Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

A review of methods to derive a Global Outlook product for the Hydrological Status and Outlook System (HydroSOS)

SUNRISE
Sustainable Use of Natural Resources to Improve Human Health and Support Economic Development

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1 Introduction

Global hydrological variability, especially in the form of extreme events such as droughts or floods, poses one of the greatest challenges and threats to the world population (WMO 2019). More than 20 million people around the world are currently at risk from flooding, for example, which is predicted to rise to 50 million by 2030, causing an estimated US$ 521 billion annual loss of GDP (Bakker and Duncan 2017). Adequate responses to hydrological variability are critically dependent on robust and reliable assessments of the status of our hydrological resources[1] from basin to global scale, and prediction systems that can give an outlook on their status over the immediate timescale of the coming days or months.

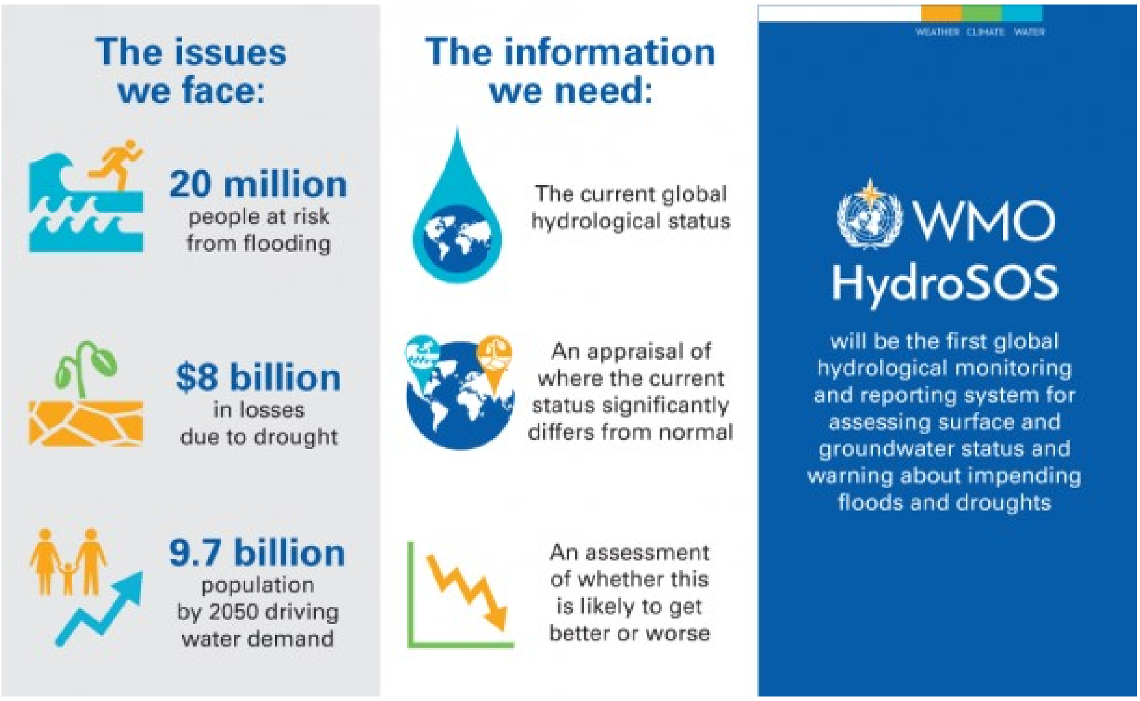

Figure 1: The global Hydrological Status and Outlook System (HydroSOS), as described on http://www.wmo.int/pages/prog/hwrp/chy/hydrosos/index.php and https://public.wmo.int/en/our-mandate/what-we-do/application-services/hydrosos. HydroSOS is a collaboration between the United Nations World Meteorological Organization (WMO), the UK's Centre for Ecology & Hydrology (CEH), the US National Center for Atmospheric Research (NCAR), the Australian Bureau of Meteorology, the US Georgia Institute of Technology's Georgia Water Resources Institute, Uganda's Ministry of Water and Environment, the US Geological Survey (USGS) and China's Nanjing Hydraulic Research Institute (NHRI).

