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Accelerating advances in continental domain hydrologic modeling

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Abstract

In the past, hydrologic modeling of surface water resources has mainly focused on simulating the hydrologic cycle at local to regional catchment modeling domains. There now exists a level of maturity amongst the catchment, global water security, and land surface modeling communities such that these communities are converging towards continental domain hydrologic models. This commentary, written from a catchment hydrology community perspective, provides a review of progress in each community towards this achievement, identifies common challenges the communities face, and details immediate and specific areas in which these communities can mutually benefit one another from the convergence of their research perspectives. Those include: (1) creating new incentives and infrastructure to report and share model inputs, outputs, and parameters in data services and open access, machine-independent formats for model replication or re-analysis; (2) ensuring that hydrologic models have: sufficient complexity to represent the dominant physical processes and adequate representation of anthropogenic impacts on the terrestrial water cycle, a process-based approach to model parameter estimation, and appropriate parameterizations to represent large-scale fluxes and scaling behavior; (3) maintaining a balance between model complexity and data availability as well as uncertainties and (4) quantifying and communicating significant advancements towards these modeling goals.

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1. Introduction

Hydrologic models have long been essential tools to help manage finite water supplies. The purposes of hydrologic models today remain much the same as nearly fifty years ago, when *Freeze and Harlan* [1969] enumerated their uses: "1) to synthesize past hydrologic events, 2) to predict future hydrologic events, 3) to evaluate the effects of artificial changes imposed by man (sic) on the hydrologic regime, and 4) to provide a means of research for improving our understanding of hydrology in general." For more than four decades, catchment domain hydrologic models have provided the hydrologic foundation upon which these purposes were realized.

Emerging water management challenges are now pushing the desired modeling domain from catchment to continental and global domains. To this end, hydrologic information at the continental and global scale is critically needed to inform water allocation in international, national and large river basins (e.g. *United Nations Economic Comission for Europe* [2014]), to achieve global water security [*Griffiths et al.*, 2013], for national water assessments [*Alley et al.*, 2013], to provide a consistent approach to evaluating water resources [*Hering et al.*, 2010; *Laniak et al.*, 2013], to provide a foundation for international flood policy [*European Union*, 2007] and operational flood forecasting services [*Mcenery et al.*, 2005; *Todini*, 2006; *Cloke and Pappenberger*, 2009; *Demeritt et al.*, 2013], to advise water quality and ecological directives [*Kallis and Butler*, 2001], and to plan for the effects of climate extremes on water resources [*Collins et al.*, 2009].

With this myriad of complex science questions and pressing societal issues, the hydrology community has evolved into several modeling communities that emphasize different aspects of the hydrologic cycle and, therefore, provide focused modeling efforts to address a subset of these questions. There is now a level of maturity amongst the respective communities such that convergence towards a collective, transformational achievement is at hand: the realization of continental domain hydrologic models capable of addressing problems of practical importance. With this same advancement in reach, each community is faced with a similar set of challenges in the representation of water management actions and infrastructure, the estimation of model parameters, the skill with

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which components of the water balance can be simulated, the spatial domain of the model, and the transferability to ungauged areas [*Wood et al.*, 2011; *Wada et al.*, 2014; *Bierkens et al.*, 2015]. Hydrologists, and especially modelers, tend to become entrenched in the traditions and commonly made assumptions of their respective communities; yet, by placing the advancements of each community in the context of a common goal – the achievement of continental domain hydrologic modeling capable of addressing problems of practical importance – a unifying theme around which the various communities could rally emerges.

This paper focuses on three modeling communities (presented alphabetically) – all of which are directly pursuing continental domain hydrologic modeling and have developed important capabilities useful for surface water resources planning across large spatial domains: the catchment modeling (CM) community, the global water security modeling (GWSM) community, and the land-surface modeling (LSM) community. The communities are briefly introduced here and further described in later sections. It should be noted that the emphasis of this paper is on the explicit modeling of surface water resources at the continental domain and, therefore, this paper does not address the specificities of large groundwater models [*de Graaf et al.*, 2015] or coupled groundwater-surface water modeling for large domains [e.g. *Maxwell et al.*, 2015]. However, we acknowledge the importance of groundwater both for its interaction with surface water and as a key water resource – indeed, in one or both of these roles, it is either implicitly or explicitly dealt with by the three above communities.

The CM community (in which most of these authors reside) is predominantly focused on model simulations of streamflow for unimpaired headwater catchments [*Gupta et al.*, 2014] and has devoted considerable effort to developing datasets and methods for parameter estimation and transferability [*Duan et al.*, 2006; *Newman et al.*, 2015]. The GWSM community focuses on streamflow simulation at the global scale [*Arnell*, 1999; *Vörösmarty et al.*, 2000; *Döll et al.*, 2003], and has devoted considerable effort to modeling the impacts of large-scale water management [*Pokhrel et al.*, 2011] with recent water security models increasing their spatial and process complexity [*Müller Schmied et al.*, 2014; *Sutanudjaja et al.*, 2014; *Wada et al.*, 2014]. The LSM community focuses on simulating land-atmosphere interactions to provide a lower boundary condition to climate

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models [*Pitman*, 2003; *Lawrence et al.*, 2011]. Recent developments in land-surface modeling seek to improve simulations of the terrestrial hydrologic cycle and land-atmosphere interactions by representing hydrologic processes more accurately [*Clark et al.*, 2015c] and an effort is now underway to provide predictions at the "hyper-resolution," such that the spatial scale of the predictions are relevant to water resource planning [*Wood et al.*, 2011; *Bierkens et al.*, 2015].

It comes as no surprise that differences in the emphases of modeling communities have also affected their respective hydrologic process foci. As no model is a perfect representation of hydrologic catchment processes, modeling communities have prioritized which water balance terms should be most accurately reproduced by their respective models. For example, the CM community has long emphasized skill in streamflow simulation because the roots of this community are in providing reliable estimates of streamflow and related processes (the "horizontal" fluxes of the hydrologic cycle) to support water resources planning and allocation. By contrast, the LSM community focuses much more on atmospheric and evapotranspiration processes (the "vertical" fluxes of the hydrologic cycle) because the roots of the community are in providing a lower boundary condition to climate models (i.e., to simulate land-atmosphere interactions). When models inevitably face difficulties in closing the water balance, the CM community usually adjusts the atmospheric fluxes (either the incoming precipitation flux or the outgoing evaporation flux) or the outgoing regional groundwater flux, whereas the LSM community adjusts runoff to close the water balance. Therefore, the water balance term that the CM community emphasizes most in its modeling efforts (streamflow) is used as an adjustment factor to close the water balance in the LSM community, while the water balance term that the LSM community emphasizes most in its modeling efforts (evapotranspiration) is used to close the water balance in the CM community. This example illustrates that – despite convergence of the communities towards the same achievement – substantial disconnects between the communities exist.

This commentary is from the perspective of members of the CM community. From this perspective, the CM community has long been tasked with the development of hydrologic models that can be used for surface water resources planning. For this reason, the CM community has been primarily motivated to develop models that focus on this

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need. Therefore, catchment models have historically been developed at the local to regional scale and the CM community is only recently considering how to apply catchment models to continental and global domains. Conversely, the LSM and GWSM communities have historically led the development of hydrologic models at the global scale to quantify the effects of climate and human alteration to the hydrologic cycle; however, the estimates of such effects have remained at coarse temporal and spatial scales and the skill in prediction of surface water resources does not lend these models to use in water resource planning.

Each modeling community has and will continue to play a unique and important role in developing continental domain hydrologic models and it is unreasonable to suggest that communities would abandon long-standing modeling efforts with substantial stakeholder investment to rally behind a singular hydrologic model or community. Yet, the questions that hydrologic models are asked to address are becoming increasingly interdisciplinary and multi-objective, creating the need to combine expertise and modeling tools from the different communities. Examples of such interdisciplinary challenges include representing the biophysical controls on transpiration, understanding the effect of climate change projections on irrigation water availability and crop water requirements, and setting operational water use limits across surface and groundwater resources to maintain economic, cultural, recreational, and ecosystem values of water. There have been a number of commentaries advocating for and discussing efforts underway to bring modeling communities together [*Wood et al.*, 2011; *Montanari et al.*, 2013; *Bierkens et al.*, 2015]; yet, there has not been a review of progress in each of the communities through the common lens of continental domain hydrologic modeling. Through such a review, we identify progress in each community and common challenges the communities face in this pursuit. Lastly, we detail research activities that can accelerate advances across all communities towards continental-domain hydrologic modeling.

