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Global hydrology 2015: State, trends, and directions

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Abstract Global hydrology has come a long way since the first introduction of the primitive land surface model of Manabe (1969) and the declaration of the "Emergence of Global Hydrology" by Eagleson (1986). Hydrological submodels of varying complexity are now part of global climate models, of models calculating global terrestrial carbon sequestration, of earth system models, and even of integrated assessment models. This paper reviews the current state of global hydrological modeling, discusses past and recent developments, and extrapolates these to future challenges and directions. First, established domains of global hydrological model applications are discussed, in terms of societal and science questions posed, the type of models developed, and recent advances therein. Next, a genealogy of global hydrological models is given. After reviewing recent efforts to connect model components from different domains, new domains are identified where global hydrology is now starting to become an integral part of the analyses. Finally, inspired by these new domains of application, persistent and emerging challenges are identified as well as the directions global hydrology is likely to take in the coming decade and beyond.

Key Points:

- Review of global hydrology over the period 1969–2015
- Identification of recent trends
- Vision on future trends and challenges

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1. Introduction

In 1986, Peter Eagleson wrote a paper for the famous "Trends and Directions" issue of WRR proclaiming the emergence of global-scale hydrology [*Eagleson*, 1986]. In this paper, he reminded hydrologists that the hydrological cycle is a global phenomenon and that human impacts on hydrology surpass the scale of a catchment. He argued that mankind has been changing land cover at continental scales as early as the advent of ancient civilization and that these changes must have had pronounced effects on the surface energy and water balance, affecting both regional climate and continental runoff. Using then unpublished work by Randall Koster, he also illustrated the strong connection between land evaporation and precipitation. Thus, understanding climatic variability as well as the human impact on climate and the hydrological cycle calls for the development of global hydrological models, and more importantly, the involvement of the hydrological community in developing these models.

At the time the paper of Eagleson appeared, there were hardly any global hydrological models. The "Bucket" model of *Manabe* [1969] was around and the first land surface models with a more sophisticated soil hydrology had been developed [e.g., *Deardorff*, 1978; *Dickinson*, 1984], all efforts lead by atmospheric scientists, not hydrologists. How different is the situation 30 years later! As will be shown hereafter, there are currently many tens of global hydrological models, built and maintained from very different earth science communities. Moreover, the number of in situ and remotely sensed data now available to force and parameterize these models, called for by *Eagleson* [1986] as well, has grown tremendously [see, e.g., *Bierkens et al*., 2014]. It thus seems that Peter Eagleson's proclamation of the emergence of global hydrology proved to be visionary indeed. So how far have we come since 1986? What are we heading for? And what are the remaining challenges? These are the questions this paper will try to answer.

2. Established Domains: Global Hydrology

The realization that a global description of terrestrial hydrology was needed lead to global hydrological modeling initiatives in different geoscientific domains more or less independently. Here the developments in three of these domains, atmospheric science, hydrology and water resources, and vegetation and carbon, are described briefly.

2.1. Atmospheric Science

It was really the atmospheric science community who was first in the development of global hydrological parameterizations. The first primitive model was published by *Manabe* [1969], where the soil was represented by a single bucket that generated runoff when full, i.e., soil moisture over field capacity being 15 cm of stored soil water everywhere. Evaporation was set equal to atmospheric demand and reduced linearly with soil water storage below 75% of soil moisture at field capacity. The model was used in an idealized regional atmospheric model of North and South America including part of the Atlantic Ocean. Before that, land surfaces of global atmospheric models (GCMs) were either assumed to have completely dry or completely wet soils causing either warm biases over land or the inability to simulate the timing and persistent of dry spells.

After *Manabe* [1969], *Deardorff* [1978] was one of the first to present a rather complete land surface scheme that explicitly included a vegetation layer, soil heat flux, effective two-layer soil hydrology, and canopy interception. Following *Deardorff* [1978], the first generation land surface models (LSMs) (e.g., OSU-LSM: *Pan and Mahrt* [1987] and *Mahrt and Pan* [1984]; BATS: *Dickinson* [1984]; SiB: *Sellers et al.* [1986]) took great efforts in precisely modeling the soil-vegetation-atmosphere exchange of momentum, moisture, and energy, including explicit plant physiology, while soil hydrology was modeled rather simplistic. Later, more sophisticated multilayered soil routines were included, ranging from using storage-based percolation to solving Richards' equation for unsaturated flow (TESSEL: *Viterbo and Beljaars* [1995]; BATS2: *Yang and Dickinson* [1996]; MOSES: *Cox et al.* [1999]; HTESSEL: *Van den Hurk et al.* [2000]; LaD: *Milly and Shmakin* [2002]).

The strong point about the efforts by the atmospheric science community to simulate global land hydrology is that from early on the community engaged in multimodel intercomparison experiments such as the different phases of the Project for Intercomparison of Land Surface Parameterization Schemes PILPS [*Henderson-Sellers et al.*, 1995] and the Global Soil Wetness projects I and II [*Entin et al.*, 1999; *Guo and Dirmeyer*, 2006]. In these projects multiple models (over 30 participating land surface models in PILPS) are run offline under similar forcing and compared to each other and to observations of surface variables (from station data and flux towers), boundary layer profiles (e.g., from weather balloons), and discharge stations. Through these comparisons several hydrological shortcomings of LSMs were discovered and corrected for. As a result, many LSMs now account for lateral surface and subsurface flow [e.g., *Liang et al.*, 1994; *Hageman and Dümenil*, 1998; *Takata et al.*, 2003] to better estimate evaporation or include larger soil stores to represent groundwater as a means to overcome warm biases [*Van den Hurk et al.*, 2000] and some even include lateral groundwater [*Fan et al.*, 2007; *Niu et al.*, 2011] and river routing [*Oki and Sud*, 1998; *Balsamo et al.*, 2009; *Niu et al.*, 2011].

LSM multimodel experiments in fully coupled mode such as GLACE [*Koster et al.*, 2006] exemplified the importance of soil moisture in land-atmosphere coupling, not only in terms of the partitioning of turbulent heat exchange into latent and sensible heating, but also in explaining the persistence and amplitude of dry and wet anomalies over land. A seminal paper from this experiment [*Koster et al.*, 2004] identified hot spots of land-atmosphere coupling where soil moisture has a significant impact on precipitation amounts (Central U.S., the Sahel, and northern India). The location of these hot spots was confirmed by *Lam et al.* [2011]. Also, subsequent studies investigated the change in land-atmosphere coupling under future climate [*Seneviratne et al.*, 2006, 2013]. One is referred to http://www.wcrp-climate.org/wgcm-overview for an overview of the many model-intercomparison experiments done under the World Climate Research Program.

Despite the positive examples described above, model-intercomparisons have also been criticized. For instance, in their opinion paper, *M. P. Clark et al.* [2011] argue that that model-intercomparisons have not been overly successful, because the choice of participating models is often haphazard and because there are generally too many structural and implementation differences among participating models to meaningfully attribute the performance differences between any two models to specific individual components and hypotheses.

Recently, many of the land surface models are evolving into land earth system models (LESMs), combining energy and momentum exchange with mature hydrology, vegetation phenology, and dynamics and carbon cycling. These models can be used in fully integrated climate models that combine a dynamic ocean, atmospheric dynamics, and chemistry with ocean and terrestrial carbon cycle models and land use change. Examples of LESMs are CLM [*Lawrence et al.*, 2011], JULES [*Bets et al.*, 2011; *D. B. Clark et al.*, 2011], Noah-MP [*Niu et al.*, 2011], ORCHIDEE [*Guimberteau et al.*, 2012], and LM3 [*Milly et al.*, 2014]. Developing and maintaining these models, often in concert with the other components of climate and earth system models that they operate under, is a huge task and generally supported by large communities of researchers and institutes. They are truly community models.

2.2. Hydrology and Water Resources

During the late 1980s and early 1990s, awareness of the shortage of global water resources [*Falkenmark*, 1989; *Gleick*, 1989, 1993] lead to the first detailed global water resources assessments comparing water availability with water use [*Shiklomanov*, 1997]. These first efforts mostly relied on statistics of water use (e.g., AQUASTAT) and observations of meteorological and hydrological variables. Shortly thereafter, the first macroscale hydrological models (MHM) appeared: WaterGap [*Alcamo et al*., 1997], WBM [*Vörösmarty et al*., 1998], and MacPDM [*Arnell*, 1999]. In these models, blue water (i.e., surface water and nonrenewable groundwater) availability was calculated by proxy by accumulating runoff over a stream network. In WaterGap, and later versions of WBM, also water demand was calculated and confronted with water availability to assess water stress [*Falkenmark et al*., 1997]. As an interesting spin-off, *Fekete et al*. [1999] used the output from WBM together with observations of discharge to create global runoff maps. Shortly thereafter, blue water availability was derived from routing runoff from land surface models over global stream networks [*Oki et al*., 2001; *Nijssen et al*., 2001].

A novel feature of MHMs like WaterGap and WBM was the inclusion of a water use model. Here inspired by work done in integrated assessment modeling [*Alcamo*, 1994], domestic and industrial water use were parameterized as a function of average income per country (GDP/capita) allowing global water use calculations as well as past reconstructions and future projections based on projections of population growth and economic development. Similarly, using a map of irrigated areas [*Döll and Siebert*, 2000], irrigation water withdrawal and consumption were calculated by estimating irrigation water requirements (crop-specific potential evapotranspiration minus available water in the soil) and country-specific irrigation efficiencies [*Döll and Siebert*, 2002]. In this paper, models that explicitly consider water use are referred to as Global Hydrology and Water Resources Models (GHWMs). GHWMs are currently at the heart of global water resources assessments that are now regularly being performed under the Global Water Systems Project [*GWSP*, 2005], the UNESCO World water Assessment Program, and the UNEP Environmental Outlook. A seminal paper on global hydrological modeling is that of *Vörösmarty et al*. [2000], showing that the influence of population growth on water scarcity is larger than that of climate change.