HydroSOS is part of the WMO Hydrological Value Chain linking climate knowledge to action along with other initiatives including the WMO HydroHub. HydroSOS is also part of the World HYdrological Cycle Observing System (WHYCOS), the WMO Hydrological Observing System (WHOS) and the Global Data-Processing and Forecasting System (GDPFS).

However, there is more to flood events than heavy rainfall (Bakker and Duncan 2017), and more to drought than precipitation deficit (Heim and Brewer 2012, Hannaford *et al.* 2019, Marthews *et al.* 2019): land surface drainage patterns, topography, soil type, vegetation cover and human management activities can all have significant effects,

[1] Resources are defined to include all rivers, lakes, soil water, aquifers (both natural and human-modified) and artificial water bodies such as reservoirs, canals and irrigated areas.

potentially causing floods to occur away from areas of high precipitation (e.g. estuarine flood events caused by high rainfall perhaps 100s of km upstream) and drought to occur away from areas of low precipitation (e.g. drought occurring in the region of Lake Nalubaale (Lake Victoria) as a result of human activity (Marthews *et al.* 2019)). Therefore, an assessment of hydrological resources is an essential addition to any meteorological outlook. However, the data required for a complete hydrological assessment and outlook system is incomplete in most regions, and data quality highly variable, with many countries lacking regular assessments of their water resources at the level of detail required for an operational system (e.g. Snow *et al.* (2016)).

The global *Hydrological Status and Outlook System* (HydroSOS) is an initiative led by the World Meteorological Organisation (WMO) to provide global scale information on surface and groundwater systems (Fig. 1). HydroSOS intends to provide not only high quality information about the current status of surface and subsurface water resources, but also predictive early warnings about the deterioration of those resources in the immediate (up to a month) future. Formulated at an initial planning meeting in Entebbe, Uganda, 26-28th September 2017, and the subsequent meeting of the WMO Commission for Hydrology (CHy) Task Team on 29th September (also in Entebbe), HydroSOS is a global consortium working at both global and regional/national levels that intends to unify existing approaches into a workable harmonised system.

Details of the plan for HydroSOS were discussed at the GEWEX meeting in Canmore, Canada in May 2018: A major focus of HydroSOS is capacity building: we will provide tools and support for National Meteorological and Hydrological Services (NMHSs) to generate appraisals of where the current status of hydrological resources significantly differs from normal. These appraisals will consistently and objectively indicate drought and flood situations as well as other hydrological extremes of importance to decision-makers in the area covered by the appraisal. The appraisal would also enable a future assessment of changes over the immediate timescale of up to a few months.

There is currently tremendous interest in the impacts of climate change, and also the development of Early Warning systems similar to the appraisals envisaged here. The national and regional appraisals to be delivered by HydroSOS will primarily be based on local-scale, ground-based data, but supplemented by both Earth Observation (EO) data and hydrological model outputs as and where appropriate. These appraisals will be delivered by NMHSs and are intended to inform government bodies within the countries concerned, water resource infrastructure managers (e.g. basin managers, dam managers), as well as aid agencies (both regional and international).