2. Community modeling efforts at continental domains

This commentary focuses on models that simulate the surface-water component of the terrestrial hydrologic cycle over continental domains. Hydrologic models utilized for

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these purposes have distinct differences from modeling efforts for purely scientific pursuits [*Wagener and McIntyre*, 2005; *Farmer*, 2015] and typically have specific needs related to the spatial and temporal resolution of the model output, the model structure and parameterization, the execution time, the robustness of results, and the model performance. Models of the terrestrial hydrologic cycle need to be capable of answering questions such as those outlined by the *National Research Council* [2012]. Such questions include: (1) How do anthropogenic modifications of water resources affect water availability? (2) What is the environmental impact of shifts and regime changes in streamflow? (3) How do water resources respond to changes in climate and land cover? (4) How does the movement of contaminants through large domains change? and (5) How is water quality impacted by changes to the climate and landscape? Answers to these questions must be provided with information on both reliability and uncertainty of the model and its outputs to inform decision-making and evaluate management tradeoffs. Additional constraints arise when these questions are asked over a continental domain, where dominant hydrologic and climate processes can vary and consistency in data, models, and approaches are essential.

The distinction between modeling communities is defined by their modeling objectives and, in turn, has resulted in differences across communities in their approaches to parameterizations of hydrologic, atmospheric, and human-engineered processes, and the emphasis placed on the evaluation of model performance. In Table 1 we present, from our own perspective, the extent to which these communities meet the modeling conditions for continental domain hydrologic models and highlight the contributions and weaknesses of each community in this context.

Table 1. Historical emphasis on various aspects of hydrologic modeling in different communities.

Modeling Community	Representation of water management	Parameter estimation	Skill in streamflow simulations	Transferability and spatial coverage
Catchment	Medium	High	High	Low
Global water security	Medium	Medium	Low	Medium
Land surface	Low	Low	Low	High

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2.1 Catchment modeling community

Models developed and utilized by the CM community have historically been applied to individual catchments [*Reed et al.* 2004; *Smith et al. 2013*], though recent applications extend catchment hydrologic models to large river basins [*Arheimer et al.*, 2012; *Weiskel et al.*, 2014] and even continental domains [*Donnelly et al.*, 2015; *Pechlivanidis and Arheimer*, 2015] through the leveraging of continental and global domain forcings and geophysical datasets [*Colombo et al.*, 2007; *Atkinson et al.*, 2008; *Viger*, 2014; *Viger and Bock*, 2014; *Newman et al.*, 2015] and providing a consistent approach to estimate spatially variable model parameter values [*Kumar et al.*, 2013b; *Samaniego et al.*, 2010]. These large-domain applications allow consistent spatial comparisons while still providing model results at the spatial scale needed for water management decisions.

Models developed and utilized by the CM community vary in complexity, ranging from lumped bucket-style rainfall-runoff models with a coarse representation of hydrologic processes [*Bergström*, 1995; *Donigian et al.*, 1995; *Leavesley and Stannard*, 1995; *Perrin et al.*, 2003] to distributed hydrologic models that attempt to explicitly represent a myriad of hydrologic and biophysical processes [*Wigmosta et al.*, 1994; *Rigon et al.*, 2006]. When used for continental-domain studies, the type of model tends to fall toward the simpler end of the spectrum, and does not provide a detailed representation of the controls of energy on snow melt and evapotranspiration, the role of spatial variability in meteorology or vegetation topography or soils on spatial variability in hydrologic fluxes, and the lateral fluxes of water across the landscape [*Gupta et al.*, 2014]. Moreover, many of the catchment models applied for continental-domain studies do not use process-based approaches to parameter estimation (i.e., the “mapping” between meteorological inputs and streamflow for individual basins) but, rather, calibration-based approaches that do not evaluate the internal hydrologic processes [*Merz and Blöschl*, 2004; *Oudin et al.*, 2008; *Andréassian et al.*, 2009]. Application of such curve-fitting methods to individual basins can sometimes lead to an inconsistent spatial representation of model parameters and hydrologic processes and greatly complicate parameter transferability efforts [*Samaniego et al.*, 2010]. A blind use of the curve-fitting approaches to parameter estimation can also lead to “getting the right answers for the

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wrong reasons" [*Kirchner*, 2006] and will hence greatly constrain the capability to use such models to extrapolate in space and time.

Two developments are necessary for the CM community to produce meaningful contributions for continental-domain applications: (1) Models should have more physical realism and explicit representation of spatial variability; and (2) Parameter estimation should be more constrained by physical considerations, to ensure the robustness of model simulations. The CM community is indeed moving in this direction [*Gupta et al.*, 2008; *Samaniego et al.*, 2010].

2.2 Global water security modeling community

The GWSM community is broadly defined here as the community of academics and policy makers who focus on quantifying global water availability and water use to describe threats to regional and global water security [*Cook and Bakker*, 2012]. As *Bierkens et al.* [2015] provide a detailed review of progress in the GWSM community, only summary comments are provided here. Whereas these models typically use a rather rudimentary representation of hydrologic processes [*Arnell*, 1999; *Döll et al.,* 2003; *Vörösmarty et al.* 2000] – though some models used for global water security assessments come from the LSM community with more detailed process representation [*Nijssen et al.*, 2001] – the GWSM community is now developing models with greater space-time resolution and process complexity that include water management impacts on the terrestrial water cycle [*Pokhrel et al*. 2012; *Sutanudjaja et al., 2014*]. Recent efforts such as those by *Wada et al.* [2014] and *Müller Schmied et al.* [2014] run global water security models at 10 km resolution globally with sub-grid parameterization of surface runoff, interflow and groundwater discharge; yet, fully realistic representations of water allocation and water demands are not accounted for in these models [*Wada et al.*, 2014].

2.3 Land surface modeling community

The efforts of the LSM community largely focus on the complex interactions and feedbacks at the boundary between the land and atmosphere through the modeling of a broad range of biophysical and hydrologic processes [*Pitman*, 2003; *Clark et al.*, 2015c; *Sato et al.*, 2015]. Land surface models are not explicitly hydrologic models, yet they still aim at simulating the dominant hydrologic processes in order to provide reasonable

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simulations of the terrestrial water cycle and land-atmosphere interactions. These models are just now beginning to account for anthropogenic effects on water availability, including water withdrawals and irrigation.

The difference between the models developed by the LSM community and other modeling communities is exemplified by their modeling objectives: the motivation of the LSM community is to simulate land-atmosphere fluxes, historically focusing on biophysical processes; whereas the motivation of other hydrologic models is to simulate streamflow, historically focusing on hydrologic processes. While this distinction has become less clear-cut over time, land-surface models still have more emphasis on biophysical processes, such as representing controls on stomatal conductance, whereas other hydrologic models have more emphasis on hydrologic processes, such as representing lateral flow. The value of land surface models for continental domain hydrologic modeling has been long been recognized (and utilized) – for example, the Variable Infiltration Capacity (VIC) model has been widely used for continental and even global scale water resource assessments [*Maurer et al.*, 2001; *Nijssen et al.*, 2001].

An interesting distinction between the LSM and CM communities is that the LSM community typically focuses on differences in process parameterizations (assuming the model parameters as given and certain) [*Henderson-Sellers et al.* 1995], while the CM community focuses on parameter estimation [*Duan et al.*, 2006]. There are many parameters in land surface models that represent the spatial variability in biophysical and hydrologic processes but these parameters are typically set to default values [*Overgaard et al.*, 2006]. Land-surface models do a credible job of relating geophysical attributes (e.g., topography, vegetation and soils) to model parameters (e.g., storage and transmission of water in soils), providing a good initial representation of spatial variability in the landscape on large-scale hydrologic simulations [*Sellers et al.*, 1996; *Chen and Dudhia*, 2001]. The LSM community however places limited effort on adjusting the default model parameter fields (e.g., through model calibration), meaning that land-surface models typically yield poor performance in simulations of streamflow at the spatial scales of interest to water managers [*Wood et al.*, 1998].