The GHWMs have gone through several rounds of improvements, increasing both functionality and resolution of the models (see Figure 1 and Table 1 for an overview). New GHWMs have been developed since 2000, notably H08 [*Hanasaki et al*., 2008a] and PCR-GLOBWB [*van Beek and Bierkens*, 2009]. New developments in these models are the inclusion of reservoir operations [*Haddeland et al*., 2006; *Hanasaki et al*., 2006], hydrodynamic routing [*van Beek et al*., 2011], floodplain inundation [*Yamazaki et al*., 2011], and determining water scarcity at a monthly time scale to account for intraannual variability of availability and demand [*Hanasaki et al*., 2008b; *Wada et al*., 2011a, 2011b]. Apart from global water stress assessments, GHWMs and MHMs have recently been used for modeling global freshwater temperature [*van Beek et al*., 2012; *Van Vliet et al*., 2012], global flood hazard and risk [*Pappenberger et al*., 2012; *Hirabayashi et al*., 2013; *Ward et al*., 2013], groundwater depletion [*Wada et al*., 2010; *Gleeson et al*., 2011], the contribution of terrestrial water stores to global sea level change [*Wada et al*., 2012; *Pohkrel et al*., 2013], methane emission [*Petrescu et al*., 2010; *Ringeval et al*., 2014], and medium range to seasonal streamflow forecasting [*Alfieri et al*., 2013; *Candogan Yossef et al*., 2013]. Most of the current MHMs and GHWMs run with a spatial resolution of 30 arc min (50 km at the equator) and with daily time steps. The newest versions of some of these models, e.g., WaterGap 3 [*Verzano et al*., 2012] and PCR-GLOBWB 2.0 [*Wada et al*., 2014], also run at 5 arc min resolution.

Finally, it is worth noticing that a number of land surface models, notably VIC [*Liang et al*., 1994] and MATSIRO [*Koirala et al*., 2014], are also considered MHMs as they possess well-established hydrological parameterizations and are regularly used for global water resources assessment studies.

2.3. Vegetation and Carbon

Dynamic vegetation models originated from the ecological community to investigate the effects of climate change on terrestrial vegetation, in particular forests. One of the earlier vegetation distribution models was BIOME [*Prentice et al*., 1992]. This model was not only used to predict the effects of contemporary climate change on vegetation, but also to understand the response of vegetation on past climate change and for past land cover reconstruction. Hydrology in this earlier model is extremely simple in that moisture limitation is calculated based on a single soil reservoir and yearly average climatology of precipitation and potential evapotranspiration. Building on the BIOME-type of models the next generation vegetation models was developed, most notably LPJ [*Sitch et al*., 2003]. Compared to its predecessors, LPJ models vegetation

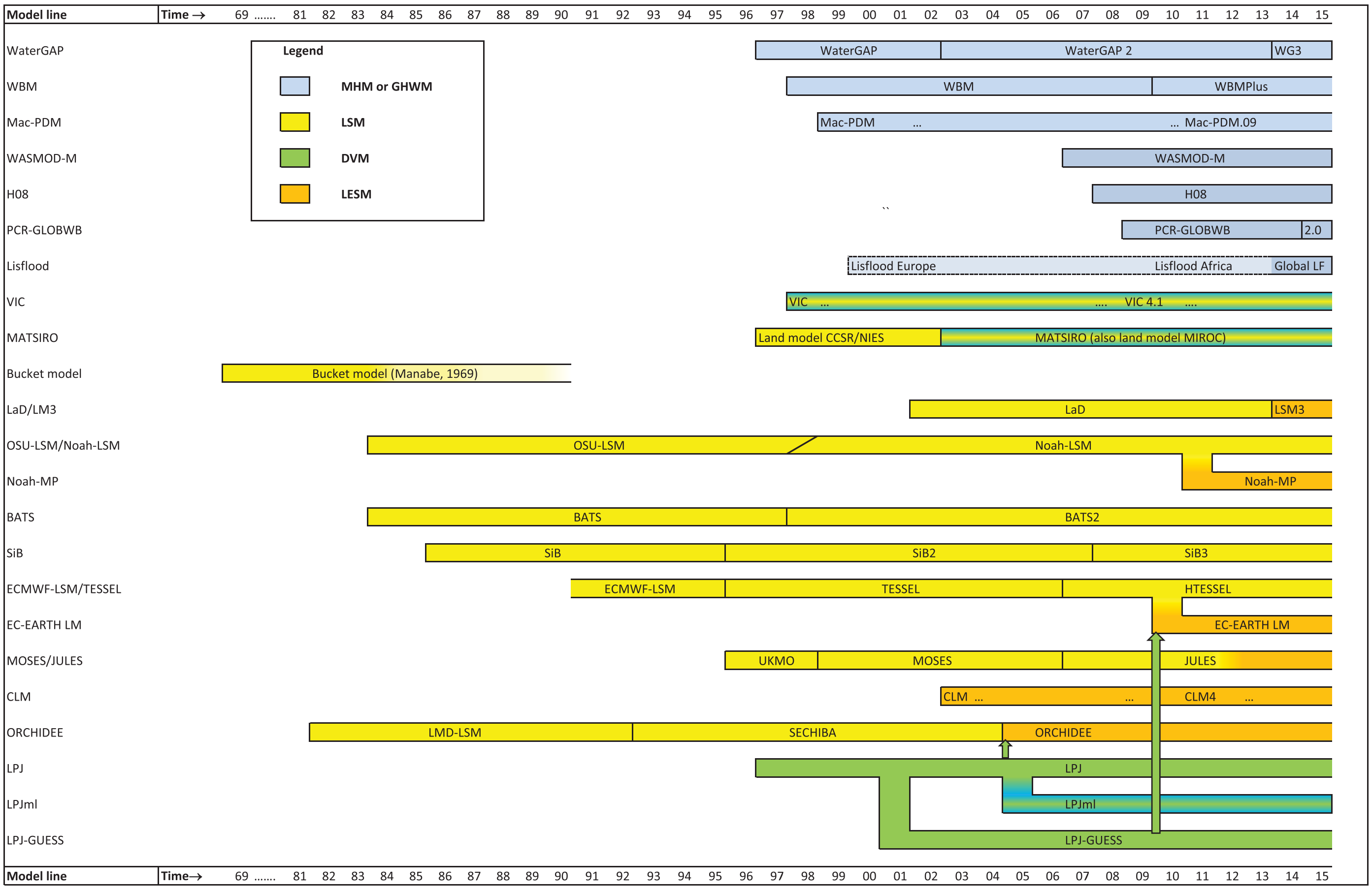

Figure 1. Genealogy of global hydrological models, representing the period 1969–2015. MHM: macroscale hydrological model (conceptual leaky bucket type; runoff generation concepts; often human impacts). In case of human impacts, global hydrology and water resources model (GHWM); LSM: land surface model (used in climate or numerical weather prediction models; energy balance); DVM: dynamic vegetation model (water, vegetation, and carbon); LESM: land models used in earth system models (water, energy, and carbon).

dynamically, including competition, adds vegetation structure and soil biogeochemistry (including carbon cycling). However, the hydrology of LPJ is still rather simple, using a two-layer bucket-type approach with any soil moisture exceeding field capacity marked as runoff. Slight hydrological improvements where implemented by *Gerten et al*. [2004]. LPJ forked into two models: (1) LPJ-Guess, which shares many of the core routines with LPJ but has a more advanced species composition and vegetation structure simulation module [*Smith et al*., 2001]; (2) LPJml [*Bondeau et al*., 2007], a modular version of LPJ, with the ability to simulate managed crops. LPJml has also been adopted by the global hydrological modeling community for water resources assessment, adding irrigation modules and reservoirs.

Despite the rather simple hydrology, a study by *Gerten et al*. [2004] showed that LPJ runoff agrees well with results from state-of-the-art global hydrological models. Also, compared to observations LPJ showed a direction and magnitude of biases that were largely similar to those from other macroscale hydrological models, rather than specific to LPJ. This shows that for global hydrology, parameterization and forcing of the land surface are as important as hydrological rigor when explaining model uncertainties.

As a simulation tool for dynamic vegetation, LPJ and its versions have been forerunners for over a decade. However, as stated in the previous section, many of the newest generation of land earth system models are slowly catching up, including dynamic vegetation and carbon dynamics.

3. Global Data Sets

Without data, global hydrological models cannot be. Good quality, freely available, and easily accessible data sets are the lifeblood of global hydrological modeling. We cannot underestimate the love and effort

Table 1. Some Important Data Sets Used in Global Modeling

Model Parameterization

GLCC land cover data: http://landcover.usgs.gov/landcoverdata.php
GLiM—Global surface lithology at 1 km: http://www.clisap.de/research/b:-climate-manifestations-and-impacts/crg-chemistry-of-natural-aqueous-solutions/global-lithological-map/ [*Hartmann and Moosdorf*, 2012]
GLHYMPS—Global HYdrogeology MaPS of permeability and porosity [*Gleeson et al.*, 2014]
Global map of irrigated areas: http://www.uni-frankfurt.de/45218039/Global_Irrigation_Map [*Döll and Siebert*, 2000]
SoilGrids1km—Global soils and soil properties at 1 km: http://soilgrids.org [*Hengl et al.*, 2014]
GRanD—Global reservoirs and dams database; contains 6862 records of reservoirs and their associated dams with a cumulative storage capacity of 6197 km^3 (>75% of the total volume of storage of reservoirs >0.01 km^3; http://sedac.ciesin.columbia.edu/data/set/grand-v1-dams-rev01)
HYDRO1k—1 km hydrological DEM and drainage network derived from GTOPO30: https://lta.cr.usgs.gov/HYDRO1K [*Verdin and Greenlee*, 1996]
HYDROSHEDS—Multiscale hydrological DEM and drainage network (finest resolution 90 m) as derived from the Shuttle Topography Mission. http://hydrosheds.cr.usgs.gov/index.php [*Lehner et al.*, 2008]
MIRCA2000—Global data set of monthly irrigated and rainfed crop areas around the year 2000. http://www.uni-frankfurt.de/45218023/MIRCA [*Portmann et al.*, 2010]

Meterological Forcing

CRU—Monthly meteorological forcing from observations 1901-current: http://www.cru.uea.ac.uk/cru/data/hrg/. TS V 1.0 [*New et al.*, 2000]; TS V 3.22 [*Harris et al.*, 2014]
ERA-40 1.25° daily meteorological forcing from ECMRWF reanalysis 1958–2001: http://apps.ecmwf.int/datasets/data/era40_daily/ [*Uppula et al.*, 2005]
ERA-Interim 0.8° daily meteorological forcing from ECMRWF reanalysis 1979-current: http://data-portal.ecmwf.int/data/d/interim_daily/ [*Dee et al.*, 2011]
GPCP—Global precipitation climatology project: daily, monthly, and climatology data sets at 1° composed from combinations of multi-satellite data (microwave, infrared), 6000 gauges and sounding observations: http://www.gewex.org/gpcp.html [*Huffman et al.*, 2001]
MERRA—Daily meteorological forcing from the NASA Goddard Earth Observing System Data Assimilation System Version 5: http://gmao.gsfc.nasa.gov/research/merra/ [*Rienecker et al.*, 2011]
NCEP-CFSR 0.5° hourly reanalysis data from NCEP/NOAA for the period 1979–2011: http://nomads.ncdc.noaa.gov/ [*Saha et al.*, 2010]
WFD—Watch forcing data set: 0.5° 3/6 hourly meteorological forcing from ECMRWF reanalysis (ERA40) bias-corrected and extrapolated by CRU TS and GPCP (rainfall) and corrections for under catch. http://www.waterandclimatechange.eu/about/watch-forcing-data-20th-century [*Weedon et al.*, 2011]

