Overestimations occur in semi-arid and arid regions, particularly in northern Africa, parts of South America and India. LPJ as well as the three hydrological models overestimate year-round runoff in Africa. Gerten et al. (2004) indicate that the reason for the biases in these regions are common to the GHM, the influence of precipitation on those rivers are masked by a variety of other processes. These processes include evaporation loss (from lakes, reservoirs, wetlands, non-perennial ponds and from the river channel), flood plain-channel interactions; seepage into groundwater; inter-basin transfers; and human water withdrawal. These processes are not yet accounted for explicitly in global vegetation models such as LPJ (Gerten et al., 2004).

SWAT is a continuous time model and operates at a daily time step but the output can be aggregated and printed at a daily, monthly, or annual time scale (according to the users preferences). The modelled area can be divided into multiple sub-basins and hydrological response units (HRU) by overlaying elevation, land cover/land use, soil and slope classes. The meteorological forcing data includes daily precipitation, and minimum and maximum temperature. SWAT has been successfully applied for water quantity and quality issues for a wide range of scales and environmental conditions around the globe and has been shown to be suitable for large scales (Schuol et al., 2008). Schuol, et al.(2008) applied the SWAT model for the whole Africa with monthly resolution, and calibrated and validated it at 207 discharge stations across the continent. In their study, the sub-basins were characterized by dominant land-use, soil and slope classes. This was necessary to keep the model at a practical size. For each of the sub-basins, the water balance was simulated for four storages volumes: snow, soil profile, shallow aquifer and deep aquifer. Surface runoff is simulated using a modification of the SCS Curve Number (CN) Method. The runoff of each sub-basin was routed through the river network to the main basin outlet. The model includes transmission losses and evaporation from the channel. The transmission losses (*tloss* (m^3H_20)) are estimated based on the channel geometry, channel bed hydraulic conductivity and the flow travel time. The transmission losses from the main channel are assumed to enter bank storage or deep aquifer. The evaporation loss from the reach is basically derived from the potential evaporation and the water available in the channel (Neitsch et al., 2005). Schuol, et al.(2008) observed that the inter-annual variability of the blue water flow (surface water and groundwater) is especially large in the Sahel, in the horn of Africa and in the Southern part of Africa, which are areas known for recurring severe droughts. These same areas presented also high standard deviation (SD) of the months per year without depleted green water storage (rainwater stored in the soil as soil moisture), indicating unreliable green water storage availability which often leads to reduced crop yield and consequently potential risk to frequent famines. The study of Schuol, et al.(2008) provided significant insights into continental fresh water availability on a sub-basin level at a monthly time step. Schuol and Abbaspour (2006) addressed some calibration and uncertainty issues using SWAT to model a four million km^2 area in West Africa. They found a large 95% prediction uncertainty band necessary to bracket 80% of the observed data, indicating that the uncertainty of the conceptual model is quite large. They indicated that some processes in the Niger that may be important, mainly related to the existing large reservoirs regulating the runoff of the river Niger. The large Inner Niger Delta, delaying the runoff and contributing to high evaporation losses, was also not included in the model. Masih et al. (2011) applied SWAT model to study the impact of different precipitation inputs in a semi-arid Karkheh River Basin in Iran and generally found better results in larger sub-basins.

SWIM is a comprehensive GIS-based tool for hydrological and water quality modelling in mesoscale watersheds (from 100 to 10,000 km^2) which was based on two previously developed tools: SWAT and MATSALU. The model interface is built in a GIS and operates on a daily time step. The recommended resolution of the DEM varies from 30 m cell size up to 1000 m, depending on the application (Krysanova and Wechsung, 2000).The weather parameters necessary to drive the model are daily precipitation, air temperature and solar radiation. In addition, data for soils, crop management, and point sources of pollution have to be provided. River discharge and concentrations of nitrogen in the basin outlet are needed for model validation. SWIM belongs to the intermediate class of models, combining mathematical process description with some empirical relationships (Krysanova et al., 1998). The model integrates hydrology erosion, vegetation, and nitrogen/phosphorus dynamics at the river basin scale and uses climate input data and agricultural management data as external forcing. The hydrological module is based on the water balance equation, taking into account precipitation, evaporation, percolation, surface runoff, and subsurface runoff for the soil column subdivided into several layers. The transmission losses in the rivers are taken into account by a special module that accounts for transmission losses. The simulated hydrological system consists of four control volumes: the soil surface, the root zone, the shallow aquifer, and the deep aquifer. The percolation from the soil profile is assumed to recharge the shallow aquifer. Return flow from the shallow aquifer contributes to the streamflow. The soil column is subdivided into several layers in accordance with the soil data base. The water balance for the soil column includes precipitation, evaporation, percolation, surface runoff, and subsurface runoff. The water balance for the shallow aquifer includes ground water recharge, capillary rise to the soil profile, lateral flow, and percolation to the deep aquifer. Krysanova, et al. (1998) indicated that very flat areas with many lakes, where travel-time becomes large, are excluded in the model. Model applications (Krysanova and Wechsung, 2000) in a number of river basins in the range of about 100 to 24,000 km^2 drainage area have shown that the model is capable to describe realistically the basic ecohydrological processes under different environmental conditions, which includes the spatial and temporal variability of main water balance components (evaporation, groundwater recharge, runoff generation) (Krysanova and Wechsung, 2000). Krysanova, et al. (1998) indicate that the model has to be further tested, especially for upscaling purposes in basins up to several thousand km^2 with 'nested' sub-basins and with different resolutions of input data.

HBV is a conceptual hydrological model extensively used in operational hydrological forecasting and water balance studies. It was first introduced by Bergström (1992) an later updated. The model consists of three main modules: snow accumulation and melt, soil moisture accounting and river routing and response modules (Abebe et al., 2010). The model has been applied in a wide range of scales without modification of it structure. Climatic inputs to the model are precipitation and temperature generally on a daily time step, and daily or monthly estimates of potential evaporation. The HBV model has gradually been developed into a semi-distributed model. This means that a basin may be separated into a number of sub-basins and that each one of these is distributed according to elevation and vegetation.