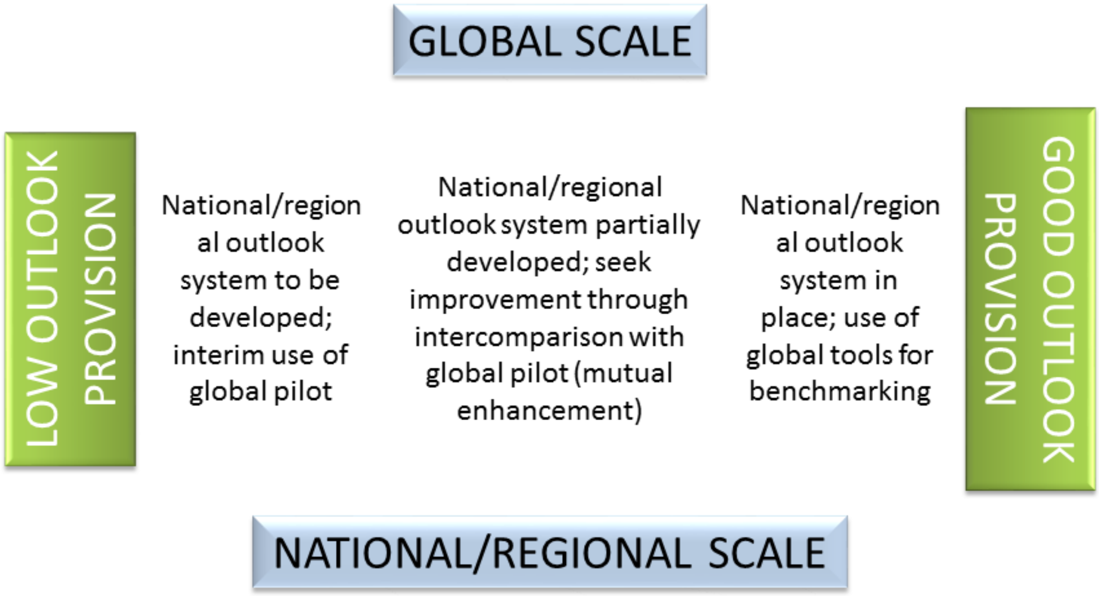

Figure 2: Use of the global outlook system (the 'global pilot') in HydroSOS and its relationship to national/regional outlooks.

1.1 Global pilot

HydroSOS is a bottom-up project or *enabling action* (Snow *et al.* 2016), and will include both an integration of existing capacity as well as including member states that currently do not operate any hydrological status and outlook system. Thus the inclusion of a Global Hydrological Status and Outlook is not intended to replace but rather to supplement and be informed by regional products.

There is an important role to be played by global-scale data and model outputs (hereafter the "global pilot"). Application of the global pilot, whether as part of hybrid simulations (e.g. nudging-based data assimilation) or running alongside a regional/national system (e.g. intercomparison), brings opportunities for mutual enhancement that will not only accelerate the capacity building process, but also improve the global pilot itself as well (Fig. 2):

(1) GLOBAL TO REGIONAL ENHANCEMENT: Using these global systems to enhance the national and regional level capacity for delivering regular, national or regional *Hydrological Status and Outlook* documents (to be achieved through applying consistent methods such as gap-filling and bias-correction see e.g. Pozzi *et al.* (2013)).

and (2) REGIONAL TO GLOBAL ENHANCEMENT: Improving existing global products by allowing them to be informed by generally higher quality information at regional/national spatial scales (to be achieved e.g. through identifying where and when the global product is not correctly reproducing the local product and analysing the causes). This can either be through directly inserting the data into the global system, or through the use of 'derived products' (see below) if appropriate technology or data licensing agreement is not available.

Importantly, in order to encourage capacity-building at national and regional levels, the global product will not be used to replace the national/regional products (Fig. 2): predictions based on global products may perhaps be closer to observations under some circumstances, but generally not consistently, and global products have significant uncertainties that must be factored in to decision-making at this level (Marthews *et al.* in prep. 2018).

2 Methods

2.1 Previous approaches

Providing an assessment of the current hydrologic environment and a best estimate of future status has been undertaken many times before at the national or regional scale (Hannaford *et al.* 2019). As an example, in the UK the Centre for Ecology & Hydrology (CEH) has provided *Hydrological Outlooks* since 1988 (http://www.hydoutuk.net/), most recently extended to include more online resources through the *CEH Drought Portal* https://eip.ceh.ac.uk/droughts (Hannaford *et al.* 2019). Since the late 1990s, some national climate outlooks have also been brought together on an operational basis through Regional Climate Outlook Forums (RCOFs https://public.wmo.int/en/our-mandate/climate/regional-climate-outlook-products).