Model Calibration and Validation

EWA-Friend European catchment data: http://www.bafg.de/GRDC/EN/04_spcldtbss/42_EWA/ewa_node.html
FLUXNET: Water vapor, energy, and CO$_2$ land-atmosphere fluxes from towers: http://fluxnet.ornl.gov/obtain-data
GRACE—Gravity recovery and climate experiment: http://grace.jpl.nasa.gov/
GRDC global runoff data: http://www.bafg.de/GRDC/EN/Home/homepage_node.html
ISMN—Global network of soil moisture data: https://ismn.geo.tuwien.ac.at/ismn/ [*Dorigo et al.*, 2011]
MOPEX—US catchment data: ftp://hydrology.nws.noaa.gov/pub/gcip/mopex/US_Data/
RIVDIS—Global river discharge, 1807–1991, Version 1.1: http://www.daac.ornl.gov [*Vörösmarty et al.*, 1996]

that goes into the derivation of global data sets, be it from compiling statistical data, digitizing and combining maps or time series and processing of remotely sensed images. The efforts are such that large organizations are needed to support data-compilation and maintenance (e.g., USGS, NASA, ESA, NOAA, FAO, and WMO), but let us not forget the many small groups that are able to compile invaluable data used by many. The efforts are tremendous but so are the benefits, both for the science community that is able to improve its models and make progress, as well as for the authors themselves by receiving large citation counts. Table 1 provides a (nonexhaustive) list of data sets that are often used in global hydrological models. We can divide these into three categories:

1. Data used in model parameterization, mostly high-resolution parameter fields: HYDRO1k-1km hydrological DEM and drainage network [*Verdin and Greenlee*, 1996]; HydroSHEDS—global river network at 15 arc sec (500 m) [*Lehner et al.*, 2008] and 3 arc sec (100 m) (surface elevation); GLCC—global land cover at 1 km; global soils and soil properties at 1 km [*Hengl et al.*, 2014]; GLiM—global surface lithology at 1 km [*Hartmann and Moosdorf*, 2012]; GLHYMP—global map of permeability and porosity [*Gleeson et al.*, 2011, 2014]; global map of irrigated areas [*Döll and Siebert*, 2000]; MIRCA2000—global data set of monthly irrigated and rainfed crop areas around the year 2000 [*Portmann et al.*, 2010]; GRanD—global database of reservoirs and dams [*Lehner et al.*, 2011].
2. Data sets of meteorological forcing: GPCP—precipitation [*Huffman et al.*, 2001]; CRU TS3.21 [*Harris et al.*, 2014]; ERA-40 [*Uppula et al.*, 2005]; NCEP-CFSR [*Saha et al.*, 2010]; ERA-INTERIM [*Dee et al.*, 2011]; MERRA [*Rienecker et al.*, 2011]; WFD [*Weedon et al.*, 2011].

3. Data sets for validation, i.e., global online databases of field observations: discharge (GRDC, MOPEX, and EWA-FRIEND); evaporation and carbon fluxes (FLUXNET); soil moisture (ISMN) [*Dorigo et al*., 2011]. Added to these are the many remotely sensed products (from high to very low resolutions) measuring various hydrological states, e.g., soil moisture [*De Jeu et al*., 2008], evaporation [*Sheffield et al*., 2006; *Miralles et al*., 2011], total terrestrial water storage [*Swenson et al*., 2006; *Famiglietti and Rodell*, 2013], and lake and reservoir levels [*Swenson and Wahr*, 2009; *Gao et al*., 2012]. These remotely sensed products are not mentioned in Table 2 as they are but a small sample of the many different products available.

Despite this euphoria about data availability, it is also important to note that the number of registered rain gauges and discharge gauges in the world peaked by the end of the 1970 and has been rapidly diminishing in number thereafter.

4. Genealogy of Models and Function

Based on their domains of origin (see section 2), global hydrological models can be categorized into different types. From atmospheric science: Land Surface Models (LSM) and Land Earth System Models (LESM); from global hydrology and water resources: Macroscale Hydrological Models (MHM). In case dams and water abstractions are modeled they are denoted as Global Hydrology and Water Resources Models (GHWM); from vegetation and carbon modeling: Dynamic Vegetation Models (DVG). Table 2 provides an overview of the models mentioned, their defining properties, key publications and, when available, the URL where the model description can be found or the code be downloaded.

It should be noted that apart from this (certainly not complete) list of global modeling efforts, there are many (continental scale) hydrological models (RHM) around with similar functionalities as the GHMs mentioned. Also, worth mentioning is a different class of models that has been developed during the last decade: Fully Implicit Partial Differential Equations (FI-PDE). These models are configured to be as physically based as possible, e.g., three-dimensional variably saturated flow coupled to shallow water equations for surface runoff, even boasting a surface energy balance. Using high-performance computing technology, these models started out with mesoscale catchments but are currently being upscaled to basins and continents [*Kollet and Maxwell*, 2006; *Camporese et al*., 2010; *Brunner and Simmons*, 2012; *Maxwell*, 2013]. With global hydrological models ever increasing their resolution and physically based catchment models their domains, the two approaches are bound to meet in the middle in the near future. Despite their large data needs, these FI-PDE may well be the future of global hydrology (see *Bierkens et al*. [2014] for examples of these models and their functionalities).

Figure 1 provides a genealogical overview of the different types of models. Horizontal is the time line, starting with the Bucket model of *Manabe* [1969]. Each bar is a model line, the color based on its model type: LSM (yellow), MHM/GHWM (blue), DVG (green), LESM (orange), and, if known, the various names and versions in each model line. It can be seen that model lines cease to exist, evolve into new versions or even to other model types (LSM to LESMs), or split up in two lines.

5. Building Bridges

5.1. Multimodel Intercomparison Projects (MIPs)

Particularly in the atmospheric science, multimodel comparisons, e.g., PILPS [*Henderson-Sellers et al*., 1995], GSWP [*Entin et al*., 1999; *Guo and Dirmeyer*, 2006], and GLACE [*Koster et al*., 2006], have proven to be very effective in exposing model weaknesses, provide model uncertainty estimates, and eventually lead to improvement of model components. For a long time, model intercomparison projects (MIPs) were absent from the MHM and GHWM community. The first MIP that involved four of such models was the EU-funded WATCH project [*Harding et al*., 2011]. Moreover, WATCH also included five LSMs and one DVG. Recently, an even larger MIP called ISI-MIP [*Schellnhuber et al*., 2014] finished. This intersectoral MIP included over 30 global modeling groups from various sectors such as agriculture (including agro-economic models), water, ecosystems, infrastructure, and health sectors resulted in a multimodel multisectoral effect analysis. The results of this MIP have been cited extensively in the IPCC AR5 working group 2 report. Currently, ISI-MIP II is running, with over 130 groups participating.

The power of a multimodel analysis can be seen in Figure 2 [*Schewe et al*., 2014]. Here nine MHMs, one LSM, and one DVG are forced with bias-corrected climate change projections from five different CMIP5 global

Table 2. Nonexhaustive Overview of the Various Large-Scale Models From the Different Communities and Their Properties (Selected and Extended From *Bierkens et al.* [2014]

Model Name	Class of Model (Six Types)^a	Domain	Resolution (Space and Time)	Discretization Type (Grid, Polygon or Subcatchment)	Soil and Groundwater Dynamics	Routing	Human Water Use/ Reservoirs	Surface Energy Balance	Vegetation	Carbon Cycling	Reference Marking Start of Different Versions	Institutes	url
WaterGAP WaterGAP 2 WaterGap 3	GHWM	Globe	0.5°; 5′; daily	Grid	Vertical soil, groundwater reservoir	1-D kinematic wave + Manning channel network	Yes/Yes	No	Fixed, climatology of phenology, irrigated area change	No	*Alcamo et al.* [1997], *Alcamo et al.* [2003], and *Verzano et al.* [2012]	Kassel University (Germany) Goethe University Frankfurt (Germany)	www.watergap.de
WBM WBMPlus	GHWM	Globe	0.5°; daily	Grid	Vertical soil, groundwater reservoir	1-D Muskingum-Cunge over channel network	Yes/Yes	No	Fixed, climatology of phenology, irrigated area change		*Vörösmarty* [1998] and *Wisser et al.* [2010]	University of New Hampshire (USA) City University of New York (USA)	www.wsag.unh.edu/wbm.html
Mac-PDM Mac-PDM.09	MHM	Globe	0.5°; daily	Grid	Vertical soil	Basin aggregation of runoff	No/No	No	Fixed	No	0.01: *Arnell* [1999] 0.09: *Gosling and Arnell* [2011]	University of Reading (UK) University of Nottingham (UK)	
WASMOD-M	MHM	Globe	0.5°; monthly	Grid	Single linear reservoir of total land moisture	Basin aggregation of runoff	No/No	No	Fixed and spatially uniform	Bo	*Widén-Nilsson et al.* [2007]	Uppsala University (Sweden)	
H08	GHWM	Globe	1.0°; daily (3 h for energy balance)	Grid	Vertical soil	Accumulation along 1.0° channel network	Yes/Yes	Yes	Simple crop growth model	No	*Hanasaki et al.* [2008a]	Institute for Environmental Studies (Japan)	http://h08.nies.go.jp/h08/index.html
PCR-GLOBWB PCR-GLOBWB 2.0	GHWM	Globe	0.5°; 5′; daily	Grid	Vertical soil, groundwater reservoir or lateral groundwater (optional)	Kinematic wave + Manning channel network, approximate floodplain inundation	Yes/Yes	No	Fixed, climatology of phenology, irrigated area change	No	1.0: *van Beek and Bierkens* [2009] and *van Beek et al.* [2011]; 2.0: *Wada et al.* [2014]	Utrecht University (Netherlands) Deltares (Netherlands)	www.globalhydrology.nl
Lisflood	RHWM/GHWM	Europe, Globe	Europe (5 km), globe (0.1°) daily	Grid	Vertical soil, groundwater reservoir	Kinematic wave + Manning over channel network	Yes/Yes	No	LAI-observed LAI Climatology	No	*De Roo et al.* [2000] and *Van der Knijff et al.* [2010]	EC-JRC at ISPRA (Italy)	http://floods.jrc.ec.europa.eu/lisflood-model.html
VIC-VIC 4.1	LSM/MHM	Globe	0.5°; daily (3 h for energy balance)	Grid	Vertical soil, groundwater-like reservoir	Unit hydrograph per cell + linearized St. Venant over channel network	No/No	Yes	Fixed, climatology of phenology	No	*Liang et al.*[1994] and H. Gao et al.^{b}	Princeton University (USA) University of Washington (USA)	http://www.hydro.washington.edu/Lettenmaier/Models/VIC/index.shtml
MATSIRO	LSM/GHWM	Globe	1.0°; daily daily (6 h for energy balance)	Grid	Vertical soil, groundwater reservoir	CAMA flood: 1-D diffusive wave + Manning for friction slope channel network, floodplain inundation	Yes/Yes	Yes	Simple crop growth model	No	*Takata et al.* [2003] and *Koirala et al.* [2014]	IIS, University of Tokyo (Japan)	
Bucket model of *Manabe* [1969]	LSM	Idealized version of North and South America. Thereafter mostly regional applications.	2.5°–5° depending on latitude	Grid	Single soil reservoir of 1 m and maximum capacity of 15 cm soil moisture	Basin aggregation of runoff	No/No	Yes	None, assuming bare soil only	No	*Manabe* [1969], *Robock et al.* [1995], *Schaake et al.* [1995], *Mouelhi et al.* [2006]	Geophysical Fluid Dynamics Laboratory Princeton (USA) Princeton University (USA)	
LaD (extension of *Manabe*)	LSM	Globe	1.0°; daily daily (subdaily for energy balance)	Grid	Vertical soil, groundwater reservoir	Basin aggregation of runoff	No/No	No	Fixed	Yes	*Milly and Shmakin* [2002]	NOAH Geophysical Fluids Dynamics Laboratory (USA)	
LM3 (part of ESM2)	LESM	Globe	1.0°; daily daily (subdaily for energy balance)	Grid	Vertical soil, groundwater reservoir and topography-based groundwater dynamics	Nonlinear storage-outflow relationship per cell along the channel network	No/No	No	Fully dynamic	Yes	*Milly et al.* [2014]		http://www.gfdl.noaa.gov/land-model