Lakes have a significant impact of runoff dynamics and the routing in major lakes is, therefore, modelled explicitly. The HBV model is normally operated on daily time steps. It has a simple interception storage for forested areas but interception is neglected for open areas. As an alternative to using long-term mean values to potential evaporation as input to the model, daily values can be calculated as being proportional to air temperature, but with monthly coefficients of proportionality. From the interception storage, evaporation equal to the potential evaporation will occur as long as water is available (Lindström et al., 1997). The response function of the model transforms excess water from the soil moisture routine to discharge to each sub-basin. It consists of two reservoirs connected in series by constant maximum percolation rate and one transformation function (Abebe et al., 2010, Lindström et al., 1997). Loon, et al. (2009) adapted the HBV model for the study of drought simulation in European catchments and their results show that the HBV model reproduces observed discharges fairly well and the adapted approach gives a better representation of the groundwater storage during drought periods than the original HBV. Bergström and Graham (1998) applied the HBV model to a large scale catchment of the Baltic Sea in northern Europe, which has a total land area of 1.6 million km^2 with the aim of studying the possibility of upscaling the model to a continental scale. They run the model on a daily basis over a 14-year period and obtained successful results in calibration and validation. Koeniger et al.(2008) transferred the HBV concept to the GIS PCRaster (cf. PCR-GLOBWB model) and applied a fully distributed HBV-type model to a large river basin in Germany to analyse the tritium balance. Love, et al. (2009) indicate that even thought the HBV was developed and initially applied in Sweden for humid temperate conditions, it has also been used successfully in semi-arid and arid countries such as Australia, Iran and Zimbabwe. Furthermore, they showed the importance of interception and introduced a model structure improvement for a semi-arid basin in Zimbabwe.

GWAVA typically operates on 0.5˚ or 0.1˚ latitude-longitude grid and is driven by monthly time series of climate data such as rainfall and evaporation. Model outputs include simulated monthly flows and a cell-by-cell comparison of water availability. The runoff is estimated independently for each cell and resulting flows are routed through adjacent 'downstream' cells to derive the total flows at any point. GWAVA can be used to examine scenarios of change, both for climate and water demands. GWAVA has been applied to Eastern and Southern Africa, West Africa, the Caspian Sea basin, South America, and the Ganges-Brahmaputra basin, and is currently being applied to Europe and globally. The model incorporates additional water resource components such as reservoir operations, lakes and wetlands, groundwater abstractions, return flows, and water transfers that modify water quantity and flow regime. The routing routine includes a transmission loss term to account for reductions in river flows due to evaporation and infiltration, which can be high in semi-arid areas. Groundwater availability is assessed and water demands (population, industrial and agricultural demands) are included in the model (CEH, 2011, Meigh et al., 1999). Meigh, et al. (1999) included a simple sub-model for rainfall interception losses in forested areas and an additional loss term in the groundwater component to represent drainage losses from the groundwater store. They applied the model to a region covering the whole of eastern and southern Africa, mapped water availability and demand and computed a water availability index for each country for the current conditions and for 2050 conditions. Moreover, within the PROMISE project, GWAVA was set up to model the West African region, including 22 countries and a wide range of hydrological regimes and climates. The model was set up and run to simulate baseline conditions across the region. A reasonable degree of calibration against observed flows was attained. The main controlling factors on the parameters of the GWAVA model are the soil type and land cover type (PROMISE, 2003).

WASMOD-M model is a distributed version of the monthly catchment model WASMOD and is driven by time series of monthly precipitation, temperature, and potential evaporation on a 0.5˚ x 0.5˚ grid. Gridded potential evaporation is pre-processed from temperature and water vapour pressure. It generally runs on a monthly or annual time step and can be calibrated for monthly and annual time series as well as for long-term average runoff. A daily version of WASMOD- M was developed by Gong et al.(2009) .The model does not include routing delays from lakes, wetlands, and the river reach itself, as well as dam regulation (Widén-Nilsson et al., 2009). Widén-Nilsson et al. (2007) present the WASMOD-M as a conceptual water-budget model with two state-variables and five tuneable parameters. Measured runoff from 663 gauging stations in 257 basins discharging to oceans or large lakes was used for parameter-estimation and model validation. Widén-Nilsson et al. (2007) state that availability and preparation of input data files is a major problem in global water-balance modelling. Uncertainties and differences in model-input data, especially precipitation, are major sources of uncertainty in model output. WASMOD-M, as many hydrological models, does not include regulation effects in the river basins simulation. Widén-Nilsson et al. (2007) used long –term-average runoff in their study instead of time series to minimize the effect of the regulation problem on model calibration. They assumed that regulation did not affect average flow volumes. WASMOD-M does not include time-delayed routing and therefore the inter-annual variations in basins with monthly or yearly delays are not simulated.

LISFLOOD is a GIS-based hydrological rainfall-runoff-routing model (implemented in the PCRaster Environmental Modelling language, wrapped in a Python based interface) which is capable of simulating the hydrological processes that occur in a catchment. This model was developed with the aim of introducing a tool that can be used in large and transnational catchments for a variety of applications, including flood forecasting, and assessing the effects of river regulation measures, land-use change and climate change. The model is designed to be applied across a wide range of spatial and temporal scales. LISFLOOD is grid-based, and applications so far have employed grid cells of as small as 100 metres for medium sized catchments, up to 5000 metres for modelling the whole of Europe (van der Knijff and de Roo, 2008).The forcing meteorological data includes rainfall, potential evaporation (for bare soil, closed canopy and open water reference surfaces), and daily mean air temperature. The potential evaporation estimates can be calculated from standard meteorological observations (JRC, 2011). LISFLOOD is currently being used and tested for flood forecasting, scenario modelling, and drought forecasting (JRC, 2011). The soil is represented by two layers. Long-term water balance can be simulated (using a daily time step), as well as individual flood events (using hourly time intervals, or even smaller) (van der Knijff and de Roo, 2008).The processes simulated include: interception of rainfall by vegetation, evaporation of intercepted water, leaf drainage, snow accumulation and snowmelt, direct evaporation from the soil surface, water uptake and transpiration by plants, infiltration, preferential flow through macro-pores, surface runoff, gravity-driven vertical flow within and out of the soil, rapid and slow groundwater runoff, channel routing using kinematic (and optionally dynamic) wave. In addition, special options exist to simulate the effect of reservoirs and polders. If detailed river cross-section data are available, it is possible to use dynamic wave river routing. If only the downstream part of a catchment is simulated, one can represent the upstream parts using (measured) inflow hydrographs. LISFLOOD needs spatially distributed input maps on topography, the river channel network, land cover (CoRINE land use classes), and soils (soil depth and texture class). Soil and vegetation parameters are linked to the soil texture and land use classes through look-up tables (JRC, 2011).