A small number of previous projects have also had a global scope and similar intention to the HydroSOS project, notably the *Global Drought Early Warning System* (GDEWS) (Table A1) where a network of regional and continental systems were prepared operationally by the participating nations of that region or continent on a collaborative basis, and then integrated into a web-based Global Drought Monitor (GDM) map (Heim and Brewer 2012).

It is very useful to analyse the problems that were encountered by the GDEWS, because similar problems must be anticipated by HydroSOS and finding appropriate solutions at this early stage in the project would be advantageous. For example, GDEWS found it to be unhelpful to insist on a universal definition of drought because of the wide variety of sectors affected by drought, its diverse geographical and temporal distribution and the demand placed on water supply by human-use systems, which meant that agreement could only be obtained for five broad categories of drought intensity D0 to D4 (Heim and Brewer 2012, Pozzi *et al.* 2013). In HydroSOS, we will not be defining drought indicators, but rather sharing more basic physical information such as anomalies in the soil moisture, river flow and other quantities. This is discussed below.

2.2 The HydroSOS approach

Since its beginning in June 2018, HydroSOS has been working at both the global and regional levels (Fig. 2) towards providing a state-of-the-practice estimate of the current hydrologic status and future outlook for particular countries and regions, linking in with existing products and services provided by NMHSs (Wood 2017). HydroSOS plans to provide the crucial global scale information needed to help citizens understand the current status of the world's freshwater systems and adapt in light of the near-future outlook by harnessing new technologies and link up other initiatives to enable us to better answer questions like: "How much water is there in rivers around the world at the moment?", "Is the current situation normal?", and "How might the global flood/drought situation change in the coming few months?".

In order to deliver this, HydroSOS will develop a worldwide operational system that is capable of providing:

(1) An indication of current global hydrological conditions

(2) An appraisal of where this status departs significantly from 'normal'

and (3) An assessment of where conditions are likely to get worse over coming weeks and months.

HydroSOS will create an ensemble of hydrological analyses, with flexibility to add or remove products over time. In the initial (pilot) phase of HydroSOS, when capability at differing spatial scales cannot be assumed to be consistent across NMHSs, development at the global scale and the regional scale will be separate (Fig. 2). After this initial phase, the intention is to move to a more harmonised system ensuring that outlook information is consistent across both spatial scales (Fig. 3). In this pilot phase, the products that will be considered are the ECMWF *GLoFAS* product (hereafter "GLoFAS"), the SMHI *World-wide HYPE* (hereafter "SMHI") product, the Princeton University *Global Flood and Drought Monitor* product (hereafter "GFDM") and the eartH2Observe multi-model ensemble reanalysis (hereafter "E2O") (Table A1).

A key part of HydroSOS will be to identify 'derived products' that can easily be transferred between the regional and global systems. Initially, simple hydrological variables will be chosen (e.g. precipitation, soil moisture, runoff over a catchment, snow water). For each of these variables, the separate systems (global and regional, Fig. 2) will calculate the anomaly of these variable at the daily timescale compared to the climatological mean for that month. In this way, the anomalies are comparable at any scale.

These data will potentially be merged and visualised in a web portal (e.g. EDgE http://192.171.173.135/Apps/#climate-change, Pouget *et al.* (2017); q.v. Fig. 4). The outlook timescale for HydroSOS will be 1 month.