Table 2. (continued)

Model Name	Class of Model (Six Types)[a]	Domain	Resolution (Space and Time)	Discretization Type (Grid, Polygon or Subcatchment)	Soil and Groundwater Dynamics	Routing	Human Water Use/ Reservoirs	Surface Energy Balance	Vegetation	Carbon Cycling	Reference Marking Start of Different Versions	Institutes	url
OSU-LSM Noah-LSM Noah-3.4 Noah-MP	LSM/LESM	Globe	1/8° hourly over US	Grid	Vertical soil MP: optional groundwater	Basin aggregation of runoff MP: with local runoff delay (dynamic TOPMODEL)	No/No	No	Fixed, climatology of phenology MP: optional dynamic phenology and carbon storage	Yes	*Pan and Mahrt* [1987], *Mahrt and Pan* [1984], *Ek et al.* [2003], and *Niu et al.* [2011]	N: National Centers for Environmental Prediction (NCEP) (USA) O: Oregon State University (Dept. of Atmospheric Sciences) (USA) A: Air Force (both AFWA and AFRL—formerly AFGL, PL) (USA) H: Hydrologic Research Lab—NWS (now Office of Hydrologic Dev—OHD) (USA) NCAR National Center for Atmospheric Research, Boulder, Colorado (USA)	http://www.ral.ucar.edu/research/land/technology/lsm.php
BATS BATS2	LSM	Globe	Variable, typically 3° globally, subdaily time steps	Grid	Vertical soil	Basin aggregation of runoff	No/No	Yes	Fixed land cover; LAI dependent on soil temperature	No	Bats: *Dickinson* [1984]. Bats: *Yang and Dickinson* [1996]. Bats2: *Dickinson et al.* [1998]	University of Texas at Austin (USA) National Center for Atmospheric Research (USA)	
SiB SiB2 SiB3	LSM	Regional and globe	Variable; 1° globally; 10 m tot half-hourly time steps	Grid	Vertical soil	Basin aggregation of runoff	No/No	No	Dynamic + phenology + plant physiology	Yes	SiB: *Sellers et al.* [1986]. SiB2: *Sellers et al.* [1996]. SiB3: *Baker et al.* [2008]	Atmospheric Science, Colorado State University, Fort Collins (USA)	http://biocycle.atmos.colostate.edu/research/models/sib3/
ECMWF-LSM TESSEL HTESSEL	LSM/LESM	Globe	Variable, 0.25°–1.0° globally; 3 h time steps	Grid	Vertical soil	Basin aggregation of runoff Htessel can be coupled to TRIP [*Oki and Sud*, 1998] for river routing	No/No	Yes	Fixed + climatology of phenology; coupling with LPJGeuss is possible (in EC-EARTH)	Optional: coupling with LPJGeuss is possible	*Blondin* [1991], *Viterbo and Beljaars* [1995], *Balsamo et al.* [2009], and *Weiss et al.* [2014]	European Centre for Medium Range Weather Forecasting (UK)	http://www.ecmwf.int/en/research/climate-reanalysis/era-interim/land
MOSES JULES	LSM/LESM	Globe	0.5°; 3 h time steps	Grid	Vertical soil	Routing over 1° grid using an advection scheme	Yes (irrigation only)/Yes	Yes	Dynamic + phenology + plant physiology Optional: dynamic vegetation using TRIFFID	Yes	*Cox et al.* [1999], *Mercado et al.* [2007], *Bets et al.* [2011], and *D. B. Clark et al.* [2011]	Centre for Ecology and Hydrology (UK) Met Office Hadley Centre (UK) University of Exeter (UK)	https://jules.jchmr.org
SECHIBA + STOMATE + LPJ = ORCHIDEE	LSM/LESM	Globe	0.5°; half hourly time steps	Grid	Vertical soil	No built-in routing; but has been used with routing schemes	Yes (irrigation only)/No	Yes	Dynamic + phenology + plant physiology	Yes	*Ducoudré et al.* [1993], *Krinner et al.* [2005], and *Guimberteau et al.* [2012]	Institut Pierre Simon Laplace (France) Laboratoire des Sciences du Climat et de l'Environment (France)	http://labex.ipsl.fr/orchidee/

Table 2. (continued)

Model Name	Class of Model (Six Types)[a]	Domain	Resolution (Space and Time)	Discretization Type (Grid, Polygon or Subcatchment)	Soil and Groundwater Dynamics	Routing	Human Water Use/ Reservoirs	Surface Energy Balance	Vegetation	Carbon Cycling	Reference Marking Start of Different Versions	Institutes	url
CLM (common land model) CLM2.0-CLM4.5 (after 2002 community land model)	LESM	Globe	Variable, standard 0.9° by 1.25° lat-lon; 6 h	Grid	Vertical soil, groundwater reservoir	Linear reservoir per cell along the channel network	Irrigation only/No	Yes	Dynamic + phenology + plant physiology + dynamic vegetation + land use change	Yes	CLM: *Dai et al.* [2003]. CLM4: *Lawrence et al.* [2011]	National Center for Atmospheric Research (USA), Boulder, Colorado (USA)	http://www.cesm.ucar.edu/models/clm/
LPJ (1997)	DVM	Globe	0.5°; daily	Grid	Vertical soil: two layers, bucket-type approach	Linear reservoir per cell along the channel network	No/No	No	Dynamic + phenology + simple plant physiology	No	*Sitch et al.* [2003]	PIK- Potsdam Institute for Climate Research, Potsdam (Germany) Max Planck Institute for Biogeochemistry, Jena (Germany) Lund University, Lund (Sweden)	http://www.nateko.lu.se/lpj-guess/ http://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml https://www.bgc-jena.mpg.de/
LPJ V2: LPJGuess (2001)	DVM	Globe	0.5°; daily	Grid	Vertical soil	Linear reservoir per cell along the channel network	No/No	No	Dynamic + phenology + simple plant physiology Species+ distribution + stand properties	No	*Smith et al.* [2001]	Lund University, Lund (Sweden)	http://www.nateko.lu.se/lpj-guess/
LPJ V3: LPJml (2005)	DVM	Globe	0.5°; daily	Grid	Vertical soil	Linear reservoir per cell along the channel network	Irrigation only/Yes	No	Dynamic + phenology + simple plant physiology + managed land use (crops)	Yes	*Bondeau et al.* [2007], *Rost et al.* [2008], *Biemans et al.* [2011]	PIK—Potsdam Institute for Climate Research (Germany)	Http://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml

[a]MHM: macroscale hydrological model (conceptual leaky bucket type; runoff generation concepts; often human impacts). In case of human impacts, global hydrology and water resources model (GHWM); LSM: land surface model (used in climate or numerical weather prediction models; energy balance); DVM: dynamic vegetation model (water, vegetation, and carbon); LESM: land models used in earth system models (water, energy, and carbon).

[b]Water budget record from variable infiltration capacity (VIC) model, submitted to Algorithm Theoretical Basis Document for Terrestrial Water Cycle Data Records, Univ. of Wash., Seattle 2009.