2.3 CLOSING REMARKS

From the preceding review of hydrological models, it can be inferred that an adequate macroscale tool to model the hydrology and forecast droughts in sub-Saharan Africa is not an easy task. Most of the existing global hydrological models fail to adequately represent runoff, soil moisture and other hydrological parameters in arid and semi-arid regions (Döll et al., 2003, Gerten et al., 2004, Gosling and Arnell, 2010, Milly and Shmakin, 2002, Nijssen et al., 1997, Voß and Alcamo, 2008). Several models do not represent groundwater flow and surface water-groundwater interactions including wetlands in a suitable way, which can be an important factor in the overall water balance of a watershed (Beckers et al., 2009). Lohmann et al. (1998) evaluated the water balances of the sixteen PILPS[3] Phase 2(c) land surface schemes (LSMs) by comparison of predicted and observed stream flow, evaporation and soil

---

[3] Project for Intercomparison of Land-surface Parameterization Schemes

moisture changes. Their results showed that although driven with the same forcing data, the models are dominated by different processes and therefore showed significant differences in their water-balance components. Responses to events were quite different as a result. However, most of the models predicted too much runoff in the dry part of the basin and, hence, under-predicted the spatial variability in the runoff fraction. In the same way, all models tended to over-predict the evaporation in winter, and under-predict it in summer. Their results suggest that most of the schemes could be improved by refining the parameterizations of soil-evaporation interactions.

In the Haddeland, et al. (2011) comparison, the components of the contemporary global water balance under naturalized conditions (human impact such as reservoir and withdrawals are not included) were assessed in the simulation period 1985-1999. In their study, no major difference in the inter-annual variations have been found between the models run at daily or sub-daily time steps, or between models using different evaporation or runoff schemes. In arid and semi-arid areas, the spread of simulated runoff and evaporation is relatively large, and the coefficient of variation (CV) is high for both evaporation and runoff. The largest absolute differences are found in the tropics, whereas the largest relative differences are found in arid areas. The resulting runoff was overestimated in the semi-arid and arid basins and they state that this may be partly due to the non-consideration of water extractions in these areas, and to the fact that the models miss two key processes; the transmission loss along the river channel which is significant along major rivers in arid zones, and the re-infiltration and subsequent evaporation of surface runoff generated in part of the catchment.

Haddeland, et al. (2011) show with their model intercomparison that there are considerable differences in simulated evaporation and runoff between the models, which can have a large impact on the assessment of water resources availability in some regions. They state that climate change studies need to use not only multiple climate models, but also multiple hydrological models. They conclude that when studying the impacts of climate change on the global water cycle and water resources, definite conclusions cannot be based on the results of a single model. This issue is also stressed in Hirabayashi et al. (2005).

The uncertainty in all the forcing data (mainly precipitation) is also an important issue that cannot be overlooked. Even a perfect model, if forced with biased precipitation will fail to accurately represent runoff, soil moisture and other hydrological fluxes. In Africa there are many regions with a lack of good precipitation observations, and this is a limiting factor to properly identify the limitations of each model. One way to quantify the uncertainty arising from input data is by using an ensemble approach.

3. SELECTION CRITERIA

Five selection criteria were set for assessing the suitability of the process driven hydrological models for drought forecasting at a continental scale in Africa. These selection criteria are as follows:

1. Represented processes and fluxes
2. Model applicability to African climatic conditions and physiographic settings
3. Data requirements and resolution of the model (spatial and temporal resolution)
4. Capability of the model to be downscaled to a river basin scale
5. Operational model for drought early warning system at large scales

The mentioned criteria are listed in order of importance considered for the evaluation and are justified hereafter. First, the weaknesses and strengths in the representation of different hydrological processes and fluxes of every global hydrological model should be assessed. 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 such as evaporation, surface water-groundwater interactions, soil moisture and channel losses are among the key components that should be included in the model. However, including all these processes 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.

The choice of grid size is a compromise between that needed to represent spatial variability and the availability of suitable data (CEH, 2011). Moreover, for semi-distributed and distributed models, grid size selection is intricately linked to the spatial scale in which the model will be applied.

Thus, some models may not be so easily downscaled to a river basin scale without making significant changes in the structure of the model. In the same way, it may not be possible to upscale a model that was developed for a mesoscale basin to the continental or global scale. The selected model needs to be applied both at a continental scale as well as at a river basin scale, and therefore should be capable to be used for both scales without important modifications in its formulation.

Finally, the model needs to be operational, as long as the main aim of the model selection is to provide a tool for the end-users of an early warning system that can help mitigate the effects of droughts in Africa. Hence, a model that can easily be implemented in a forecasting environment is preferred. Hence, the model should not fail often (or recover easily), have reliable error and inconsistency checks, be able to run with just parts of input data (e.g. when input sources fail), be able to fit into an operational environment and should preferably be user friendly.

4. COMPARISON OF THE MODELS

The sixteen models described in section 2 were evaluated qualitatively with the criteria previously defined, without undertaking simulations. The resulting detailed evaluation is presented in Table 2 for the LSMs and in Table 3 for the GHMs.

It is important to remark that the description and comparison of the models are based on the available literature and information obtained during the preparation of this review. These included mainly published articles and in some case the user manual or personal communication with the developers of the model. Some models are not very well documented and therefore some information might not be complete and precise.