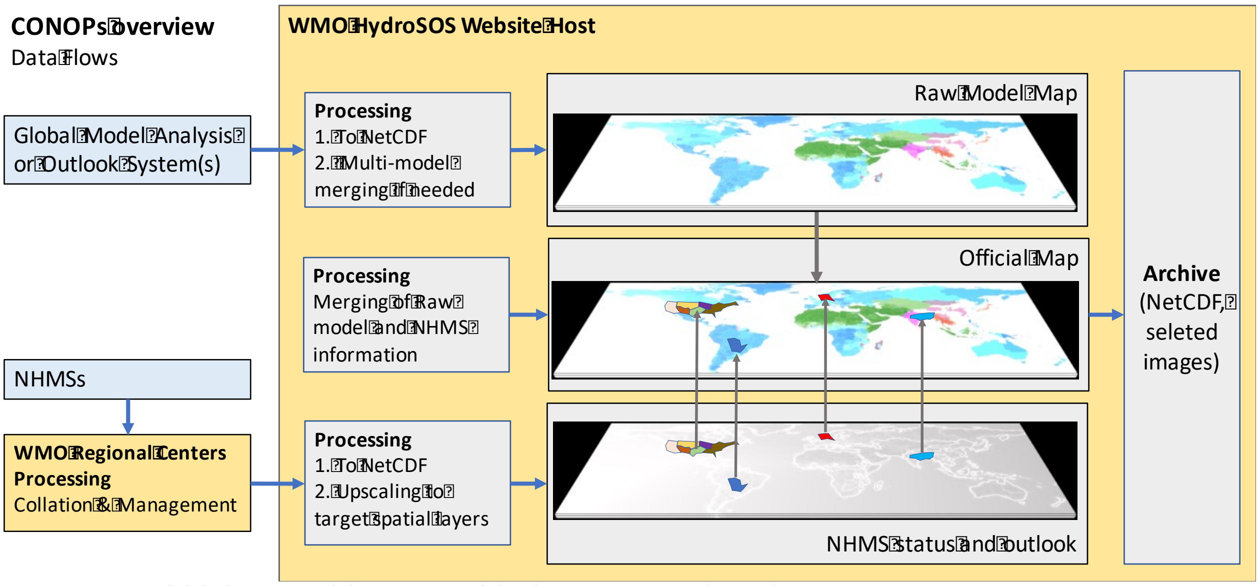

Figure 3. HydroSOS Concept of Operations (CONOPs) overview of data flows (Wood 2017).

2.2.1 Regional scale (the South Asia and Lake Victoria Pilot studies)

Fig. 2 is a conceptual diagram showing how the global derived data products can be merged with the regional products. The two initial pilot regions are South Asia and the region around Lake Nalubaale (Lake Victoria). Other regions will be included as the initial phase progresses, chosen according to the availability of existing Hydrological Status and Outlook data that can also be used to trial the system (e.g. South America, West Africa, Europe). The range of availability and quality of hydrological data in different regions around the world will be instructive with regards to the design and application of the global-regional linked system.

2.2.2 Global scale (the Global Pilot study)

Land Surface Models (LSMs), which map extreme meteorological events to extreme event impacts, have undergone a huge diversification in recent years, with great improvements in their ability to model mechanistic physical processes within ecosystems and greater sophistication in their characterisation of many processes including land-atmosphere feedbacks (Dadson *et al.* 2013). However, models do still have significant uncertainties, especially in their representation of hydrological extremes. WaterMIP, EDgE, ISI-MIP, eartH2Observe and other similar multi-model intercomparisons have shown that models provide diverse predictions and this is dependent on model sophistication in representing hydrological processes as well as calibration (Marthews *et al.* in prep. 2018).

The eartH2Observe project carried out a comprehensive study of how useful such global products might be in a regional context, with studies in Bangladesh, Morocco, Ethiopia and Colombia. An overview report by Sterk *et al.* (2017), shows that in many cases, the average of the multi-model ensemble of uncalibrated models can give useful information. In Bangladesh, the mean of the ensemble outperformed the locally calibrated model for flood analysis, in Morocco it was successful in reproducing monthly discharge data, in Ethiopia the results varied between basins, depending on the physical characteristics of the basins (areas with significant in-catchment storage were not well represented by the models), and in Colombia, the multi-model ensemble gave reasonable monthly discharges.