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The development trajectory of the LSM community is one toward greater model complexity [*Wood et al.*, 2011; *Bierkens et al.*, 2015; *Clark et al.*, 2015c]. This is manifest in both an increase in process complexity – as evident in the number of biophysical and hydrologic processes explicitly included in these models [*Sellers et al.*, 1997; *Pitman*, 2003; *Clark et al.*, 2015c] – and an increase in spatial complexity [*Wood et al.*, 2012]. It is reasonable to hypothesize that increases in model complexity should increase the realism of process representation; yet more complex models are often criticized for their reliance on point-scale equations, which may not apply to spatially heterogeneous supports. Further, the computational expense of complex models restricts the ability to extensively experiment with different parameters and structures in order to improve model simulations. Moving towards finer resolutions has been shown to result in more realistic models in atmospheric sciences (e.g. *Ban et al.* [2014]; *Rasmussen et al.* [2014]), and, based on this precedent, the LSM community has great expectations on moving towards hyperresolution models [*Wood et al.*, 2011]. However, modeling of subsurface processes is fundamentally different; opposite to atmospheric processes, the parameterization of subsurface processes remains challenging regardless of scale [*Beven et al.*, 2014].

3. Overcoming gaps across modeling communities: Integrating diverse research perspectives

Process-based hydrologic modeling has recently been described as a complex interdisciplinary pursuit [*Clark et al.*, 2015b]. As such, the diversity in the approaches and scientific traditions of the different hydrologic communities gives us the opportunity to learn from each other and accelerate modeling advances. We believe this collaborative perspective is indicative of a larger shift towards integrated and interdisciplinary efforts to create Earth System Models that seek to provide a good representation of all elements of the water cycle [*Wood et al.*, 2011; *Bierkens et al.*, 2015; *Clark et al.*, 2015c]. In our opinion the development and performance of continental-domain hydrologic models is considerably constrained by the following factors and these constraints are irrespective of the current progress made by each modeling community:

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1) Lack of consistency and quality assurance evaluation in large domain datasets of meteorology, geophysical attributes (topography, vegetation, soils, geology), water management data, and hydrologic states and fluxes;
2) Inadequate model representation of dominant hydrologic processes and limited attention to physical constraints in model parameter estimation; and
3) Lack of consistent evaluation of model performance (for example, benchmarking of models), quantification of uncertainty, and communication of modeling tools and results to the water resources planning community.

Given that data quality is paramount to hydrologic modeling efforts, a substantial portion of this section is focused on that topic. We also believe that this is an area where collaboration could begin immediately and outcomes would be highly impactful to the communities. Common challenges also exist in how physical processes can be represented, such as: (1) how to explicitly resolve land, subsurface, and atmosphere interactions, (2) how to discretize the spatial and temporal domains, and (3) how to parameterize connectivity and feedback between processes. Lastly, upon model evaluation, quantification of uncertainty and communication of modeling tools and results is discussed. These sections capture the major modeling challenges that are shared across communities and how the different communities can mutually benefit from synergistic advancements.

3.1 Data consistency, exchange, evaluation, and quality assurance

Advancing hydrologic modeling for water resources planning at continental domains requires high resolution input data that are quality assured and consistent across the domain. Many new global datasets are provided through open access portals (Table 2), which have created enormous potential to this end. These datasets mainly originate from the LSM and GWSM communities, but also from the earth observation community and public portals of governmental agencies, including those doing operational hydrologic modeling, such as flood forecasting. Although the datasets often claim to have high resolution they may not be ready for immediate use, particularly in catchment modeling and for water resources planning. For instance, the global datasets may be difficult to use for some or all of the following reasons: insufficient metadata, incompatible formats, lack

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of information on accuracy of the data at the resolution needed for local catchments, or lack of coverage across a large domain. To fully utilize these datasets, it is essential for the communities to collaborate through the exchange, and quality assurance evaluation of such datasets. Therefore, new incentives and infrastructure to report and share corrected versions of these and future databases is required through data services and open access, machine-independent formats for model replication, re-analysis, and use by researchers in other scientific communities.

Table 2. Some examples of open data from global or continental databases that enable catchment modeling at the continental scale.

Type of Variables	Dataset	Data source
Meteorological forcing:	ERA-40, ERA-INTERIM	http://apps.ecmwf.int/datasets/
	GPCC	www.dwd.de
	CRU	http://www.cru.uea.ac.uk/data
	WATCH, WFDEI	http://www.eu-watch.org/
	E-OBS	http://eca.knmi.nl/dailydata/
	CORDEX	http://wcrp-cordex.ipsl.jussieu.fr/
	DayMET	http://daymet.ornl.gov/
	PRISM	http://www.prism.oregonstate.edu/
	1/8^{o} CONUS	http://cida.usgs.gov/thredds/catalog.html?dataset=cida.usgs.gov/thredds/dcp/conus_pr
	NEXRAD MPE	http://amazon.nws.noaa.gov/hdsb/data/nexrad/nexrad.html
Geophysical data:		
Topography and Routing	Hydrosheds and Hydro1K	http://eros.usgs.gov/
Land-use	ESA CCI	http://www.esa-landcover-cci.org/
	Globcover	http://due.esrin.esa.int/page_globcover.php
	Corine	http://www.eea.europa.eu/publications/COR0-landcover
	GLC2000	http://www.eea.europa.eu/data-and-maps/data/global-land-cover-2000-europe
Lake and Wetlands	GLWD	http://www.worldwildlife.org/pages/global-lakes-and-wetlands-database
	FLAKE-Global	http://www.flake.igb-berlin.de/
	ILEC World Lake database	http://www.ilec.or.jp/en/
Soil types	ESD, DSMW, HWSD	http://www.fao.org/soils-portal
Permeability and porosity	GLHYMPS	http://crustalpermeability.weebly.com/glhymps.html
Water management:		
Reservoirs	GRAND	http://www.gwsp.org/products/

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Agriculture	CAPRI	http://www.capri-model.org
	MIRCA2000	https://www.uni-frankfurt.de/45218031/data_download
Irrigation	GMIA	http://www.fao.org/nr/water/aquastat/irrigationmap/index10.stm
	GIAM	http://waterdata.iwmi.org/global_irr.php
Hydrologic data:		
River discharge	GRDC	http://www.bafg.de/GRDC/EN/Home/homepage_node.html
	FRIEND	http://ne-friend.bafg.de
	USGS	http://water.usgs.gov/nwis
	MOPEX	http://www.nws.noaa.gov/ohd/mopex/
	WHYCOS	http://www.whycos.org/whycos/
Evapotranspiration	Fluxnet	http://fluxnet.ornl.gov
	MODIS	http://modis.gsfc.nasa.gov/data/
Snow	GlobeSnow	http://www.globsnow.info/
	NSIDC	www.nsidc.org
Glaciers	WGMS	www.wgms.ch

3.1.1 Meteorological forcing data

Open-access meteorological datasets have recently been developed by the climate research community, either based on interpolation of observations (e.g. CRU, E-OBS, GPCC), derived from climate models (e.g., CORDEX), or from re-analysis of forecast-model results (e.g. ERA40, ERA-interim) (Table 2). The latter have also been corrected with observations to be especially suitable for hydrological modeling, such as the WATCH data [*Weedon et al.*, 2011]. Models for operational hydrology, such as flood forecasting models, have a particular need for real-time forcing data and therefore could and do, to an extent, contribute important data of this type.

Although the global meteorological and climate model results show promise for incorporation into modeling efforts, they may show an inconsistent water balance because these models are tuned to close the energy balance. This means that modeled water variables, such as soil moisture, may include large uncertainties and require bias correction [*Yang et al.*, 2010]. In future collaboration, the CM community could evaluate and give feedback to the LSM community on uncertainty and inconsistencies by applying inverse modeling approaches to judge precipitation patterns and magnitudes over catchments. This was an expertise introduced by CM pioneers (e.g. *Wallén* [1924]) but that has now lost attention.