Table 2 Evaluation of the five LSMs considered

Selection criteria	LSM									
	VIC		MATSIRO		LaD		ORCHIDEE		HTESSEL	
1. Represented processes and fluxes										
Represented processes										
Interception	✓	f (LAI)	✓	f (LAI)	×		✓	f(veget cover)	✓	f (LAI)
Evaporation	✓	Penman-Monteith	✓	Bulk formula	×✓	Energy approach	✓	Bulk formula	✓	Penman-Monteith
Snow	✓	Energy Balance	✓	Energy Balance	✓	Energy Balance	✓	Energy Balance	✓	Energy Balance
Soil	✓	2 or 3 Layers	✓	5 Layers	✓	1 Layer	✓	1 Layer	✓	4 Layers
Groundwater	×		×		✓	1 Layer	×		×✓	1 Layer, linear reservoir
Runoff	✓	Satur Excess / β function	✓	Infilt and Satur Excess /GW	✓	water content excess in root zone	✓	Sat Ex	✓	VIC/ Darcy
Reservoirs, lakes	×		×		×		×		✓	
Routing	✓	Linear transfer function	×✓	(can be coupled to TRIP)	×		✓	3 fluxes routed through 3 reservoirs with 3 time constant	×✓	Coupled with CaMa-Flood
Water use (withdrawal)	×		×		×		×		×	
Energy balance	✓		✓		✓		✓		✓	
Calibration parameters	×✓	Several	×		×		×		✓	
2. Data requirements and resolution of the model										
Input data										
Meteorologial	Daily or sub-daily precipitation, air temperature and wind speed		6 hourly data of rainfall and snowfall rate, temperature, humidity, pressure, downward radiation and wind speed		Downward short and longwave radiation, precipitation, surface pressure, temperature, humidity and wind speed		3 hourly rainfall and snowfall rate, temperature, short and longwave radiation, specific humidity, pressure and wind speed		Rainfall and snowfall rate, temperature, short and longwave radiation, specific humidity, pressure and wind speed	
Resolution of the model										
Spatial	1/16°-2° (gen 0.5°)		Varies but generally 1°		< 1°		1°		> 0.25° (glob 0.5°)	
Temporal	Daily		Daily		Hourly and daily		30 minutes		Hourly	
3. Model applicability to African conditions										
Applicability of the model in semi-arid regions	×		×		×		✓		✓	
4. Capability of the model to be downscaled to a river basin scale										
Model capable to be downscaled?	✓		✓		×		×		✓	
✓ Considered										
× Not considered										
×✓ Partially considered										

Table 3 Evaluation of the 11 GHMs considered

Selection criteria	GHM										
	WaterGAP	PCR-GLOBWB	Mac-PDM	WBMplus	LPJ	SWAT	SWIM	HBV	GWAVA	WASMOD-M	LISFLOOD
1. Represented processes and fluxes											
Represented processes											
Interception	✓ f (LAI)	✓ f(veget cover)	✓ f(veget cover)	×✓ As part of ET	✓ f (LAI)	✓ f (LAI)	×	×✓ HBV$_x$ (modif)	✓ f(veget cover)	×	✓ f (LAI)
Evaporation	✓ Priestley-Tailor	✓ Penman-Monteith	✓ Penman-Monteith	✓ Hamon	✓ Priestley-Tailor	✓ P-M / P-T / Hargreaves	✓ Priestley-Tailor or P-M	✓ Input	✓ Penman-Monteith	✓ From PET, AW and land moisture	✓ Input
Snow	✓ degree day	✓ degree day	✓ degree day	✓ degree day	✓ degree day	✓ degree day	✓ degree day	✓ degree day	✓ degree day	✓ 2 temperatures thresholds	✓ degree day
Soil	✓ 1 layer	✓ 2 Layers	✓ 1 Layer	✓ 1 Layer	✓ 2 Layers	✓ ≤ 10 Layers	✓ ≤10 Layers	✓ 2 Layers	✓ 1 Layer	✓ 1 Layer	✓ 2 Layers
Groundwater	×	✓ 1 Layer, infilt. capacity	×	×	×	✓ Shallow + deep aq (GW flow eq)	✓ Shallow + deep aq (GW flow eq)	×	✓ Monthly GW availavility estimation	×	✓ 2 paralel linear reservoir
Runoff	✓ β function	✓ Improved Arno scheme	✓ Satur Excess / β function	✓ Saturation Excess	✓ Saturation Excess	✓ modif SCS or G&A inf	✓ modif SCS	✓ Saturation Excess	✓ Sat Ex / βf	✓ f (land moisture)	✓ Infiltration Excess
Reservoirs, lakes	✓	✓	×	✓	×	✓	✓	×	✓	×	✓
Routing	✓ Constant flow velocity	✓ KWA of SVE	×	✓ Muskingum-Cunge	×	✓ VSC or Muskingum-Cunge	✓ Muskingum	✓ Muskingum-Cunge	✓ Muskingum-Cunge	×	✓ KWA
Water use (withdrawal)	✓	×	×	✓	×	✓	×	×	✓	×	×
Energy balance	×	✓ Open waters	×	×	×	×	×	×	×	×	×
Calibration parameters	✓ γ runoff coeff	×	×	×	×	✓ Several	×	✓ Several	×	✓ 5 tuneable parameters	×
2. Data requirements and resolution of the model											
Input data											
Meteorologial	Monthly precipitation, temperature, no. of wet days per month, cloudiness and average daily sunshine hours	Monthly or daily precipitation, actual evapotranspiration, snow and ice dynamics	Daily or monthly precipitation, no. if wet days, temperature, relative humidity or vapour pressure, net radiation, and wind speed	Monthly precipitation, temperature and potential evapotranspiration	Monthly air temperature, precipitation, no. of wet days, cloud cover	Daily precipitation, minimum and maximum temperature	Daily precipitation, air temperature and solar radiation	Daily precipitation, temperature and estimates of potential evaporation	Monthly time series of rainfall and evaporation	Monthly time series of precipitation, temperature, and potential evaporation	Daily rainfall, potential evaporation and daily mean air temperature
Resolution of the model											
Spatial	0.5˚	0.5˚	10 min - 2˚	0.5˚	In general 0.5˚	Subbasins	30m and larger	Semi-distributed	0.1˚ or 0.5˚	0.5˚	100m and larger
Temporal	Daily	Daily	Daily	Daily	Daily	Daily	Daily	Daily	Daily	Monthly	Hourly / Daily
3. Model applicability to African conditions											
Applicability of the model in semi-arid regions	×	✓	×	×	×	✓	✓	×	×✓	×	✓
4. Capability of the model to be downscaled to a river basin scale											
Model capable to be downscaled?	×	✓	✓	✓	×	✓	×✓	✓	✓	×	✓

✓ Considered
× Not considered
×✓ Partially considered

With a view to providing a framework for the selection of process driven models for drought forecasting, the following scheme is presented (Figure 4), which can be adapted for different spatial scales, climatic conditions and end user forecasting requirements.