Despite the known uncertainties, *eartH2Observe* also showed that global modelling system can perform reasonable well if they include data assimilation and the use of best-available data sources (Fig. 3).

The products currently available operationally at the Global scale (GloFAS, SMHI and GFDM) still have only one model embedded in them, and therefore cannot represent the full spread of predictions for land surface fluxes. It has been shown that an ensemble mean is always better than any single model. Therefore HydroSOS will use a multi-model approach to provide services.

3 Discussion

Droughts affect more people worldwide every year than any other natural hazard (Mishra and Singh 2010) and floods account for the largest proportion of deaths worldwide attributable to extreme natural events (IPCC 2012). As emphasised by Heim and Brewer (2012) in the context of drought, global-scale monitoring, mitigation and response systems can provide important benefits to all nations affected by hydrological extremes. Ongoing and anticipated climate change increases the urgency of developing an operational system to achieve this (Snow *et al.* 2016).

The HydroSOS project provides an important opportunity to improve greatly the provision of hydrological outlooks in many countries around the world and to realise at least some of these benefits. The informational foundation we need is still inadequate for a fully-fledged global system, but it is improving and hydrological outlooks are increasingly accepted as an essential tool that can allow local, regional and national bodies to make plans for future variability in hydrological extreme events such as flood and drought.

3.1 End users

The end users of HydroSOS outlooks are set out through the WMO Hydrological Value Chain initiative (Fig. 1) linking climate knowledge to action and include the NMHSs themselves (primarily), sector experts (e.g. government departments, agricultural extension agencies), non-governmental stakeholders (e.g. aid agencies, media), but not community-level users (AMCOMET 2014). For regional and global outlooks, potential end users include regional organisations (e.g. regional climate outlook forums, RCOFs), transnational basin management commissions (e.g. the Lake Victoria Basin Commission, the Mekong River Commission, the Nile Basin Initiative) and international aid agencies (e.g. World Health Organisation (WHO), the UN International Strategy for Disaster Reduction (UNISDR) and others working within the Sendai Framework for Disaster Risk Reduction). Commercial entities, regional capacity-development programmes and training initiatives (students) may also benefit from outputs of the type to be produced by HydroSOS.

In addition to anomalies, the HydroSOS will aim to give uncertainties to the products. This is potentially very important information required by end users in data-sparse regions of the world, allowing local decision-makers to allocate funds so as to achieve the best return in terms of improved predictive capability. For example, if a particular region has highly uncertain rainfall, but very predictable flow responses for any given rainfall input, then money would be better spent improving precipitation prediction; however if a particular region has very consistent rainfall but high uncertainty in its flow responses then an investment in better observational data and flow prediction tools would be more appropriate.

3.2 Conclusions

Globally, hydrological variability poses one of the greatest threats to the world's population and there are an increasing number of people at risk from water-related hazards (e.g. flood, drought) and rapidly growing demands on water resources. However, there is currently no global system which is capable of assessing the current status of surface and groundwater systems or predicting how they will change in the immediate future.

Working through National Meteorological and Hydrological Services (NMHSs) and other appropriate bodies, HydroSOS intends to provide this system. By assembling and collating the necessary information at all relevant spatial scales, HydroSOS will directly enhance capacity at national, regional and global level for delivering regular *Hydrological Status and Outlook* documents, leading to a much improved system of local appraisal of hydrological conditions and a future assessment of trends over the immediate timescale of up to a few months. Ultimately, this will enable citizens to understand much better the current status of the world's freshwater systems and adapt in the light of world-class near-future outlooks. In this way, HydroSOS will make a strong contribution to increasing the resilience of society to the detrimental impacts of future climate change.