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3.1.2 Geophysical data

Innovative hydrological assessments are emerging based on the new global digital elevation models with river routing, such as HYDRO1K and HYDROSHEDS [e.g. *Lehner et al.*, 2008]. These datasets facilitate application of catchment models on the continental scale world-wide (e.g. *Arheimer et al.* [2012]; *Donnelly et al.* [2015]; *Pechlivanidis and Arheimer* [2015]). Recent studies from the CM community, however, also show that this routing can be misleading and inconsistent with global databases on river gauging stations, especially for catchments smaller than 5,000 km^2 [e.g. *Donnelly et al.*, 2013; *Kauffeldt et al.*, 2013].

Global databases hosting information on geology and soils often require substantial modification to be used in hydrologic models. For example, soil types and geologic classes often need to be merged into hydrologically relevant groups. In addition to using topographic data to guide the scale of spatial discretization and routing within catchment models, it is important to account for the level of detail that may be desirable to other modeling communities and organizations, such as the GWSM community. Closer cooperation and increased communication between hydrologists, geographers, and the earth observation communities would help to advance and improve the geophysical databases. As an example, the US Geological Survey has produced a national geospatial fabric for hydrologic modeling in the continental United States [*Viger*, 2014; *Viger and Bock*, 2014], which includes a river routing network, land surfaces that contribute to the network, preliminary spatial catchment model parameters, and points located along the network for model calibration and evaluation.

3.1.3 Water management data

Dynesius and Nilsson [1994] found that 77 percent of the river discharge from the northern hemisphere was affected by the fragmentation of river channels by dams and water regulation. In general, the LSM and the CM communities mainly model pristine conditions to understand natural process interactions. The GWSM community has made major efforts during the last decades to construct and use global databases on water management, both on reservoirs for various purposes (e.g.[*Lehner and Döll*, 2004]) and of agricultural interactions with the water balance (e.g.[*Allen et al.*, 1998; *Wriedt et al.*,

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2009; *Portmann et al.*, 2010; *Siebert et al.*, 2010; *Britz et al.*, 2011]). Recently, the CM community has started to use these data in more detailed catchment models for continental domains (e.g.[*Donnelly et al.*, 2015]). These applications have identified limitations to these databases and highlight the need for regular updates of this information; for instance, *Donnelly et al.* [2015] analyzed the water balance and river dynamics and identified trends in model bias that match societal changes affecting crop production and irrigation patterns. This is one example of potential mutual benefits from sharing data and results in a closer cooperation between the CM and GWSM modeling communities.

Water management data remains one of the most challenging limitations to data needs in large-domain modeling. Global or continental datasets of water management data are often not available at the resolution of the water management practices. While a national effort is underway to provide water use information at catchment units derived at this level of detail [*Alley et al.*, 2013], this goal will not be realized for some time. In other countries and continents, water management data is collated from many regulatory agencies and supplied in different formats, which complicates their application in hydrologic models. Further issues arise due to non-public water management practices such as small abstractions or reservoir operations, which are often not required to be reported but still result in changes to the hydrologic system at the catchment scale.

Global databases of lakes and reservoirs do not match river networks and databases on land use may show large discrepancies between the datasets. For example, Globcover and ESA CC1 (Table 2) show large differences in land cover because they reflect different time-periods and different monitoring techniques. Lastly, time varying data sets of land-cover change are needed to accurately handle the anthropogenic changes to the landscape and effects on streamflow.

3.1.4 Hydrologic data

Model evaluation and improvement requires data on model states, fluxes and output. Such data originate from in-situ measurement and earth observations, including remotely sensed information; in other cases, outputs from other models with associated uncertainty are used. In the CM community, empirical methods and uncertainty analysis are

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fundamental to the modeling process and, therefore, measured hydrological data is of critical importance. Several large-sample databases on river flow currently exist; for example, the Global Runoff Data Center (GRDC; http://www.bafg.de/GRDC/EN/Home/homepage_node.html) is hosting such data to stimulate data sharing between scientists and hydrological institutes. Yet, problems with using the data are often related to insufficient or incorrect metadata, lack of knowledge of catchment characteristics or anthropogenic impact (e.g. see method section in *Donnelly et al.* [2015]) and inconsistency in scale between the model output and the observed hydrologic data. Uncertainties in both time and space for these existing datasets must be provided so modelers can fully evaluate their utility and use them appropriately. For example, the data may be provided on a daily time step but, due to large uncertainties at this time step, the datasets may only be useful for model evaluation at mean monthly, seasonal, or annual resolutions.

Using hydrological variables derived from earth observation products to validate hydrological models poses additional problems as the signal from the satellite is often mixed with other datasets and hydrologic algorithms. For instance, a meteorological grid and the Penman–Monteith equation are included in the MODIS product on evapotranspiration [*Mu et al.*, 2007, 2011] resulting in a bias when comparing this dataset to hydrologic models using other equations and meteorological grids. These problems could be overcome in a more close cooperation between the hydrologic modeling communities and the earth observation community, where the actual signal from the satellites could be directly assimilated in the hydrologic models to make most out of the competence from both research communities for modeling of historical or near real-time conditions.

3.2 Model development and refinement

From a hydrologic modeling perspective, the performance of continental-domain hydrologic models is considerably constrained by both inadequate model representation of dominant hydrologic processes and limited attention given to introducing physical constraints in model parameter estimation. These issues are related because studies that implement parsimonious models typically place more effort on parameter estimation. The

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research needs – discussed in the following sections – consider issues of model complexity and parameter estimation and transferability.

3.2.1 Define appropriate model structure and parameterizations

Different approaches to hydrologic modeling span the continuum of complexity from "physically explicit" models which provide a detailed representation of the dominant physical processes, to "conceptual" models which take an aggregated approach [*Singh and Frevert*, 2005; *Clark et al.*, 2015a]. Model complexity can be defined in terms of (1) process complexity, i.e., the granularity of process representation, from explicit representation to "lumping" of physical processes; and (2) spatial complexity, i.e., the granularity of spatial variability and spatial connectivity, the "lumping" and connectivity of the physical landscape.

The most appropriate model structure for water management applications is likely some mix of the lumped and physically explicit modeling paradigms. There is a need to ensure that models have both sufficient complexity to represent the dominant physical processes and appropriate parameterizations to represent large-scale fluxes and scaling behavior. The key is to find the right level of generalization while avoiding over-simplification [*Savenije*, 2010]. For future conditions, models need to be able to accurately represent these processes without data assimilation. Such model identification requires exploring tradeoffs across the continuum of model complexity, based on extensive multivariate and multi-scale model evaluation [*Göhler et al.*, 2013; *Clark et al.*, 2015a, 2015b; *Cuntz et al.*, 2015; *Razavi and Gupta*, 2015].

Increasingly complex models come with some disadvantages. The greater computational needs of complex models can constrain the capability to extensively experiment with different model structures and parameter values – experimentation necessary to improve model fidelity, that is, the extent to which model simulations faithfully represent observed processes. The greater computational needs of complex models can also constrain capabilities to characterize uncertainty, for example, through model simulations with multiple equally plausible ensemble members. These computational constraints underscore the need for models of intermediate complexity – physically realistic, yet sufficiently computationally agile to enable model experimentation and uncertainty characterization.

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3.2.2 Define appropriate model parameter values

Defining appropriate parameter values is critical to providing credible hydrologic model simulations at scales relevant to water managers. Yet, the definition of appropriate parameter values is difficult for two reasons: (1) it is necessary to define suitable *a priori* distributions of model parameters, such as default model parameters with an uncertainty range; and (2) it is necessary to refine *a priori* parameter distributions by evaluating model simulations with different parameter values.