As justified in the selection criteria, firstly the process representation is critically looked at. Therefore, the decision tree starts with the list of processes that are thought to be required for an adequate forecast of droughts. A distinction in a second step is made with the processes that are thought to be required for hydrological forecasting in (semi-) arid regions. Secondly, the input data availability and possibility to use alternative data are studied. In the third step the ability of the model to be downscaled is considered. Fixed grid sizes and limitations of applicability to certain basin sizes are mainly considered here. Finally, a model that can be used operationally is preferred so it should be easily implemented in a forecasting environment (as previously indicated).

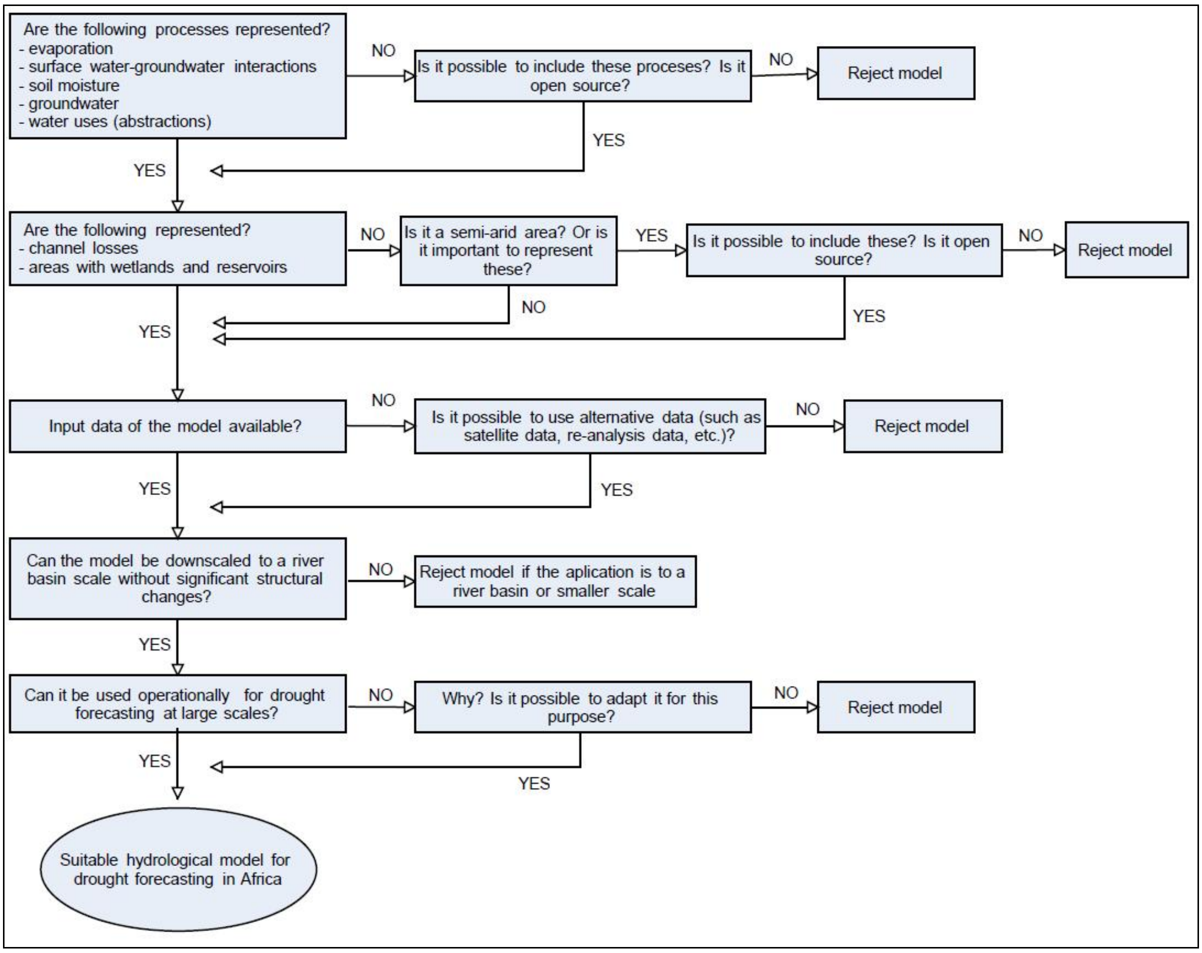


Figure 4 Decision tree for selecting a suitable hydrological model for drought forecasting in Africa

Figure 5 presents a stacked Venn diagram following the framework presented in Figure 4 for the models described. From this figure it can be observed that from the initial selection of sixteen macroscale hydrological models, only five were selected as suitable for drought forecasting in Africa. The bigger box (A) presents all the models considered in this comparison, box (B) presents the models that include the processes that are relevant for drought forecasting in Africa (or their code can be easily accessed and modified in order to include these processes). Box (C) includes the models that were not rejected due to high-data requirements, but it can be seen that in this particular comparison, no model was rejected due to high-data requirements. This is due to the fact that, even thought data availability is scarce in Africa, the meteorological forcing will be forecasted by ECMWF in a sub-daily time scale for all the climatological parameters, and also given that models like SWAT with high data requirements can also be applied in a simpler way with few parameters. The last box (D) presents the models that can be used for drought forecasting in Africa both at regional as well as at continental scale. The SWIM model is rejected here given that it is still not adequate for application at continental or global scale (but this may be modified). In this diagram the last criteria which evaluates whether the models are suited for operational purposes is not included due to the difficulty of assessing this. It is also considered that the model structure is reviewed here, and not the implementation of that structure. All models reviewed are continuous in time (i.e. are not event models), and we assume that if necessary can be modified to be suitable for use in an operational environment.