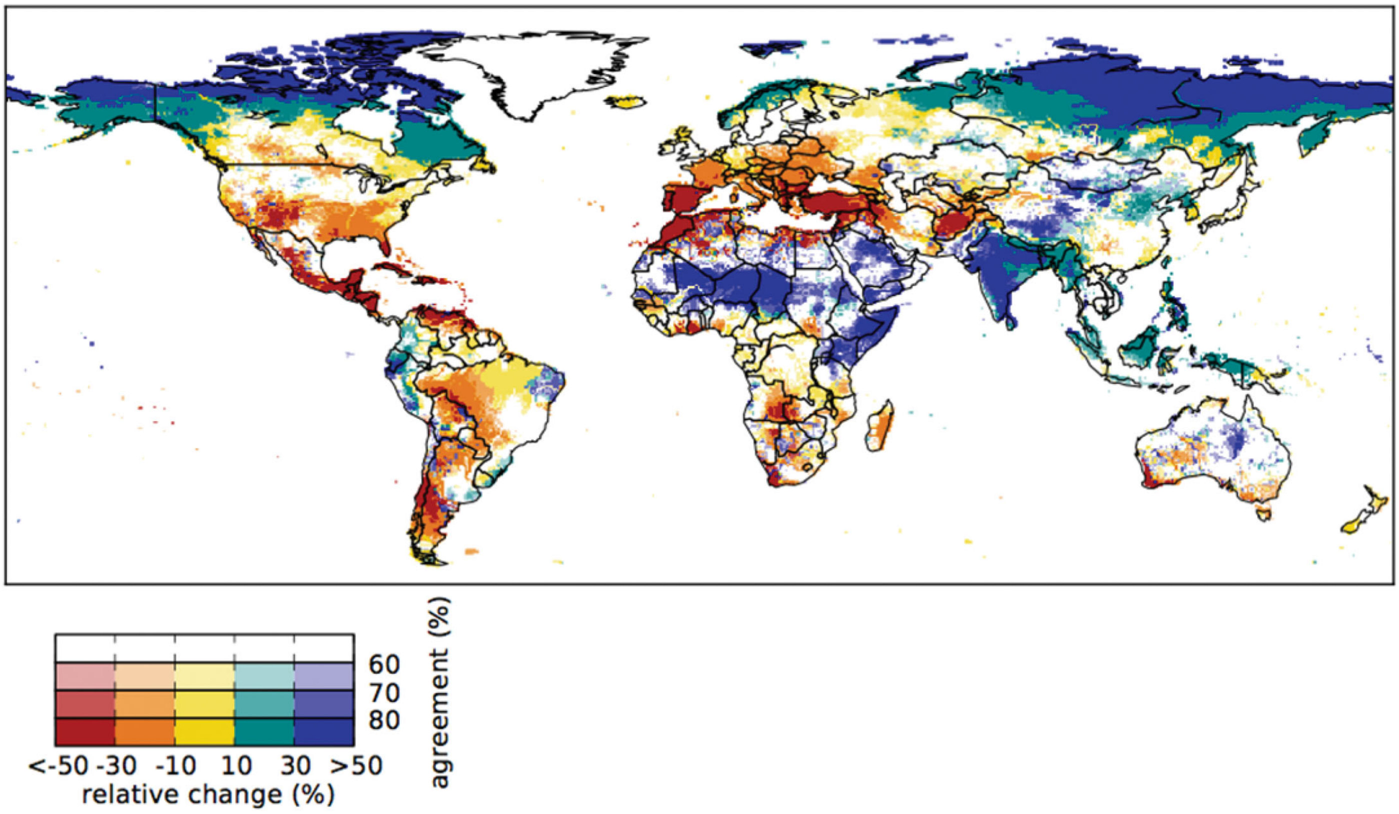

Figure 2. Relative change in annual discharge at 3°C temperature change compared with present day, under RCP 8.5. Color hues show the multimodel mean change, and saturation shows the agreement on the sign of change across all MHM-GCM combinations (percentage of model runs agreeing on the sign). Reproduced from *Schewe et al.* [2014].

climate models (GCMs), resulting in $11 \times 5 = 55$ different model outputs per climate scenario. Figure 2 shows for representative concentration pathway RCP8.5 the change in anneal mean discharge at 3°C global mean temperature change. The colors provide the dominant sign of the change, while the brightness of the color expresses to what degree the 55 model outputs agree. This analysis provides a very powerful method to identify regions of robust change. A caveat here is that all GCMs have been bias-corrected with the same forcing data set (WFD) [*Weedon et al.*, 2011]. This is likely to cause underestimation of the total model error. A likely better way of analyzing multimodel output is to refrain from bias-correction (or only correct for the number of rain days to avoid permanent drizzle), test for each model separately whether a significant change occurs between control and future projection and then count the number of models agreeing on a significant change in the same direction; see *Sperna Weiland et al.* [2012] for an example of this method.

5.2. Convergence and Coupling of Model Components

With so many global modeling groups working together in projects, reading each other's papers or participating in model intercomparisons, it is not unexpected that many parts of the various global models have very similar components. First, there are only so many ways in which one can simulate soil water storage change (leaky bucket, Darcy or full Richard's equation) or model evaporation (Thornwaite, Blaney-Criddle, Priestley-Taylor, and Penman-Monteith). Second, it is often more convenient to include and recode a proven and published component in one's own model then to start conceptualizing this anew. For example, PCR-GLOBWB [*van Beek et al.*, 2011] uses similar optimization criteria to simulate reservoir operations as *Haddeland et al.* [2006] and has adopted the flooding irrigation scheme that was implemented previously in WBMplus [*Wisser et al.*, 2010]. To give another example, the LESM ORCHIDEE [*Guimberteau et al.*, 2012] uses the DVM LPJ [*Sitch et al.*, 2003] for modeling climate-induced land cover change. Moreover, coupling modules for different parts of the earth system is customary in climate and earth system models, especially if they are community models ingesting efforts from many different groups. Efficient coupling tools and protocols have been developed that enable the exchange of state and output variables between different models or mode components (OASIS, CPL7, WRF-Hydro, OpenMI, and CSDMS). Third, many global hydrological models use the same data sets to parameterize their models (see Table 1), either because the data set is one of its kind, or simply the best around at the time. Finally, few model groups can withstand the temptation to venture into other domains and explore new exciting questions. As a result, many groups work on the extension of model functionality: GHWMs adding energy balances or plant physiology becoming LHM-like; LESM adding routing, inundation, reservoirs, and water human water abstractions, thus becoming more “GHMW-ish.”

Although this convergence of global hydrological models has certainly lead to better models, it has also created substantial entanglement between them. This effectively prohibits the use of an ensemble of these models (such as in Figure 2) probabilistically as model errors are likely statistically dependent and the ensemble mean not necessarily unbiased. This becomes evident when looking at multimodel validation studies [*Gerten et al*., 2004] and comparing validation studies [e.g., *Döll et al*., 2003; *Gosling and Arnell*, 2011; *van Beek et al*., 2011]. These show that if models are not calibrated on a basin-by-basin basis—which is not a good idea-, similar biases are found for the same basins: river flows in basins in semiarid regions are generally overestimated, the peak in Arctic and Monsoon rivers underestimated, and the timing of the peak of the Amazon simulated too early. These biases are considerable. Also, results in Europe and the conterminous U.S. are generally better than in the rest of the world. Unfortunately, this situation has not improved during the last 10 years. Possible reasons for this structural lack of improvement are the limited quality of rainfall forcing over Africa, South-America, (sub)-arctic and mountain regions, shortcomings in simulating runoff generation and lack of floodplain inundation algorithms in most models.

6. Back to Eagleson [1986]: Achievement and Missed Opportunities

From the review above it is clear that Peter Eagleson [*Eagleson*, 1986] was right on many accounts. First, he foresaw the emergence of global-scale hydrology as a necessary part of integrated models of physical, chemical, and biological systems of the earth. This indeed happened. From three distinct domains, a large number of global hydrological models have been developed. Global-scale hydrology is now a flourishing research field supported by a broad range of disciplines and many groups that are increasingly interacting. Second, *Eagleson* [1986] also called for encouraging young hydrologists to make a career in global hydrology. This has also happened, although hydrologists were relatively late to step onto the plate. After the first hydrologists contributed to the development of LSMs with improved runoff representations (e.g., VIC), global hydrology by hydrologists took off in the late 1990s with the advent of the GHWMs. Moreover, more and more hydrologists are now involved in global change issues that transcend traditional engineering hydrology, thus requiring broader knowledge on the Earth System. Again, this is a prerequisite that was mentioned in the *Eagleson* [1986]. Third, *Eagleson* [1986] also noticed that a necessary condition for global hydrology to flourish is the development of observational methods to fill the grid squares of global hydrological models with data: parameters, forcing, and states. But even he could not foresee the number, richness and resolution of data sets currently available (Table 1), economically collected due to proceedings in remote sensing and easily accessible due to the invention of internet technology.

So was it all a great success? No, there are missed opportunities. One can identify at least two research areas in catchment hydrology that should have interacted with global hydrology to the mutual advantage of both communities. First, despite the involvement of hydrologists in global-scale hydrology, runoff processes in GHMs are still represented rudimentary. They are mostly limited to saturated overland flow and subgrid representations (if at all present) based on TOPMODEL [*Beven and Kirkby*, 1997], the Variable Capacity Infiltration concept [*Liang et al*., 1994], or the (improved) ARNO scheme [*Dümenil and Todini*, 1992]. At the same time, during the advent of GHMs, a whole generation of catchment hydrologists was searching for new runoff mechanisms and understanding hydrologic response [*Hrachowitz et al*., 2014]. These insights could have been of great use to improve runoff generation in MHMs. On the other hand, a common joke among large-scale modelers is that every catchment hydrology group has its own model that works excellently in its own experimental catchment. Deriving more generic relations between mechanisms of runoff generation on the one hand and climate and geological setting on the other hand could be greatly helped by tying these individual catchments studies together with high-resolution global hydrological models. An interesting recent approach to facilitate such a step is the unifying framework proposed by *Clark et al*. [2015].

Second, the number of free parameters in global hydrological models is staggering and regularization methods used to limit these are generally crude. If calibration is attempted, it is often on a catchment-by-catchment basis [*Müller Schmied et al*., 2014] making parameters not transferrable from one basin to the other [*Sperna Weiland*, 2011]. There is thus a great need for more sophisticated calibration methods for GHMs. However, calibration has been a major topic in catchment hydrology for years. Whole generations of hydrologists have been focusing on parameter nonuniqueness or equifinality [*Beven*, 1993] and developed sophisticated and efficient Markov Chain Monte Carlo methods to deal with the parameter estimation under equifinality [e.g., *Beven and Binley*, 1992; *Duan et al*., 1992; *Vrugt et al*., 2003; *Kuczera et al*., 2006; *Vrugt et al*., 2009]. However, this line of research has generally focused on low-dimensional lumped-parameter conceptual rainfall-runoff models. Adaptation of their methods to the computationally more demanding calibration of GHMs would benefit both lines of research. Promising in this respect are Monte-Carlo-based sequential data-assimilation methods by which both parameters and states can be jointly estimated using multiple information observation types [*Wanders et al*., 2014]. However, also here the number of free parameters allowed is limited, and regularization rather crude. A more sophisticated regionalization scheme, such as the multiscale approach by *Samaniego et al*. [2010] could be a way forward here.

7. New Domains: Hydrology and . . .

As global hydrological models are extended with new capabilities they are growing out of their traditional domains and venture into new ones. Following is a short description about new domains of application where global hydrological models are starting to be used to aid analyses.

7.1. Food Security

Hydrology and crop science have gone hand-in-hand ever since the advent of agrohydrology in the 1960–1970s [*Kirkham et al*., 1974; *De Wit*, 1978; *Feddes et al*., 1979]. Nevertheless, at the global scale, estimates of crop production often rely on extrapolating productivity trends, possibly accounting for CO_2 fertilization and increase in water productivity, where it is generally assumed that water resources in current production areas are sufficient to support future growth [e.g., *Idso*, 2011]. However, recently hydrologists and ecologists have started to use DVMs to estimate the potential for future food production, taking account of the limited availability for blue and green water [*Rockström et al*., 2009; *Gerten et al*., 2011; *Kummu et al*., 2014]. Other groups have started to assess the sustainability of food production by determining which fraction of crop water use comes from nonsustainable water, i.e., fossil groundwater and surface water below the environmental threshold [*Gleeson et al*., 2012; *Esnault et al*., 2014]. Despite the increased use of GHMs in food security research, true GHM-based projections of future food security are questionable because so many factors remain uncertain. For instance, it is not known how much nonrenewable water resources can be used for food production before they run out or become economically unattainable. Also, the effects of possible (genetic) alterations to crops on the increase in water productivity and global crop distribution are uncertain factors, as well as the future availability and costs of nutrients, e.g., phosphate.