The *a priori* distributions of model parameters are typically obtained using transfer functions that relate geophysical attributes including climate, topography, vegetation, soils to model parameters. Examples of transfer functions include pedotransfer functions, that relate the sand, silt and clay content to the storage and transmission properties of soils [*Clapp and Hornberger*, 1978], empirical functions to relate topographic characteristics to parameters that control runoff generation [*Balsamo et al.*, 2009], or defining different model parameters for different vegetation classes [*Bonan et al.*, 2002] or different hydroclimate regimes [*Liston*, 2004]. The challenges in *a priori* parameter estimation are (1) the large uncertainty in geophysical attributes (e.g., soil maps) translates to large uncertainty in a priori parameter estimates; (2) the often weak relation between geophysical attributes and model parameters, with, in some cases, the "conceptual" model parameters having no direct geophysical interpretation; and (3) the complex spatial scaling of model parameters, which can make it difficult to identify appropriate methods to aggregate (or disaggregate) the model parameters across the space (for example, effective parameter values are often applied at a scale larger than the parameter values can be observed). *A priori* parameter distributions may also be derived using a hydrological signature approach to parameter estimation in gauged catchments (e.g. using recession analysis to set storage-discharge relationships or drought analysis to set ecologically-required soil water storage [*Gao et al.*, 2014]), and then transferring this information to surrounding ungauged locations.

Refining the *a priori* parameter distributions is very difficult for continental-domain applications. The approach of basin-by-basin model calibration can lead to very different parameter sets throughout the model domain resulting in a "patchwork quilt" of model

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parameter values; this provides inconsistencies in spatial comparisons and challenges to transfer model parameters to ungauged basins [*Blöschl et al.*, 2013]. Some approaches have been developed to address these issues. One approach calibrates model parameters based on regionalized flow statistics [*Yadav et al.*, 2007], which provides hydrologic calibration information in ungauged basins, hence avoiding the need to transfer parameters across space. Another approach calibrates the coefficients in the transfer functions [*Kumar et al.*, 2013a; *Samaniego et al.*, 2010], providing spatial consistency across the model domain. Other approaches include the transfer of calibrated parameters that are satisfactory for multiple nearby basins [*Lindström et al.*, 2010] or by taking the median of parameter estimates resulting from several different regionalization schemes [*Viviroli et al.*, 2009]. The effectiveness of both of these approaches is constrained by the compensatory effects among different model parameters, and there is still considerable opportunity for advancement by defining orthogonal multivariate hydrologic signatures to provide information on parameters in different parts of the model.

An additional issue of parameter regionalization is identifying the appropriate information to transfer to ungauged areas. Two important components are the identification of influential (and non-influential) parameters, and the geographic and temporal scales at which parameters exert control on model function. Parameters that have little or no variability in model response should not be included in model calibration [*Bock et al.*, 2015]. The reduction of number of parameters for model calibration is important for the efficiency of calibration, and reducing uncertainty in model output [*van Griensven et al.*, 2006]. Poorly constrained calibration greatly increases the potential for equifinality of optimization, and thus getting the right answer for the wrong reason [*Troch et al.*, 2003; *Kirchner*, 2006].

Lastly, calibration and parameter regionalization for ungauged basins is still not well understood, despite a large amount of research and attention in this area[*Blöschl et al.*, 2013]. Approaches such as the transfer of model parameters from gauged to ungauged locations [see *Blöschl et al.* [2013] for a review] or calibration to estimates of hydrologic signatures [*Yadav et al.*, 2007] have seen limited testing at continental and global scales (for an exception see *Troy et al.* [2008]).

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3.3 Model performance, uncertainty and communication of results

The evaluation and communication of model results, performance and uncertainty across large domains remains challenging. Different management priorities require adequate model performance for different properties of a hydrograph (for example, adequate prediction of high flows, low flows or flow variability). It is critical to systematically assess model performance across spatial and temporal scales to understand how model structure, parameterization and hydroclimatic setting affect model performance. Furthermore, evaluation of model performance points out the need to understand the uncertainty of the observations used for model evaluation [*Hamilton and Moore*, 2012; *McMillan et al.*, 2012; *Westerberg and McMillan*, 2015] as well as uncertainties in other water balance terms.

Benchmarking of hydrological models is one way to accomplish these goals. In discussing models from the LSM community, *van den Hurk et al.* [2011] point out that benchmarking of model performance "urgently needs attention in the wider scientific community." Benchmarking of a national domain flood-forecasting operational hydrology model identified key processes to be improvement and these improvements were then shown to reduce the overall error in flood forecasting [*Arheimer et al.*, 2011]. The CM community has much to offer on this topic and has produced a number of continental domain models and datasets for this purpose (for example, *Duan et al.* [2006]; *Newman et al.* [2015]). By examining incremental improvements to model performance in a systematic way, the relative effects of the factors that influence model performance and provide a common path forward to improve hydrologic modeling efforts can be better understood. Yet, benchmarking will take progress only so far and efforts must also be directed toward a better understanding, quantification and communication of uncertainty in addition to communication of models and results to the water resources planning community. The CM community has made inroads in involving end-users in model development and structure to ensure that results are communicated in a manner that is most meaningful to those who need to use them [*Henriksen et al.*, 2003] but all hydrologic modeling communities need to consider how to effectively immerse the water resources planning community into modeling process and results.

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4. Concluding remarks

In the past, hydrologic modeling of surface water resources has mainly focused on simulating the hydrologic cycle at local to regional modeling domains. Emerging water management challenges, including changes to global climate and transboundary water issues, are now pushing the desired modeling domain from catchment to continental and global domains. With this myriad of complex science questions and pressing societal issues, the hydrology community has, over time, evolved into several modeling communities that emphasize different aspects of the hydrologic cycle and, therefore, provide focused modeling efforts to address a subset of these questions.

There now exists a level of maturity amongst the catchment, global water security, and land surface modeling communities such that these communities are converging towards continental-domain hydrologic models. With this similar advancement in reach, each community is faced with a similar set of challenges in the representation of water management actions and infrastructure, the estimation of model parameters, the skill with which components of the water balance can be simulated, the spatial domain of the model, and the transferability to ungauged areas. This commentary, written from the perspective of the catchment hydrology community, underscores the positive aspects of the diversity of scientific approaches in the hydrologic community while arguing that a focused research effort between hydrologic modeling communities would achieve advances in continental-domain modeling more rapidly than the efforts of any one community forging ahead on their own. Specific collaborative research efforts include:

(1) Creating new incentives and infrastructure to report and share model inputs, outputs, and parameters in data services and open access, machine-independent formats for model replication or re-analysis.

(2) Ensuring that hydrologic models have sufficient complexity to represent the dominant physical processes and adequate representation of anthropogenic impacts on the terrestrial water cycle, a process-based approach to model parameter estimation, and appropriate parameterizations to represent large-scale fluxes and scaling behavior.

(3) Quantifying and communicating significant advancements towards these modeling goals.

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(4) Ensuring a balance between model complexity and data availability as well as uncertainties.

In our world, where ever greater proportions of rivers and land area are modified by humans, collaboration is essential to understand terrestrial water availability; a review of community efforts towards continental domain hydrologic modeling illuminates pathways for collaboration that benefit not only each respective community but also accelerates progress towards a common goal that can address questions of pressing societal relevance.

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References

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith (1998), *Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56*, FAO - Food and Agriculture Organization of the United Nations, Rome.

Alley, W. A. et al. (2013), *Progress Toward Establishing a National Assessment of Water Availability and Use*, U.S. Geological Survey Circular 1389, U. S. Geological Survey.

Andréassian, V., C. Perrin, L. Berthet, N. Le Moine, J. Lerat, C. Loumagne, L. Oudin, T. Mathevet, M.-H. Ramos, and A. Valéry (2009), HESS Opinions "Crash tests for a standardized evaluation of hydrological models," *Hydrol Earth Syst Sci*, *13*(10), 1757–1764, doi:10.5194/hess-13-1757-2009.

This article is protected by copyright. All rights reserved.

Accepted Article

Arheimer, B., G. Lindström, and J. Olsson (2011), A systematic review of sensitivities in the Swedish flood-forecasting system, *Atmospheric Res.*, *100*(2–3), 275–284, doi:10.1016/j.atmosres.2010.09.013.

Arheimer, B., J. Dahné, C. Donnelly, G. Lindström, and J. Strömqvist (2012), Water and nutrient simulations using the HYPE model for Sweden *vs.* the Baltic Sea basin – influence of input-data quality and scale, *Hydrol. Res.*, *43*(4), 315, doi:10.2166/nh.2012.010.