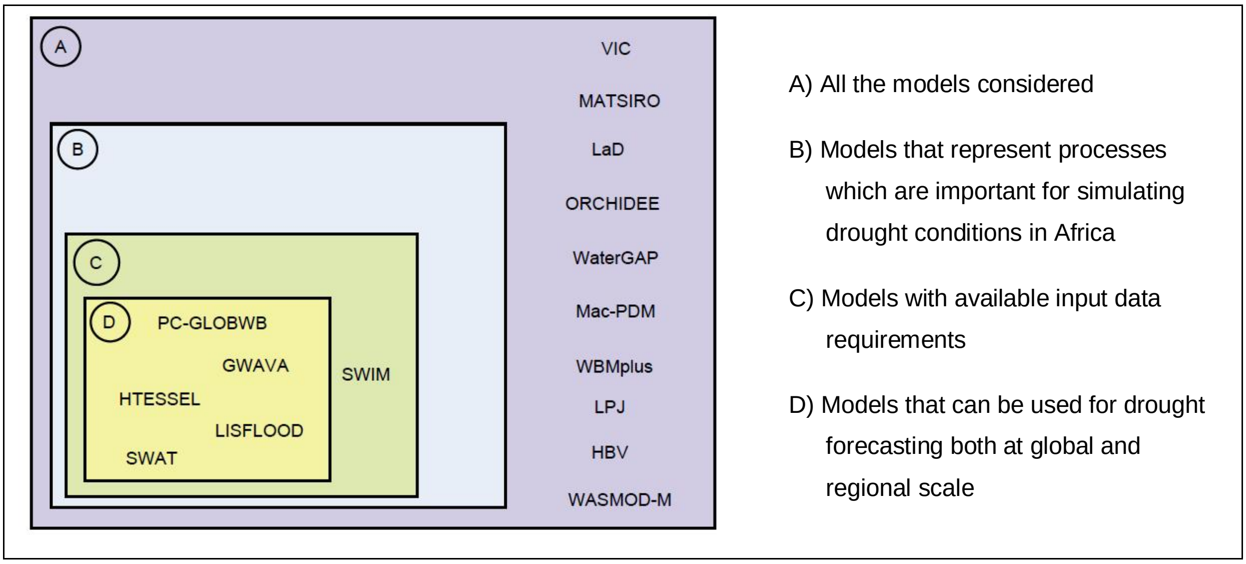


Figure 5 Stacked Venn diagram for the selection of models

5. CONCLUSION AND FINAL REMARKS

Several hydrological models that are widely used or are reported to be used in important applications were reviewed with the purpose of assessing their suitability for drought forecasting in Africa. From the review, it can be noticed that not all of these models sufficiently represent all the important water balance components for semi-arid areas. This may be due to the fact that most models do not represent the hydrological processes that could be significant in arid regions, such as transmission losses along the river channel and re-infiltration and subsequent evaporation of surface runoff.

A framework for selecting models for drought forecasting was presented in this report and used to reduce the original selection of models to a subset of models which are considered suitable for drought forecasting, in some cases assuming some possible adaptations. The suitability of the models was assessed applying a set of criteria which included the representation of the most relevant processes, applicability of the model to be used operationally for drought early warning with the available data, and the capability of the model to be downscaled to a smaller scale. Among the sixteen 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.

It has to be noted that this report supplements deliverable 4.1 and that models which are excluded within this assessment may still be able to be used for drought assessment as direct model output of a coupled atmospheric-land surface scheme. However, a dedicated hydrological model as assessed in this report may be able to give a more accurate representation of the relevant hydrological fluxes within the basins.

6. REFERENCES

Abebe NA, Ogden FL, Pradhan NR (2010) Sensitivity and uncertainty analysis of the conceptual HBV rainfall-runoff model: Implications for parameter estimation. Journal of Hydrology 389: 301-310

AMS (1997) Meteorological drought - Policy statement. Bulletin of the American Meteorological Society 78: 3

Balsamo G, Beljaars A, Scipal K, Viterbo P, van den Hurk B, Hirschi M, Betts AK (2009) A Revised Hydrology for the ECMWF Model: Verification from Field Site to Terrestrial Water Storage and Impact in the Integrated Forecast System. Journal of Hydrometeorology 10: 623-643

Balsamo G., Boussetta S, Dutra E, Beljaars A, Viterbo P, Hurk B (2011) Evolution of land-surface processes in the IFSECMWF Newsletter 127, Spring 2011.

Beckers J, Smerdon B, Wilson M (2009) Review of hydrologic models for forest management and climate change applications in British Columbia and Alberta. Forrex Forum for Research and Extension in Natural Resources., Kamloops, British Columbia, Canada.

Bergström S (1992) The HBV model: Its structure and applications SMHI, RH, 4, Norrköping, Sweden

Bergström S, Graham LP (1998) On the scale problem in hydrological modelling. Journal of Hydrology 211: 253-265

Boussetta S, Balsamo G, Beljaars A, Kral T, Jarlan L (2011) Impact of a satellite-derived Leaf Area Index monthly climatology in a global Numerical Weather Prediction model. Int J Remote Sensing (accepted), also available as ECMWF Tech Memo 640

Candogan Yossef N, van Beek LPH, Kwadijk JCJ, Bierkens MFP (2011) Skill assessment of a global hydrological model in reproducing flow extremes. Hydrol Earth Syst Sci Discuss 8: 3469-3505

GWAVA: Global Water Availability Assessment model (2011) http://www.ceh.ac.uk/sci_programmes/Water/GWAVA.html. Cited May 2011

d'Orgeval T, Polcher J, de Rosnay P (2008) Sensitivity of the West African hydrological cycle in ORCHIDEE to infiltration processes. Hydrol Earth Syst Sci 12: 1387-1401