4 Appendix

Table A1: A selection of existing near-real-time global forecast products used to predict hydrological extremes (e.g. drought, flood). Regional data sources are too numerous to be included in this table (unless they are components of a global product, e.g. the African Flood and Drought Monitor). Global data sources of climate data are also excluded even though meteorological indices (e.g. PP below) can be calculated from them. Available variables are not listed directly in this table, but given as the following codes:

- *P = precipitation available, i.e. can calculate measures of meteorological drought such as Standardised Precipitation Index SPI (PP = at least one of these is also available directly; n.b. data will come directly from the forcing data set, not the hydrological model in use).*
- *E = actual evapotranspiration available, i.e. can combine with precipitation data to calculate measures of aridity (EE = at least one of these is also available directly; n.b. data will be calculated from the forcing data set, without using the hydrological model).*
- *F = streamflow data and/or runoff available, i.e. can calculate inundation risk and measures of hydrological drought/flood such as flow exceedance or streamflow percentile (FF = at least one of these is also available directly)*
- *A = soil moisture data available, i.e. can calculate measures of agricultural drought such as Soil Moisture Anomaly SMA (AA = at least one of these is also available directly)*
- *V = vegetation response data available (e.g. fAPAR, NDVI), i.e. can calculate measures of vegetation stress such as the Vegetation Health Index VHI (VV = at least one of these is also available directly)*

Global resource	*Spatial resolution(s) available*	*Forecasts / Historical*	*Notes*
Global Flood Awareness System (GloFAS) 2.0 http://www.globalfloods.eu/ provided by the European Centre for Medium-range Weather Forecasts (ECMWF)	0.1°	GLoFAS 30-day v2.0: Daily forecasts of PP, FF* for +30 days, updated daily GLoFAS Seasonal v2.0: Daily forecasts of PP, FF* for +16 weeks, updated monthly Both forecasts available historically (back to 1981)	* = Only exceedances available, not actual flow data GLoFAS uses daily ERA5/ECMWF ensemble Integrated Forecasting System (IFS) forcing data and HTESSEL/LisFlood for land surface calculations.
SMHI: HydroGFD2 and World-wide HYPE http://hypeweb.smhi.se/ provided by the Swedish Meteorological and Hydrological Institute (SMHI)	Forecast products available on a catchment basis (median catchment size 1020 km^2)	Daily forecasts of F for +10 days, updated daily Monthly mean forecasts of P, E, F, A for +6 months, updated monthly	See Arheimer *et al.* (2018). Forcing data is SMHI's Hydrological Global Forcing Data HydroGFD2 (Berg *et al.* 2018) based on bias adjusted ERA products and forecasts from ECMWF. Hydrological

Global resource	*Spatial resolution(s) available*	*Forecasts / Historical*	*Notes*
			simulations are from a world-wide setup of the HYPE model (an open-source, process-oriented and semi-distributed model) run at a daily timestep. Daily historical data (back to 1981 at 0.5°, updated monthly) not considered because only available for selected regions and catchments.
Global Flood and Drought Monitor (GFDM) **https://platform.princetonclimate.com/PCA_Platform/globalMonitor.html** **provided by Princeton University, USA**	Currently 0.25° (~25 km), but currently upgrading to 5 km	Daily forecasts of PP, E, FF, AA for +7 days, updated weekly Monthly forecasts of PP for +6 months, updated monthly Both forecasts available historically (back to 1995). Historical data also includes V.	Details not yet online: details taken from the African Flood and Drought Monitor and Latin American Flood and Drought Monitor (on which the global system will be partly based).
Global Drought Early Warning System (GDEWS) and Global Drought Information System (GDIS) **https://www.drought.gov/gdm/current-conditions** **provided by NOAA, USA**	1.0° (~110 km)	Monthly PP for 1900-2019	See Heim and Brewer (2012)
Global Drought Observatory (GDO) **http://edo.jrc.ec.europa.eu/gdo** **provided by the Joint Research Centre (JRC), Italy**	Historical PP available at 1.0° (~110 km), AA and VV available at 1/12th° (~1 km)	10-day (dekad) historical data for PP, AA, VV (back to 2011, updated ~monthly)	
EartH2Observe. Water Cycle Integrator. **https://wci.earth2observe.eu/**	0.25°	Historical.	

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