Arnell, N. W. (1999), A simple water balance model for the simulation of streamflow over a large geographic domain, *J. Hydrol.*, *217*(3–4), 314–335, doi:10.1016/S0022-1694(99)00023-2.

Atkinson, R. A., R. Power, D. Lemon, R. O'Hagan, D. Dee, and D. Kinny (2008), *CSIRO Water for a Healthy Country National Research Flagship report*, CSIRO, Australia.

Ban, N., J. Schmidli, and C. Schär (2014), Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations, *J. Geophys. Res. Atmospheres*, *119*(13), 7889–7907, doi:10.1002/2014JD021478.

Bergström, S. (1995), The HBV model, in *Computer models of watershed hydrology.*, edited by V. P. Singh, pp. 443–476, Centre for Agriculture and Biosciences International.

Beven, K., H. Cloke, F. Pappenberger, R. Lamb, and N. Hunter (2014), Hyperresolution information and hyperresolution ignorance in modelling the hydrology of the land surface, *Sci. China Earth Sci.*, *58*(1), 25–35, doi:10.1007/s11430-014-5003-4.

Bierkens, M. F. P. et al. (2015), Hyper-resolution global hydrological modelling: what is next?, *Hydrol. Process.*, *29*(2), 310–320, doi:10.1002/hyp.10391.

Blöschl, G., M. Sivapalan, T. Wagener, A. Viglione, and H. H. G. Savenije (Eds.) (2013), *Runoff Prediction in Ungauged Basins*, Cambridge University Press.

Bock, A. R., L. E. Hay, G. J. McCabe, S. L. Markstrom, and R. D. Atkinson (2015), Parameter regionalization of a monthly water balance model for the conterminous United States, *Hydrol Earth Syst Sci Discuss*, *12*(9), 10023–10066, doi:10.5194/hessd-12-10023-2015.

Britz, W., P. H. Verburg, and A. Leip (2011), Modelling of land cover and agricultural change in Europe: Combining the CLUE and CAPRI-Spat approaches, *Agric. Ecosyst. Environ.*, *142*(1–2), 40–50, doi:10.1016/j.agee.2010.03.008.

Chen, F., and J. Dudhia (2001), Coupling an Advanced Land Surface–Hydrology Model with the Penn State–NCAR MM5 Modeling System. Part I: Model Implementation and Sensitivity, *Mon. Weather Rev.*, *129*(4), 569–585, doi:10.1175/1520-0493(2001)129<0569:CAALSH>2.0.CO;2.

This article is protected by copyright. All rights reserved.

Clark, M. P. et al. (2015a), A unified approach for process-based hydrologic modeling: 1. Modeling concept, *Water Resour. Res.*, *51*(4), 2498–2514, doi:10.1002/2015WR017198.

Clark, M. P. et al. (2015b), A unified approach for process-based hydrologic modeling: 2. Model implementation and case studies, *Water Resour. Res.*, *51*(4), 2515–2542, doi:10.1002/2015WR017200.

Clark, M. P. et al. (2015c), Improving the representation of hydrologic processes in Earth System Models, *Water Resour. Res.*, doi:10.1002/2015WR017096.

Cloke, H. L., and F. Pappenberger (2009), Ensemble flood forecasting: A review, *J. Hydrol.*, *375*(3–4), 613–626, doi:10.1016/j.jhydrol.2009.06.005.

Collins, R., P. Kristensen, and N. Thyssen (2009), *Water resources across Europe — confronting water scarcity and drought*, Office for Official Publications of the European Communities, Luxembourg.

Colombo, R., J. V. Vogt, P. Soille, M. L. Paracchini, and A. de Jager (2007), Deriving river networks and catchments at the European scale from medium resolution digital elevation data, *CATENA*, *70*(3), 296–305, doi:10.1016/j.catena.2006.10.001.

Cook, C., and K. Bakker (2012), Water security: Debating an emerging paradigm, *Glob. Environ. Change*, *22*(1), 94–102, doi:10.1016/j.gloenvcha.2011.10.011.

Cuntz, M. et al. (2015), Computationally inexpensive identification of noninformative model parameters by sequential screening, *Water Resour. Res.*, doi:10.1002/2015WR016907.

Demeritt, D., S. Nobert, H. L. Cloke, and F. Pappenberger (2013), The European Flood Alert System and the communication, perception, and use of ensemble predictions for operational flood risk management, *Hydrol. Process.*, *27*(1), 147–157, doi:10.1002/hyp.9419.

Döll, P., F. Kaspar, and B. Lehner (2003), A global hydrological model for deriving water availability indicators: model tuning and validation, *J. Hydrol.*, *270*(1–2), 105–134, doi:10.1016/S0022-1694(02)00283-4.

Donigian, A. S., Jr., B. R. Bicknell, and J. C. Imhoff (1995), Hydrological Simulation Program - Fortran (HSPF)., in *Computer models of watershed hydrology*, edited by V. P. Singh, pp. 395–442, Centre for Agriculture and Biosciences International.

Donnelly, C., J. Rosberg, and K. Isberg (2013), A validation of river routing networks for catchment modelling from small to large scales, *Hydrol. Res.*, *44*(5), 917, doi:10.2166/nh.2012.341.

This article is protected by copyright. All rights reserved.

Accepted Article

Accepted Article

Donnelly, C., J. C. M. Andersson, and B. Arheimer (2015), Using flow signatures and catchment similarities to evaluate the E-HYPE multi-basin model across Europe, *Hydrol. Sci. J.*, doi:10.1080/02626667.2015.1027710.

Duan, Q. et al. (2006), Model Parameter Estimation Experiment (MOPEX): An overview of science strategy and major results from the second and third workshops, *J. Hydrol.*, *320*(1–2), 3–17, doi:10.1016/j.jhydrol.2005.07.031.

Dynesius, M., and C. Nilsson (1994), Fragmentation and Flow Regulation of River Systems in the Northern Third of the World, *Science*, *266*(5186), 753–762, doi:10.1126/science.266.5186.753.

European Union (2007), *Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks*.

Farmer, W. F. (2015), Estimating records of daily streamflow at ungaged locations in the southeast United States, Ph.D. Disseration, Tufts University, Medford, Massachusetts, USA.

Freeze, R. A., and R. L. Harlan (1969), Blueprint for a physically-based, digitally-simulated hydrologic response model, *J. Hydrol.*, *9*(3), 237–258, doi:10.1016/0022-1694(69)90020-1.

Gao, H., M. Hrachowitz, F. Fenicia, S. Gharari, and H. H. G. Savenije (2014), Testing the realism of a topography-driven model (FLEX-Topo) in the nested catchments of the Upper Heihe, China, *Hydrol Earth Syst Sci*, *18*(5), 1895–1915, doi:10.5194/hess-18-1895-2014.

Göhler, M., J. Mai, and M. Cuntz (2013), Use of eigendecomposition in a parameter sensitivity analysis of the Community Land Model, *J. Geophys. Res. Biogeosciences*, *118*(2), 904–921, doi:10.1002/jgrg.20072.

De Graaf, I. E. M., E. H. Sutanudjaja, L. P. H. van Beek, and M. F. P. Bierkens (2015), A high-resolution global-scale groundwater model, *Hydrol Earth Syst Sci*, *19*(2), 823–837, doi:10.5194/hess-19-823-2015.

Van Griensven, A., T. Meixner, S. Grunwald, T. Bishop, M. Diluzio, and R. Srinivasan (2006), A global sensitivity analysis tool for the parameters of multi-variable catchment models, *J. Hydrol.*, *324*(1–4), 10–23, doi:10.1016/j.jhydrol.2005.09.008.

Griffiths, J., R. B. Lambert, and UNESCO (2013), *Free flow: reaching water security through cooperation*.

Gupta, H. V., T. Wagener, and Y. Liu (2008), Reconciling theory with observations: elements of a diagnostic approach to model evaluation, *Hydrol. Process.*, *22*(18), 3802–3813, doi:10.1002/hyp.6989.

This article is protected by copyright. All rights reserved.