7.2. Economics

Hydroeconomics is an established field within water resources with a large body of literature. Hydroeconomic theory and models are used for water prizing, optimal water allocation, and guiding investments in water infrastructure [*Harou et al*., 2009]. Since the 1960s, hydroeconomic models have been developed, mostly for water valuation and using demand functions in the optimal allocation of water [e.g., *Graveline et al*., 2014]. They commonly exist of a physical network of water stores (i.e., reservoirs and groundwater) connected by links (channels, rivers, and distribution networks) to nodes of water demand. The models become economic because they work with economic demands, i.e., willingness to pay as a function of availability and function, and water allocation maximizes the aggregated net economic benefit (value) of water use in the system [*Harou et al*., 2009]. Although these hydroeconomic models are commonly used at the catchment scale, steps toward global applications are under way; see, for instance, a regional applications (MENA region) that combines use the outputs from a GHWM with the WEAP [*Yates et al*., 2005] water allocation model and optimal investment analysis [*Droogers et al*., 2012]. Another type of economic models consists of economy-wide general equilibrium models that find global optima between imports and exports. Recently, a global economic equilibrium model (GTAP) was used in tandem with a GHWM (HN08) to analyze the effect of climate change on global virtual water trade [*Konar et al*., 2013]. This interesting new development is based on the water-footprint and virtual water trade framework developed by *Hoekstra and Chapagain* [2008], which can be seen as one of the first hydroeconomic analyses at the global scale.

7.3. Energy

There are several possible connections between energy and water, and GHMs are starting to be used in several of these. The first and most obvious one is the relation between river discharge and hydropower generation [*Lehner et al*., 2005]. Here GHMs are used to compute potential hydropower capacity based on discharge and surface slope or height above sea level. A second, more recent application is projecting changes in discharge and surface water temperature under climate change to assess changes in cooling water capacity [*Van Vliet et al*., 2012]. Finally, water availability is pivotal to resolving the food, water, and energy nexus: what are the potentials to change to a low-carbon economy with energy partly or mostly supplied from biomass? However, most studies on the potential for future bioenergy production have considered either currently available land deemed productive or explored what-if scenarios of guaranteed resource availability [*De Vries et al*., 2007; *Slade et al*., 2014]. Only recently, *Gerbens-Leenes et al*. [2012] assessed the water consumption related to energy crops (in fact its water footprint, which also includes water use in biofuel production) and assessed the water scarcity induced by energy crop production. However, a full-scale global hydrological analysis using a GHM to assess the water limitations to energy crop production and its effect on surface and groundwater depletion has not been done yet.

7.4. Biodiversity

Loss of biodiversity due to land use change, climate change, and pollution has been a research topic for many decades, both empirically [*Tittensor et al*., 2014] as by modeling, the latter initially as part of integrated assessment models (e.g., GLOBIO in IMAGE) [*Alkemade et al*., 2009]. Dynamic vegetation models (DVMs) have been specifically developed to assess changes in global terrestrial ecosystems under climate change (see *Cramer et al*. [2001] and *Hickler et al*. [2013] for early and recent examples). But recently global hydrological models have been used to simulate changes in aquatic ecosystems. For instance, *Xenopoulos et al*. [2005] used a GHWM to investigate the change in number of fish species as a result of mean streamflow changes induced by climate change and water withdrawal. A similar study was performed by *Döll and Zhang* [2010] with an extended list of streamflow indicators representing alterations of streamflow regimes relevant to aquatic ecology. *Van Vliet et al*. [2013a, 2013b] used a LSM to analyze the effects of climate change on the abundance of several fish species globally, but considered not only changes in streamflow, but also changes in water temperature. Finally, *Vörösmarty et al*. [2010] presented a global analysis of aquatic biodiversity and human water security threats as a result of a large number of stressors related to catchment alterations, pollution, water system alterations, and biotic factors. The GHWM WBMPlus provided a number important variables for this study. These results show that GHMs are quickly becoming core tools in global terrestrial and aquatic biodiversity assessments.

7.5. Web-Based Hydroclimate Services

With the advent of global hydrology and the increasing success of medium-range and seasonal forecasting products as well as easily available multimodel GCM projections, an increasing number of groups are setting up (often still experimental) web-based hydroclimate services. These can be categorized into: (1) estimates of the current state of the hydrological cycle (mostly flood and drought status) and forecasts thereof; (2) mapping services showing GHM outputs; (3) interactive maps with risk indicators; (4) web-tools to provide risk-based analysis and test adaptation measures. Examples of the first type are the European drought observatory (www.edo.jrc.ec.europa.eu), the African and Latin American drought monitors (http://stream.princeton.edu/), the US drought monitor (www.emc.ncep.noaa.gov/mmb/nldas/drought/), the European flood awareness system (https://www.efas.eu/), and the eWaterCycle Project (http://forecast.ewatercycle.org/). Examples of the second class are Global-RIMS (http://globalrims.sr.unh.edu/) and clones of the same system representing results of other GHMs (e.g., www.globalhydrology.nl/maps). A well-known example of the third class of webs-services is the Aqueduct water risk atlas of the World Resources Institute (http://www.wri.org/our-work/project/aqueduct) that presents risk indicators based on outputs from several LSMs and GHWMs (e.g., VIC, WaterGap, and PCR-GLOBWB). An interesting new development is the Global Flood

10 year protection

Type or select a country, basin or state, and start to assess flood risks

By Country

Annual Expected Urban Damage $378.0M

Annual Avoided Urban Damage $403.4M

Optimistic | As usual | Pessimistic | 2030

Current Annual Expected Urban Damage $378.0M

Increased Impact Due To Socio-economic Change $1.7B

Increased Impact Due To Climate Change $1.3B

2030 Annual Expected Urban Damage $3.4B

RCP/SSP Selector:

	SSP1	SSP2	SSP3	SSP4	SSP5
RCP 2.6	○	○			○
RCP 4.5	○	○	○	○	○
RCP 6.0	○	●	○	○	○
RCP 8.5					○

Water Allocation Priorities
- ○ Equal priorities
- ● Default priorities
- ○ Downstream demand
- ○ User defined priorities

Adaptation Measures
- ○ Limiting urban-industry demand
- ○ Increasing supply
- ○ Increase water usage efficiency
- ● Custom

Reduce irrigated area [%]
Reduce Urban demand [%]
Reduce Industry demand [%]

Year: 2084
Avg. rainf. 312
Max. Rainf. 411
Min Rainf. 161

Figure 3. Examples of global hydroclimate services; (top) global flood analyzer (World Resources Institute) showing current and future flood risk for given protection levels; (bottom) Water2Invest.com, a web-based tool to analyze future water scarcity and the effectiveness of adaptation measures to close the water gap.

Analyzer (http://floods.wri.org) (Figure 3) providing for a given protection level current and future projected GDP and population affected by floods, attributing increased risk to climate change and socioeconomic change. Information is based on ensemble runs with PCR-GLOBWB, GLOFRIS flood extent estimates, and damage functions [*Winsemius et al.*, 2013; *Ward et al.*, 2013]. Figure 3 also presents an example of the fourth type of service, i.e., the web-based tool Water2Invest.com that allows one to estimate the future water gap and then analyze adaptation options to close it as well as their costs. Obviously, these are just a few examples of many initiatives now being developed. Many of these services are partly overlapping and lack an extensive audience and the resources to endure. However, they are interesting experiments driving the development of clever communication of GHM results as well as the web-based modeling technology that may help nonexpert users to perform global hydrological scenario analyses with a few mouse clicks.

8. Future Challenges and Directions

As the field of global hydrology and global hydrological modeling unfolds and develops into a mature geoscientific discipline, many challenges need to be overcome before it can reach its full potential. Following is a short selection of challenges and possible directions to tackle them. Following the author's background, this mainly revolves around challenges to global hydrology and water resources modeling.

8.1. Long Outstanding Issues

There are quite a number of long outstanding issues that need to be resolved to further improve the hydrology of GHMs. Comparison statistics between GHM output and observed discharges are really not that great without a basin-to-basin calibration [*Gerten et al*., 2004; *van Beek et al*., 2011; *Müller Schmied et al*., 2014]. As hydrologists we would like to think that this mainly caused by poor quality precipitation products, and indeed precipitation is one of the largest causes of uncertainty in GHM-output [*Döll and Fiedler*, 2008; *Biemans et al*., 2009]. Despite the larger number of precipitation products (see Table 1), not one of them performs much better than the others, many of them perform poorly in areas with high relief [*Immerzeel et al*., 2013] and none of them is properly validated over the tropics. It is expected that the Global Precipitation Measurement mission (GPM), combining precipitation estimates from a constellation of multiple satellites validated with measurements from ground radars and gauges, will be a large step forward to obtain globally reliable precipitation products. Obviously, precipitation cannot be blamed for everything. As stated in section 6, runoff generation processes at the surface and shallow subsurface are often conceptualized rudimentary in many GHMs without much account of local geology and hydroclimatology. Also, the timing of yearly runoff peaks in many GHMs is off in many large basins for lack of representing floodplain flooding processes and in the arctic basins for lack of a proper representation of snow and permafrost dynamics [*Candogan Yossef et al*., 2012]. Moreover, discharge is often overestimated in basins with large semiarid regions (e.g., Nile, Niger, and Murray-Darling) [*van Beek et al*., 2011; *Müller Schmied et al*., 2014], most likely by lack of a proper representation of wetland and floodplain evaporation and water consumption.