De Roo APJ, Wesseling CG, Van Deursen WPA (2000) Physically based river basin modelling within a GIS: the LISFLOOD model. Hydrological Processes 14: 1981-1992

Döll P, Kaspar F, Lehner B (2003) A global hydrological model for deriving water availability indicators: model tuning and validation. Journal of Hydrology 270: 105-134

Dutra E, Balsamo G, Viterbo P, Miranda PMA, Beljaars A, Schär C, Elder K (2010) An improved snow scheme for the ECMWF land surface model: description and offline validation. Journal of Hydrometeorology 11: 899-916

Fekete BM, Vörösmarty CJ, Roads JO, Willmott CJ (2004) Uncertainties in precipitation and their impacts on runoff estimates. Journal of Climate 17: 294-304

Gerten D, Schaphoff S, Haberlandt U, Lucht W, Sitch S (2004) Terrestrial vegetation and water balance--hydrological evaluation of a dynamic global vegetation model. Journal of Hydrology 286: 249-270

Giannini A, Saravanan R, Chang P (2003) Oceanic Forcing of Sahel Rainfall on Interannual to Interdecadal Time Scales. Science 302: 1027-1030

Gong L, Widen-Nilsson E, Halldin S, Xu CY (2009) Large-scale runoff routing with an aggregated network-response function. Journal of Hydrology 368: 237-250

Gosling SN, Arnell NW (2010) Simulating current global river runoff with a global hydrological model: model revisions, validation, and sensitivity analysis. Hydrological Processes 25: 1129-1145

Haddeland I, Clark DB, Franssen W, Ludwig F, Voß F, Arnell NW, Bertrand N, Best M, Folwell S, Gerten D, Gomes S, Gosling SN, Hagemann S, Hanasaki N, Harding R, Heinke J, Kabat P, Koirala S, Oki T, Polcher J, Stacke T, Viterbo P, Weedon GP, Yeh. P (2011) Multi-Model Estimate of the Global Terrestrial Water Balance: Setup and First Results. Journal of Hydrometeorology 12

Hirabayashi Y, Kanae S, Struthers I, Oki T (2005) A 100-year (1901–2000) global retrospective estimation of the terrestrial water cycle. Journal of Geophysical Research 110: D19101

LISFLOOD Model (2011) http://floods.jrc.ec.europa.eu/lisflood-model. Cited 01/07/2011 2011

Koeniger P, Schwientek M, Uhlenbrook S, Leibundgut C, Krause WJ (2008) Tritium balance in macro-scale river basins analysed through distributed hydrological modelling. Hydrological Processes 22: 567-576

Krysanova V, Müller-Wohlfeil D-I, Becker A (1998) Development and test of a spatially distributed hydrological/water quality model for mesoscale watersheds. Ecological Modelling 106: 261-289

Krysanova V, Wechsung F (2000) SWIM (Soil and Water Integrated Model) User Manual Potsdam Institute for Climate Impact Research, Potsdam, Germany.

Lehner B, Döll P (2004) Global Lakes and Wetlands Database GLWDGLWD Documentation.

Lehner B, Döll P, Alcamo J, Henrichs T, Kaspar F (2006) Estimating the Impact of Global Change on Flood and Drought Risks in Europe: A Continental, Integrated Analysis. Climatic Change 75: 273-299

Liang X, Lettenmaier DP, Wood EF, Burges SJ (1994) A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J Geophys Res 99: 415–414

Lin C (2010) Soil moisture analysis and seasonal forecast of drought - Final Progress Report Drought Research Initiative (DRI), Canada.

Lindström G, Johansson B, Persson M, Gardelin M, Bergström S (1997) Development and test of the distributed HBV-96 hydrological model. Journal of Hydrology 201: 272-288

Lohmann D, Lettenmaier DP, Liang X, Wood EF, Boone A, Chang S, Chen F, Dai Y, Desborough C, Dickinson RE, Duan Q, Ek M, Gusev YM, Habets F, Irannejad P, Koster R, Mitchell KE, Nasonova ON, Noilhan J, Schaake J, Schlosser A, Shao Y, Shmakin AB, Verseghy D, Warrach K, Wetzel P, Xue Y, Yang Z-L, Zeng Q-c (1998) The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) phase 2(c) Red-Arkansas River basin experiment:: 3. Spatial and temporal analysis of water fluxes. Global and Planetary Change 19: 161-179

Loon AFv, Lanen HAJv, Seibert J, Torfs PJJF (2009) Adaptation of the HBV model for the study of drought propagation in European catchmentsEGU General Assembly 2009, Vienna, Austria, 19-24 April 2009, pp. 9589-9589.

Love D, Uhlenbrook S, van der Zaag P (2009) Challenges of regionalising a conceptual model in semi-arid meso-catchments10th International WATERNET/WARFSA/GWP-SA Symposium, Entebe, Uganda, pp. 23.

Loveland TR, Reed BC, Brown JF, Ohlen DO, Zhu Z, Yang L, Merchant JW (2000) Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. Journal of Remote Sensing 21: 1303--1330

Ludwig F, Haddeland I, Clark D, Voß F (2009) The Watch – GWSP Modeling Framework and Modelintercomparison Wageningen University, Wageningen, The Netherlands.

Masih I, Maskey S, Uhlenbrook S, Smakhtin V (2011) Assessing the Impact of Areal Precipitation Input on Streamflow Simulations Using the SWAT Model. JAWRA Journal of the American Water Resources Association 47: 179-195

Meigh JR, McKenzie AA, Sene KJ (1999) A Grid-Based Approach to Water Scarcity Estimates for Eastern and Southern Africa. Water Resources Management 13: 85-115

Melone F, Barbetta S, Diomede T, Peruccacci S, Rossi M, Tessarolo A, Verdecchia M (2005) Report: Review and selection of hydrological models - Integration of hydrological models and meteorological inputs. RISK-AWARE RISK-Advanced Weather forecast system to Advice on Risk Events and management (http://www.smr.arpa.emr.it/riskaware/).