Accepted Article

Gupta, H. V., C. Perrin, G. Blöschl, A. Montanari, R. Kumar, M. Clark, and V. Andréassian (2014), Large-sample hydrology: a need to balance depth with breadth, *Hydrol Earth Syst Sci*, *18*(2), 463–477, doi:10.5194/hess-18-463-2014.

Hamilton, A. S., and R. D. Moore (2012), Quantifying Uncertainty in Streamflow Records, *Can. Water Resour. J. Rev. Can. Ressour. Hydr.*, *37*(1), 3–21, doi:10.4296/cwrj3701865.

Henriksen, H. J., L. Troldborg, P. Nyegaard, T. O. Sonnenborg, J. C. Refsgaard, and B. Madsen (2003), Methodology for construction, calibration and validation of a national hydrological model for Denmark, *J. Hydrol.*, *280*(1–4), 52–71, doi:10.1016/S0022-1694(03)00186-0.

Hering, D. et al. (2010), The European Water Framework Directive at the age of 10: A critical review of the achievements with recommendations for the future, *Sci. Total Environ.*, *408*(19), 4007–4019, doi:10.1016/j.scitotenv.2010.05.031.

Van den Hurk, B., M. Best, P. Dirmeyer, A. Pitman, J. Polcher, and J. Santanello (2011), Acceleration of Land Surface Model Development over a Decade of Glass, *Bull. Am. Meteorol. Soc.*, *92*(12), 1593–1600, doi:10.1175/BAMS-D-11-00007.1.

Kallis, G., and D. Butler (2001), The EU water framework directive: measures and implications, *Water Policy*, *3*(2), 125–142, doi:10.1016/S1366-7017(01)00007-1.

Kauffeldt, A., S. Halldin, A. Rodhe, C.-Y. Xu, and I. K. Westerberg (2013), Disinformative data in large-scale hydrological modelling, *Hydrol Earth Syst Sci*, *17*(7), 2845–2857, doi:10.5194/hess-17-2845-2013.

Kirchner, J. W. (2006), Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology, *Water Resour. Res.*, *42*(3), W03S04, doi:10.1029/2005WR004362.

Laniak, G. F. et al. (2013), Integrated environmental modeling: A vision and roadmap for the future, *Environ. Model. Softw.*, *39*, 3–23, doi:10.1016/j.envsoft.2012.09.006.

Lawrence, D. M. et al. (2011), Parameterization improvements and functional and structural advances in Version 4 of the Community Land Model, *J. Adv. Model. Earth Syst.*, *3*(3), M03001, doi:10.1029/2011MS000045.

Leavesley, G. H., and L. G. Stannard (1995), The Precipitation-Runoff Modeling System - PRMS, in *Computer models of watershed hydrology*, edited by V. P. Singh, pp. 281–310, Centre for Agriculture and Biosciences International.

Lehner, B., and P. Döll (2004), Development and validation of a global database of lakes, reservoirs and wetlands, *J. Hydrol.*, *296*(1–4), 1–22, doi:10.1016/j.jhydrol.2004.03.028.

This article is protected by copyright. All rights reserved.

Accepted Article

Lehner, B., K. Verdin, and A. Jarvis (2008), New Global Hydrography Derived From Spaceborne Elevation Data, *Eos Trans. Am. Geophys. Union*, *89*(10), 93–94, doi:10.1029/2008EO100001.

Lindström, G., C. Pers, J. Rosberg, J. Strömqvist, and B. Arheimer (2010), Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales, *Hydrol. Res.*, *41*(3-4), 295, doi:10.2166/nh.2010.007.

Maurer, E. P., G. M. O'Donnell, D. P. Lettenmaier, and J. O. Roads (2001), Evaluation of the land surface water budget in NCEP/NCAR and NCEP/DOE reanalyses using an off-line hydrologic model, *J. Geophys. Res. Atmospheres*, *106*(D16), 17841–17862, doi:10.1029/2000JD900828.

Maxwell, R. M., L. E. Condon, and S. J. Kollet (2015), A high-resolution simulation of groundwater and surface water over most of the continental US with the integrated hydrologic model ParFlow v3, *Geosci Model Dev*, *8*(3), 923–937, doi:10.5194/gmd-8-923-2015.

Mcenery, J., J. Ingram, Q. Duan, T. Adams, and L. Anderson (2005), NOAA'S Advanced Hydrologic Prediction Service: Building Pathways for Better Science in Water Forecasting, *Bull. Am. Meteorol. Soc.*, *86*(3), 375–385, doi:10.1175/BAMS-86-3-375.

McMillan, H., T. Krueger, and J. Freer (2012), Benchmarking observational uncertainties for hydrology: rainfall, river discharge and water quality, *Hydrol. Process.*, *26*(26), 4078–4111, doi:10.1002/hyp.9384.

Merz, R., and G. Blöschl (2004), Regionalisation of catchment model parameters, *J. Hydrol.*, *287*(1–4), 95–123, doi:10.1016/j.jhydrol.2003.09.028.

Montanari, A. et al. (2013), "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022, *Hydrol. Sci. J.*, *58*(6), 1256–1275, doi:10.1080/02626667.2013.809088.

Müller Schmied, H., S. Eisner, D. Franz, M. Wattenbach, F. T. Portmann, M. Flörke, and P. Döll (2014), Sensitivity of simulated global-scale freshwater fluxes and storages to input data, hydrological model structure, human water use and calibration, *Hydrol Earth Syst Sci*, *18*(9), 3511–3538, doi:10.5194/hess-18-3511-2014.

Mu, Q., F. A. Heinsch, M. Zhao, and S. W. Running (2007), Development of a global evapotranspiration algorithm based on MODIS and global meteorology data, *Remote Sens. Environ.*, *111*(4), 519–536, doi:10.1016/j.rse.2007.04.015.

Mu, Q., M. Zhao, and S. W. Running (2011), Improvements to a MODIS global terrestrial evapotranspiration algorithm, *Remote Sens. Environ.*, *115*(8), 1781–1800, doi:10.1016/j.rse.2011.02.019.

This article is protected by copyright. All rights reserved.

Accepted Article

National Research Council (2012), *Challenges and Opportunities in the Hydrologic Sciences*, The National Academies Press, Washington, D. C.

Newman, A. J. et al. (2015), Development of a large-sample watershed-scale hydrometeorological data set for the contiguous USA: data set characteristics and assessment of regional variability in hydrologic model performance, *Hydrol Earth Syst Sci*, *19*(1), 209–223, doi:10.5194/hess-19-209-2015.

Nijssen, B., G. M. O'Donnell, D. P. Lettenmaier, D. Lohmann, and E. F. Wood (2001), Predicting the Discharge of Global Rivers, *J. Clim.*, *14*(15), 3307–3323, doi:10.1175/1520-0442(2001)014<3307:PTDOGR>2.0.CO;2.

Oudin, L., V. Andréassian, C. Perrin, C. Michel, and N. Le Moine (2008), Spatial proximity, physical similarity, regression and ungaged catchments: A comparison of regionalization approaches based on 913 French catchments, *Water Resour. Res.*, *44*(3), W03413, doi:10.1029/2007WR006240.

Overgaard, J., D. Rosbjerg, and M. B. Butts (2006), Land-surface modelling in hydrological perspective – a review, *Biogeosciences*, *3*(2), 229–241, doi:10.5194/bg-3-229-2006.

Pechlivanidis, I. G., and B. Arheimer (2015), Large-scale hydrological modelling by using modified PUB recommendations: the India-HYPE case, *Hydrol Earth Syst Sci Discuss*, *12*(3), 2885–2944, doi:10.5194/hessd-12-2885-2015.

Perrin, C., C. Michel, and V. Andréassian (2003), Improvement of a parsimonious model for streamflow simulation, *J. Hydrol.*, *279*(1–4), 275–289, doi:10.1016/S0022-1694(03)00225-7.

Pitman, A. J. (2003), The evolution of, and revolution in, land surface schemes designed for climate models, *Int. J. Climatol.*, *23*(5), 479–510, doi:10.1002/joc.893.

Pokhrel, Y., N. Hanasaki, S. Koirala, J. Cho, P. J.-F. Yeh, H. Kim, S. Kanae, and T. Oki (2011), Incorporating Anthropogenic Water Regulation Modules into a Land Surface Model, *J. Hydrometeorol.*, *13*(1), 255–269, doi:10.1175/JHM-D-11-013.1.