8.2. Missing Data Links

As described in section 3 and shown in Table 1, the number of valuable data sets is large and the efforts gone into collecting them enormous. Still there are some data sets on the wish list that will lead, when collected, to huge improvements in our ability to model global water resources. Examples of these are in random order: (1) there are quite a number of interbasin water diversions (e.g., California, China, and Western Europe) that have large impacts on the basin-scale water distribution. A database of these diversions (location, capacity, etc.) is urgently needed; (2) at a somewhat smaller spatial scale, it is very important to represent regional to local water distribution works to link areas of water demand to areas of water supply or availability. This becomes particularly urgent when moving to higher resolution GHWMs (see section 8.3) where it cannot be longer assumed that water demand is satisfied from cumulative flows, groundwater, and reservoirs from the same cell; (3) there is great need for a global database of channel dimensions (width, depth, and bed elevation) to further improve river routing and flood risk hazard simulations; (4) the inclusion of the GranD data set greatly improved the representation of reservoir storage in global hydrology. However, reservoir operations are a great unknown, and although several groups have tried to mimic reservoir operations by applying globally generic rules per reservoir type [*Haddeland et al*., 2006; *Hanasaki et al*., 2006; *van Beek et al*., 2011], operational rules are often very specific. A database of rules for as many reservoirs as possible would be extremely valuable; (5) global hydrogeological schematizations. The first global surface lithology maps [*Hartmann and Moosdorf*, 2012] permeability maps [*Gleeson et al*., 2011, 2014] and global groundwater models [*Fan et al*., 2013; *De Graaf et al*., 2015] have seen the light, but they only touch upon the problem of accurately representing subsurface water resources at the global scale. At the time of appearance of this paper, several groups are working on constructing or compiling these missing data sets and we are awaiting their arrival with anticipation.

Some more lines should be spent on the last issue. There is great need for an internationally recognized and accurate representation of aquifers' extent, depth (number of stacked aquifers), conductivity, and storage coefficients at the global scale. Groundwater is increasingly being used as a supplementary source of

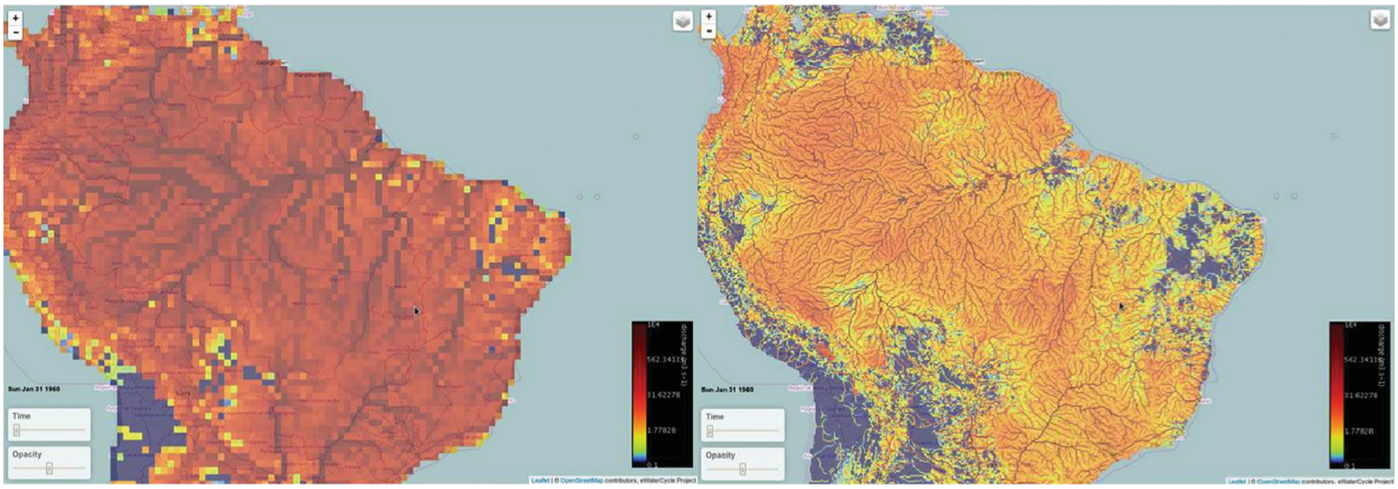

Figure 4. Toward hyperresolution: screenshots of discharge (m^3/s) from the GHWM PCR-GLOBWB 2.0 at (left) half degree resolution and (right) 5 arc min resolution.

water for food [*Wada et al*., 2014] leading to regional groundwater depletion [*Wada et al*., 2010; *Konikow*, 2011; *Gleeson et al*., 2012]. To project the development of future food security thus requires knowledge about the amount and thus longevity of groundwater resources in the world. Such knowledge is currently not available. Added to that, massive groundwater pumping leads to land subsidence (e.g., Jakarta, Mexico City, and Ho-Chi Minh City) causing structural damage and seasonal flooding. Without sufficient knowledge of hydrogeological and geomechanical subsoil properties there is no way to project what will happen to these cities in the near future nor a way to analyze the effectiveness of mitigation measures. As hydrologists we should look at the soil science community who took up the challenge to map the global soils and their properties at 1 km (www.globalsoilmap.net). It is a concerted effort whereby the world is divided into regions and subgroups become responsible for each of these regions gathering national maps and data and merge them together using modern data-driven techniques. They acquired an 18 million dollar grant from the Bill & Melinda Gates foundation to map sub-Saharan soils, while many institutes contribute in cash or in kind. In many parts of the world, groundwater is almost as important for food security as soils. So, such grants should be attainable for hydrogeological mapping as well. Even though a first effort has been made before (see www.whymap.org), progress here seems to be halted and should be kick-started by the global hydrological community at large.

8.3. Going Hyperresolution: Everywhere and Locally Relevant

Whether we like it or not, similarly to global circulation models, GHMs will be moving toward being formulated and run at increasingly higher spatial resolution. Currently, the first GHMs are running at 5 arc sec globally (Table 1 and Figure 4), while continental and basin-scale cutouts of these models run at resolutions up to 1×1 km^2 and smaller. Increasing resolution undoubtedly helps to better resolve atmospheric dynamics in GCMs, generally increasing the accuracy of model results. However, the benefits or need of very high resolutions in GHMs is less obvious. *Wood et al*. [2011] and *Bierkens et al*. [2014] provide extensive discussions about the scientific and societal merits of hyperresolution global modeling, while rightfully doubts and challenges have been brought to the table by *Beven and Cloke* [2012] and *Beven et al*. [2014].

Wood et al. [2011] and *Bierkens et al*. [2014] argue that GHM-applications such as terrestrial biogeochemical cycling (fate of N, P, C, and Si in terrestrial waters), global sediment transport, and global flood risk mapping will greatly benefit from higher resolution models. Also, there are many regions in the world where water resources models are lacking and forecasts or analyses from GHWMs, if locally relevant and accurate, would be beneficial. Moreover, the sheer ambition to try to model global hydrology and water resources at hyperresolution ($<$100 m) will boost hydrological innovation, i.e., acts as the proverbial "car of the future," as a number of fundamental challenges need to be overcome. To name three of these [*Bierkens et al*., 2014]:

1. *Breakdown of Subgrid Concepts*. When moving to higher resolution, subgrid concepts, e.g., those related to modeling saturated overland flow, glaciated areas, flooding and water use, need to be replaced by explicit physical representations. This requires new physical but computationally frugal representations,

additional data to parameterize these representations and additional computational power to resolve these. Moreover, as the parameterization of these new physical representations need to be resolution independent, upscaling, and downscaling issues [cf., *Blöschl and Sivapalan*, 1995; *Bierkens et al*., 2000] become important again [see *Samaniego et al*., 2010].

2. *Lack of Data and Epistemic Uncertainty*. As clearly argued by *Beven and Cloke* [2012], the parameterization of hyperresolution models is a huge challenge and may preclude hyperresolution models to be locally relevant as resolution is traded with accuracy. The hope is that new data sets will become available that would partly solve this issue. Also, because there are many GHMs available (Figure 1), multimodel ensemble predictions can be used at each location, which may remove some of the parameterization errors, provided they are mainly random (see section 5.2). Also, when moving to hyperresolutions almost direct comparison between model results and local observations is possible, as well as meaningful feedback from local stakeholders about the validity and value of model results [*Beven et al*., 2014].
3. *Computational Issues*. Hyperresolution global modeling results in large computational demands in terms of CPU-time and storage requirements [*Kollet et al*., 2010; *Maxwell*, 2013]. Just increasing the spatial resolution by a factor of 10 increases calculation and storage requirements by a factor of 100. Moreover, as stated before, when increasing resolution, many processes that use simple subgrid parameterizations may need to be replaced by explicit process dynamics further increasing computational efforts. Rapid developments in both hardware and software architecture support these increased computational challenges. However, efficient numerical and parallel computational methods need to be developed or adopted from other fields to fully exploit this computational capability. At the same time, it is also important to invest in methods to deduce models of reduced complexity from complex hyperresolution models, i.e., in order to perform uncertainty analysis, ensemble modeling, and data-assimilation at feasible run times.

8.4. The Human Factor: Sociohydrology and Hydroeconomy at the Global Scale

Human impacts on the terrestrial hydrological cycle have been much larger then climate change [*Gleick*, 1993; *Wada et al*., 2011b] and will exceed the effects of moderate climate change in parts of Asia and the United States [*Haddeland et al*., 2013]. However, the way human impacts are modeled in GHWMs and LESMs is very different between models, as consistent theories to model human water withdrawal, redistribution, allocation, and consumption are lacking [*Nazemi and Wheater*, 2015a] as well as the data sets to support the formulation of such theories. These differences are less conspicuous when performing global validation (e.g., using AQUASTAT), but more so when compared in single basins [*Haddeland et al*., 2013] or in future projections [*Wada et al*., 2013; *Flörke et al*., 2013]. To improve water use models *Nazemi and Wheater* [2015b] propose a "global initiative wherein regional case studies are used to validate multiple water use concepts based on multiple hypotheses for data support, water resource management algorithms and host models in a unified uncertainty assessment framework." Such an initiative would certainly help to improve current water use and allocation modules in GHWMs. However, to be able to predict how water demand, withdrawal, and consumption would develop in the future, one needs to formulate hypotheses on how the different actors involved in water use and water management would react in terms of changing policies and adapting technologies. Such a framework calls for modeling the coupled human-water system at regional scales [e.g., *Di Baldassarre et al*., 2009], now commonly referred to as sociohydrology [*Sivapalan et al*., 2012; *Di Baldassarre et al*., 2013].

Figure 5 presents an example of a framework, fitting the realms of hydroeconomics and sociohydrology, that could be used to describe in a very general manner the socio-hydro-economic system from which past and future changes in water demand, water allocation and consumption can be explained. It represents the different actors (e.g., farmers, households, factories, governmental and nongovernmental organizations, investors, etc.) having stakes in water use that determine how potentially scarce water resources are distributed between competing regions and sectors. It also portrays the possible pathways of policy response and technological adjustments as a result of changes in water availability and water demand resulting from climate and socioeconomic change. The diverging arrows signify the many different alternatives in both policies and technologies adopted. Which alternative is feasible or optimal depends on a number of constraints that have to with the physiography of the region, regional economics as well as the cultural, legal, and institutional makeup of the region. Finally, feasible and possibly optimal strategies that are chosen feedback to the water-availability and water demand subsystems influencing water abstraction, allocation and consumption.