Milly PCD, Shmakin AB (2002) Global Modeling of Land Water and Energy Balances. Part I: The Land Dynamics (LaD) Model. Journal of Hydrometeorology 3: 283-299

Mishra AK, Singh VP (2010) A review of drought concepts. Journal of Hydrology 391: 202-216

Mishra V, Cherkauer KA, Shukla S (2010) Assessment of Drought due to Historic Climate Variability and Projected Future Climate Change in the Midwestern United States. Journal of Hydrometeorology 11: 46-68

Moore R (1985) The probability-distributed principle and runoff production at point and basin scales/Le principe de la distribution des probabilités et la production d'écoulement en un point et à l'échelle d'un bassin. Hydrological Sciences Journal 30: 273-297

Neitsch S, Arnold J, Kiniry J, Williams J (2005) Soil and water assessment tool theoretical documentation, version 2005 (published on: http://swatmodel.tamu.edu/documentation) Temple, TX. USDA Agricultural Research Service and Texas A&M Blackland Research Center.

Ngo-Duc T, Polcher J, Laval K (2005) A 53-year forcing data set for land surface models. J Geophys Res 110: D06116

Nijssen B, Lettenmaier DP, Liang X, Wetzel SW, Wood EF (1997) Streamflow simulation for continental-scale river basins. Water Resour Res 33: 711-724

Nijssen B, O'Donnell GM, Lettenmaier DP, Lohmann D, Wood EF (2001a) Predicting the Discharge of Global Rivers. Journal of Climate 14: 3307-3323

Nijssen B, Schnur R, Lettenmaier DP (2001b) Global Retrospective Estimation of Soil Moisture Using the Variable Infiltration Capacity Land Surface Model, 1980â€“93. Journal of Climate 14: 1790-1808

PROMISE (2003) Predictability and variability of monsoons, and the agricultural and hydrological impacts of climate change NERC, CEH Wallingford, Wallingford, UK, pp. 8.

Ramanathan V, Crutzen PJ, Kiehl JT, Rosenfeld D (2001) Aerosols, Climate, and the Hydrological Cycle. Science 294: 2119-2124

Rost S, Gerten D, Bondeau A, Lucht W, Rohwer J, Schaphoff S (2008) Agricultural green and blue water consumption and its influence on the global water system. Water Resour Res 44: 17

Schuol J, Abbaspour KC (2006) Calibration and uncertainty issues of a hydrological model (SWAT) applied to West Africa. Advances in Geosciences 9: 7

Schuol J, Abbaspour KC, Yang H, Srinivasan R, Zehnder AJB (2008) Modeling blue and green water availability in Africa. Water Resour Res 44: W07406

Shanahan TM, Overpeck JT, Anchukaitis KJ, Beck JW, Cole JE, Dettman DL, Peck JA, Scholz CA, King JW (2009) Atlantic Forcing of Persistent Drought in West Africa. Science 324: 377-380

Sperna Weiland FC, van Beek LPH, Kwadijk JCJ, Bierkens MFP (2010) The ability of a GCM-forced hydrological model to reproduce global discharge variability. Hydrology and Earth System Sciences 7: 37

Takata K, Emori S, Watanabe T (2003) Development of the minimal advanced treatments of surface interaction and runoff. Global and Planetary Change 38: 209-222

The WBM Model Family (2009) http://www.wsag.unh.edu/wbm2.html. Cited May 2011 2011

van Beek LPH, Bierkens MFP (2009) The Global Hydrological Model PCR-GLOBWB: Conceptualization, Parameterization and Verification Utrecht University, Faculty of Earth Sciences, Department of Physical Geography, Utrecht, The Netherlands.

van der Knijff J, de Roo APJ (2008) LISFLOOD - Distributed Water Balance and Flood Simulation Model - Revised User Manual (published on http://publications.jrc.ec.europa.eu/repository/handle/111111111/7776) JRC Scientific and Technical Reports

Viterbo P, Beljaars A, Mahfouf J-F, Teixeira J (1999) The representation of soil moisture freezing and its impact on the stable boundary layer. Quarterly Journal of the Royal Meteorological Society 125: 2401-2426

Vörösmarty CJ, Moore B, III, Grace AL, Gildea MP, Melillo JM, Peterson BJ, Rastetter EB, Steudler PA (1989) Continental scale models of water balance and fluvial transport: An application to South America. Global Biogeochem Cycles 3: 241-265

Voß F, Alcamo J (2008) Technical Report No. 1: First results from intercomparison of surface water availability modules (published on: http://www.eu-watch.org/) WATCH.

Widén-Nilsson E, Gong L, Halldin S, Xu CY (2009) Model performance and parameter behavior for varying time aggregations and evaluation criteria in the WASMOD-M global water balance model. Water Resour Res 45: 14

Widén-Nilsson E, Halldin S, Xu C-y (2007) Global water-balance modelling with WASMOD-M: Parameter estimation and regionalisation. Journal of Hydrology 340: 105-118

Williams A, Funk C (2011) A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa. Climate Dynamics: 1-19

Wipfler EL, Metselaar K, van Dam JC, Feddes RA, van Meijgaard E, van Ulft LH, van den Hurk B, Zwart SJ, Bastiaanssen WGM (2011) Seasonal evaluation of the land surface scheme HTESSEL against remote sensing derived energy fluxes of the Transdanubian region in Hungary. Hydrol Earth Syst Sci 15: 1257-1271

Wisser D, Fekete BM, Vörösmarty CJ, Schumann AH (2010) Reconstructing 20th century global hydrography: a contribution to the Global Terrestrial Network- Hydrology (GTN-H). Hydrol Earth Syst Sci 14: 1-24

WRI (2002) World Resources Institute. Drylands, People, and Ecosystem Goods and Services: A Web-based Geospatial Analysis. Available online at: http://www.wri.org.

Xia Y (2007) Calibration of LaD model in the northeast United States using observed annual streamflow. Journal of Hydrometeorology 8: 1098-1110

Yamazaki D, Kanae S, Kim H, Oki T (2011) A physically based description of floodplain inundation dynamics in a global river routing model. Water Resources Research 47: 21

Zeng N (2003) Drought in the Sahel. Science 302: 999-1000