Portmann, F. T., S. Siebert, and P. Döll (2010), MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling, *Glob. Biogeochem. Cycles*, *24*(1), GB1011, doi:10.1029/2008GB003435.

Rasmussen, R. et al. (2014), Climate Change Impacts on the Water Balance of the Colorado Headwaters: High-Resolution Regional Climate Model Simulations, *J. Hydrometeorol.*, *15*(3), 1091–1116, doi:10.1175/JHM-D-13-0118.1.

Razavi, S., and H. V. Gupta (2015), What do we mean by sensitivity analysis? The need for comprehensive characterization of "global" sensitivity in Earth and

This article is protected by copyright. All rights reserved.

Accepted Article

Environmental systems models, *Water Resour. Res.*, *51*(5), 3070–3092, doi:10.1002/2014WR016527.

Rigon, R., G. Bertoldi, and T. M. Over (2006), GEOtop: A Distributed Hydrological Model with Coupled Water and Energy Budgets, *J. Hydrometeorol.*, *7*(3), 371–388, doi:10.1175/JHM497.1.

Samaniego, L., R. Kumar, and S. Attinger (2010), Multiscale parameter regionalization of a grid-based hydrologic model at the mesoscale, *Water Resour. Res.*, *46*(5), W05523, doi:10.1029/2008WR007327.

Sato, H., A. Ito, A. Ito, T. Ise, and E. Kato (2015), Current status and future of land surface models, *Soil Sci. Plant Nutr.*, *61*(1), 34–47, doi:10.1080/00380768.2014.917593.

Savenije, H. H. G. (2010), HESS Opinions "Topography driven conceptual modelling (FLEX-Topo)," *Hydrol Earth Syst Sci*, *14*(12), 2681–2692, doi:10.5194/hess-14-2681-2010.

Sellers, P. J., C. J. Tucker, G. J. Collatz, S. O. Los, C. O. Justice, D. A. Dazlich, and D. A. Randall (1996), A Revised Land Surface Parameterization (SiB2) for Atmospheric GCMS. Part II: The Generation of Global Fields of Terrestrial Biophysical Parameters from Satellite Data, *J. Clim.*, *9*(4), 706–737, doi:10.1175/1520-0442(1996)009<0706:ARLSPF>2.0.CO;2.

Sellers, P. J. et al. (1997), Modeling the Exchanges of Energy, Water, and Carbon Between Continents and the Atmosphere, *Science*, *275*(5299), 502–509.

Siebert, S., J. Burke, J. M. Faures, K. Frenken, J. Hoogeveen, P. Döll, and F. T. Portmann (2010), Groundwater use for irrigation – a global inventory, *Hydrol Earth Syst Sci*, *14*(10), 1863–1880, doi:10.5194/hess-14-1863-2010.

Singh, V. P., and D. K. Frevert (2005), *Watershed Models*, CRC Press.

Sutanudjaja, E. H., L. P. H. van Beek, S. M. de Jong, F. C. van Geer, and M. F. P. Bierkens (2014), Calibrating a large-extent high-resolution coupled groundwater-land surface model using soil moisture and discharge data, *Water Resour. Res.*, *50*(1), 687–705, doi:10.1002/2013WR013807.

Todini, E. (2006), Rainfall-Runoff Models for Real-Time Forecasting, in *Encyclopedia of Hydrological Sciences*, John Wiley & Sons, Ltd.

Troch, P. A., C. Paniconi, and E. Emiel van Loon (2003), Hillslope-storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes: 1. Formulation and characteristic response, *Water Resour. Res.*, *39*(11), 1316, doi:10.1029/2002WR001728.

This article is protected by copyright. All rights reserved.

Accepted Article

Troy, T. J., E. F. Wood, and J. Sheffield (2008), An efficient calibration method for continental-scale land surface modeling, *Water Resour. Res.*, *44*(9), W09411, doi:10.1029/2007WR006513.

United Nations Economic Comission for Europe (2014), *Convention on the Protection and Use of Transboundary Watercourses and International Lakes.*, GE.13-26823 – February 2014 – 3,129 – ECE/MP.WAT/41, United Nations, New York and Geneva.

Viger, R. J. (2014), *Preliminary spatial parameters for PRMS based on the Geospatial Fabric, NLCD2001 and SSURGO,* U. S. Geological Survey.

Viger, R. J., and A. Bock (2014), *GIS Features of the Geospatial Fabric for National Hydrologic Modeling, US Geological Survey*, U.S. Geological Survey.

Viviroli, D., H. Mittelbach, J. Gurtz, and R. Weingartner (2009), Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part II: Parameter regionalisation and flood estimation results, *J. Hydrol.*, *377*(1–2), 208–225, doi:10.1016/j.jhydrol.2009.08.022.

Vörösmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers (2000), Global Water Resources: Vulnerability from Climate Change and Population Growth, *Science*, *289*(5477), 284–288, doi:10.1126/science.289.5477.284.

Wada, Y., D. Wisser, and M. F. P. Bierkens (2014), Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources, *Earth Syst Dynam*, *5*(1), 15–40, doi:10.5194/esd-5-15-2014.

Wagener, T., and N. McIntyre (2005), Identification of rainfall–runoff models for operational applications / Identification de modèles pluie–débit pour des applications opérationnelles, *Hydrol. Sci. J.*, *50*(5), 735–751, doi:10.1623/hysj.2005.50.5.735.

Weedon, G. P., S. Gomes, P. Viterbo, W. J. Shuttleworth, E. Blyth, H. Österle, J. C. Adam, N. Bellouin, O. Boucher, and M. Best (2011), Creation of the WATCH Forcing Data and Its Use to Assess Global and Regional Reference Crop Evaporation over Land during the Twentieth Century, *J. Hydrometeorol.*, *12*(5), 823–848, doi:10.1175/2011JHM1369.1.

Weiskel, P. K., D. M. Wolock, P. J. Zarriello, R. M. Vogel, S. B. Levin, and R. M. Lent (2014), Hydroclimatic regimes: a distributed water-balance framework for hydrologic assessment, classification, and management, *Hydrol Earth Syst Sci*, *18*(10), 3855–3872, doi:10.5194/hess-18-3855-2014.

Westerberg, I. K., and H. K. McMillan (2015), Uncertainty in hydrological signatures, *Hydrol Earth Syst Sci Discuss*, *12*(4), 4233–4270, doi:10.5194/hessd-12-4233-2015.

This article is protected by copyright. All rights reserved.

Wigmosta, M. S., L. W. Vail, and D. P. Lettenmaier (1994), A distributed hydrology-vegetation model for complex terrain, *Water Resour. Res.*, *30*(6), 1665–1679, doi:10.1029/94WR00436.

Wood, E. F. et al. (1998), The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) Phase 2(c) Red–Arkansas River basin experiment:: 1. Experiment description and summary intercomparisons, *Glob. Planet. Change*, *19*(1–4), 115–135, doi:10.1016/S0921-8181(98)00044-7.

Wood, E. F. et al. (2011), Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water, *Water Resour. Res.*, *47*(5), W05301, doi:10.1029/2010WR010090.

Wood, E. F. et al. (2012), Reply to comment by Keith J. Beven and Hannah L. Cloke on "Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water," *Water Resour. Res.*, *48*(1), W01802, doi:10.1029/2011WR011202.

Wriedt, G., M. Van der Velde, A. Aloe, and F. Bouraoui (2009), Estimating irrigation water requirements in Europe, *J. Hydrol.*, *373*(3–4), 527–544, doi:10.1016/j.jhydrol.2009.05.018.

Yadav, M., T. Wagener, and H. Gupta (2007), Regionalization of constraints on expected watershed response behavior for improved predictions in ungauged basins, *Adv. Water Resour.*, *30*(8), 1756–1774, doi:10.1016/j.advwatres.2007.01.005.

Yang, W., J. Andréasson, L. Phil Graham, J. Olsson, J. Rosberg, and F. Wetterhall (2010), Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies, *Hydrol. Res.*, *41*(3-4), 211, doi:10.2166/nh.2010.004.

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