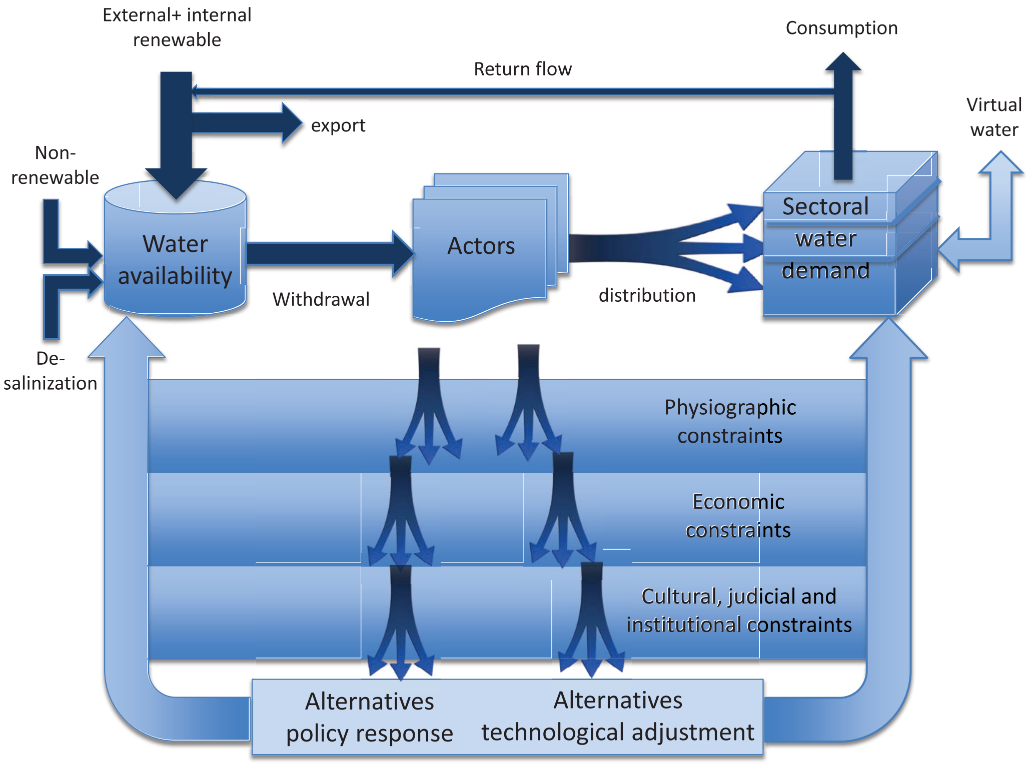

Figure 5. Socio-hydro-economic interactions and feedbacks determining policy response and technological adjustment to increasing water stress.

In this system, different actors actively compete for scarce resources and the policy and technological choices made depend on choices made in previous times. It is thus reasonable to assume that the outcomes are sensible to initial conditions and random perturbations (i.e., individual extreme drought events; choices of other actors) of the system and multiple equally like outcomes are conceivable. To capture this nonpredictability, the stylized models of sociohydrology [e.g., *Di Baldassarre et al.*, 2009; *Van Emmerik et al.*, 2014; *Srinivasan*, 2015] should be extended with stochastic perturbations. Alternatively, agent-based modeling approaches could be used [e.g., *Dermody et al.*, 2014; *Arnold et al.*, 2015]. It would not be feasible or realistic to define such models globally for each GHM grid cell. Instead, it would be necessary to divide the world into water provinces, i.e., units that are a defined by a combination of basin and administrative boundaries (similar to food producing units), and set up such models for each of these units. Propagating the model equations or agent's responses in time would then have to be done for all provinces jointly as they are connected by cross-boundary flows.

9. The Future of Global Hydrology and Beyond

The developments and associated challenges described in the previous section are extrapolations of current trends and likely to be in the center of research during the coming decade(s). However, challenged to think beyond the next decade, a number of further developments can be foreseen that are a reflection of the state of global hydrology at his full potential:

The different types of GHMs in Table 2 will all have converged to physically-based continental earth system models (PBCESMs). In these, hydrology is modeled from first principles, i.e., variable saturated flow in soil and groundwater using 3-D-Richards equation, including preferential flow, fully coupled with surface water flow simulated with shallow water equations [*Brunner and Simmons*, 2012]. Land-atmosphere interaction will be represented with a full energy balance [*Kollet and Maxwell*, 2006] coupled with a plant-physiological dynamic vegetation model, allowing the explicit calculation of plant and leaf water potentials and intercellular CO_2 content as system states [*Daly et al.*, 2004; *Brolsma et al.*, 2010], the simulation of phenology, stand

and canopy structure [*Smith et al*., 2001], and crop growth [*Bondeau et al*., 2007], with inclusion of carbon and nutrient dynamics. Modules for surface water and groundwater quality are included [e.g., *Appelo*, 1994] enabling the simulation of the fate of carbon, silica, nutrients, macrochemistry, trace elements, and emerging substances as well as ecosystem relevant parameters such as DOC and water temperature. The energy balance and roughness characteristics from the simulated vegetation structure allows a full coupling with atmospheric models, be it global climate models, numerical weather prediction models, nonhydrostatic regional circulation models, and Large Eddy Simulation. Human interaction with the hydrological cycle is modeled explicitly, as in the current generation of GHWMs, but with reservoir-specific operation rules, the inclusion of local and regional water redistribution networks and agent-based sociohydrological models to simulate the technological and policy response of local and regional stakeholders to floods, droughts or deteriorating water quality. With more than 70% of the population living in cities an urban metabolism is part of the PBCESMs.

PBCESMs will run at variable resolution, depending on the extent of the model domain, optionally with unstructured grids, with seamless upscaling and downscaling of model parameters. Efficient numerical algorithms, massive parallel computing and zettaflop (10^{21}) computational facilities will keep run times at bay. The PBCESMs are fully modular, allowing the switching on and off of various components or replace them by simple parameterizations to speed up calculation times. Parameterization of PBCESMs remains a daunting task, with ground measurements more and more replaced by hyperspectral and high-resolution airborne and spaceborne remote sensing products, including lidar-based digital elevation models for most of the globe. Also, the wikification of GHMs, a term first coined by R. Hut and N. van de Giesen (personal communication, 2015), which allows local and regional modelers and stakeholders to suggest improvements of parameters and concepts “from their own backyard” for each FBCESM’s wiki-page, helps to further improve model parameterization. The parameterization of the subsoil still remains a huge challenge.

Multimodel ensembles of PBCESMs are used in a variety of climate services providing estimates of past and current states, seamless prediction from hours to 6 months and projections under a variety of what-if scenarios. By zooming in to regions of interest, hindcasts and forecasts can be performed at higher resolutions and the impact of proposed measures (e.g., adding sand bags to elevate a levee, or breaching a levee on purpose to deviate flood waters) analyzed on the fly. In case of emergency floods, various alternative scenarios to mitigate the flood peak or prevent loss of life and economic damage are analyzed in real time and the best strategies (e.g., where to put the sandbags; when, where, and by what route to evacuate people) are distributed to mobile devices by apps or social media to inform water authorities, rescue personnel, and citizens which actions to take. Drought forecasting systems will be able to provide midterm to seasonal drought forecasts at the paddock scale. Small businesses will exploit this information to sell software for optimal irrigation application and associated water storage strategies to maximize profit under minimal water use. Farmers in developing countries will receive information on mobile devices what type of crops to plant and what would be a fair price for crop assurance.

PBCESMs are an integral part of integrated assessment models (IAMs; e.g., IMAGE, MESSAGE, International Futures). IAMs are used to support the IPSF (Intergovernmental Panel on Sustainable Futures) to explore possible global futures in terms of water security, food security, biodiversity, hazards, global trade, economic development, and general human well-being. The resolution of IAMs is sufficient to evaluate local and regional technical and policy options to close future water gaps, protect against flooding, or ensuring good water quality. Apart from business as usual storylines, scenarios are developed that explore futures with 100% sustainable water use and no biodiversity loss while maximizing food security and economic development across the globe. These scenarios are used to support bilateral and multilateral negotiations about treaties on water, energy, nature conservation, and trade. National economic outlooks will be supported by these analyses, now including the possible effect of predicted variations in large climate modes (ENSO, PDO, and NAO) on food prices and trade volumes. Operational versions of IAMs (lead times days to months) are regularly used by international relief organizations, (re)assurance companies, and the energy and commodity trade.

Water in all its forms and function is at the heart of these future model developments. Thus, understanding and modeling the terrestrial hydrological cycle, including its sensitivities and interactions with the earth (and human) system, is key. Hydrological research at all scales and from all disciplines will undoubtedly provide invaluable contributions to meet this challenge.

10. Conclusion

A review was presented of the developments in global hydrology since the paper of *Eagleson* [1986] that predicted the emergence of global-scale hydrology. It was shown that since 1986 global hydrology has developed into a large research field that transcends hydrologic science, with global hydrological models or model components contributed from global atmospheric and climate modeling, global water resources assessments and global vegetation and terrestrial carbon-cycle modeling. A Google Scholar search performed on 20 February 2015 on the terms "global hydrology," "global-scale hydrology," and "global water resources" collectively yielded 9781 references, showing a large research field indeed. Instrumental to the development of global hydrological models (GHMs) have been the construction of global data sets for validation, meteorological forcing, and validation. During the last few years, GHMs have permeated new research domains, related to food security, economics, energy, and biodiversity. Also, GHMs are contributing to integrated assessment models and are behind a growing number of web-based hydroclimate services.

Despite its success, global hydrology has failed to connect to a number of relevant developments in hydrology, in particular research on runoff generating processes and on model calibration and parameter identification methods. Also, GHMs are still reproducing discharge observations rather poorly in quite a number of basins, likely due to lack of accurate precipitation forcing, the right runoff generation mechanisms, floodplain inundation, and wetland evaporation. Apart from resolving these outstanding issues, many challenges need to be overcome for global hydrology to reach its full potential. When focusing on global water resources assessment these are (1) the improvement or construction of data sets on interbasin transfers, regional water distribution network, river cross-sectional dimensions, and hydrogeological subsurface properties; (2) challenges following from hyperresolution modeling such as replacing subgrid concepts by frugal (in CPU and parameters) physical process representations, reducing process- and parameter uncertainty and solving computational issues; (3) improving the way human water demand and human water use is modeled in global hydrology and water resources modeling. Looking further into the future, GHMs are likely to evolve into physically based continental earth system models that will constitute the central core of climate services and integrated assessment models, thereby contributing to global solutions toward food security and sustainable use of energy and resources. These developments and challenges will certainly generate a large body of exciting global hydrology research in the near future.

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