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Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water

Eric F. Wood,[1] Joshua K. Roundy,[1] Tara J. Troy,[1] L. P. H. van Beek,[2]
Marc F. P. Bierkens,[2,3] Eleanor Blyth,[4] Ad de Roo,[5] Petra Döll,[6] Mike Ek,[7]
James Famiglietti,[8] David Gochis,[9] Nick van de Giesen,[10] Paul Houser,[11] Peter R. Jaffé,[1]
Stefan Kollet,[12] Bernhard Lehner,[13] Dennis P. Lettenmaier,[14] Christa Peters-Lidard,[15]
Murugesu Sivapalan,[16] Justin Sheffield,[1] Andrew Wade,[17] and Paul Whitehead[18]

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[1] Monitoring Earth's terrestrial water conditions is critically important to many hydrological applications such as global food production; assessing water resources sustainability; and flood, drought, and climate change prediction. These needs have motivated the development of pilot monitoring and prediction systems for terrestrial hydrologic and vegetative states, but to date only at the rather coarse spatial resolutions (~10–100 km) over continental to global domains. Adequately addressing critical water cycle science questions and applications requires systems that are implemented globally at much higher resolutions, on the order of 1 km, resolutions referred to as hyperresolution in the context of global land surface models. This opinion paper sets forth the needs and benefits for a system that would monitor and predict the Earth's terrestrial water, energy, and biogeochemical cycles. We discuss six major challenges in developing a system: improved representation of surface-subsurface interactions due to fine-scale topography and vegetation; improved representation of land-atmospheric interactions and resulting spatial information on soil moisture and evapotranspiration; inclusion of water quality as part of the biogeochemical cycle; representation of human impacts from water management; utilizing massively parallel computer systems and recent computational advances in solving hyperresolution models that will have up to 10^9 unknowns; and developing the required in situ and remote sensing global data sets. We deem the development of a global hyperresolution model for monitoring the terrestrial water, energy, and biogeochemical cycles a "grand challenge" to the community, and we call upon the international hydrologic community and the hydrological science support infrastructure to endorse the effort.

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1. Need for Hyperresolution Modeling

[2] Hydrology as a scientific discipline traces its roots to the service of society. Problems related to civil infrastructure, such as provision of safe drinking water to the industrial cities of the 19th century, development of the unit hydrograph method for predicting floods, and estimating evaporation demand for managing irrigation water needs, are examples of developments central to the early underpinnings of the

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[1] Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey, USA.

[2] Department of Physical Geography, Utrecht University, Utrecht, Netherlands.

[3] Deltares, Utrecht, Netherlands.

[4] Centre for Ecology and Hydrology, Wallingford, UK.

[5] Institute for Environment and Sustainability, European Commission Joint Research Centre, Ispra, Italy.

[6] Institute of Physical Geography, Goethe University Frankfurt, Frankfurt am Main, Germany.

[7] Environmental Modeling Center, National Centers for Environmental Prediction, Suitland, Maryland, USA.

[8] UC Center for Hydrologic Modeling, University of California, Irvine, California, USA.

[9] Research Applications Laboratory, National Center for Atmospheric Research, Boulder, Colorado, USA.

[10] Department of Water Management, Delft University of Technology, Delft, Netherlands.

[11] Department of Geography and GeoInformation Science, George Mason University, Fairfax, Virginia, USA.

[12] Meteorological Institute, Bonn University, Bonn, Germany.

[13] Department of Geography, McGill University, Montreal, Quebec, Canada.

[14] Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington, USA.

[15] Hydrological Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

[16] Department of Civil and Environmental Engineering and Department of Geography, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA.

[17] School of Human and Environmental Science, University of Reading, Reading, UK.

[18] School of Geography and the Environment, University of Oxford, Oxford, UK.

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profession. As problems of water development have given way to understanding the role of environmental change in the terrestrial water cycle, a field of hydrological sciences has evolved that has concerned itself with, among other things, the development of global-scale models and the use of remote sensing data as a key source of observations. Additionally, the development of advanced weather and climate models has motivated the development of terrestrial land surface models that couple water-energy-biophysical processes [e.g., *Eagleson*, 1991, 1994].

[3] Notwithstanding notable progress in the development of new data sources and models over the last 2 decades, the current class of hydrological models falls far short of being able to address emerging societal needs for information about water at global scales. For instance, providing water of adequate quality to meet the needs of the developing world is a challenge that has been identified as central to the millennium development goals [*Sachs and McArthur*, 2005]. Understanding the hydrochemical and biogeochemical processes that control water quality in rivers, lakes, wetlands, and groundwater is crucial to meeting this goal. Current land surface models have, however, mostly had their roots in coupled land-atmosphere models, and their intent is more to partition radiation at the land surface for the purpose of providing a lower boundary condition to the atmosphere than to tracing the movement of water at and near the land surface. Accordingly, the spatial resolution of these models has largely been dictated by the spatial resolutions to which global weather and climate models are constrained by computational considerations: currently, at best, $O(100\ \text{km})$ for climate models and $O(20\ \text{km})$ for weather models (notwithstanding that somewhat higher resolutions are used by regional weather and climate models). Much higher resolutions, which we refer to here as hyperresolution (for discussion purposes, $O(1\ \text{km})$ globally and $O(100\ \text{m})$ at continental scales) are or will soon be feasible and would provide much more detailed information about the storage, movement, and quality of water at and near the land surface. Developing a predictive capability for aquatic or terrestrial ecosystems across landscapes, with water, energy, and nutrients as the drivers of these dynamic systems, faces the challenge of taking process understanding developed at the meter scale and scaling this to hydrologic modeling scales. We hypothesize that the upper limit of this scaling to achieve meaningful results is closer to 100 m than to the typical scale of current generation weather and climate models.

[4] A new generation of satellite missions is poised to provide global sources of hydrological data that will be needed at hyperresolutions, specifically, soil moisture from the Soil Moisture Active-Passive (SMAP) mission [*Entekhabi et al.*, 2010] that will provide information at $O(1\text{–}10\ \text{km})$, surface water storage change from the Surface Water and Ocean Topography mission (SWOT) [*Durand et al.*, 2010]; and snow extent and water equivalent from the CoReH2O mission [*Heliere et al.*, 2009]. Better models that are applicable to hyperresolution globally will be needed to provide the core of data assimilation systems that will be needed to exploit these new data sources [e.g., *Kollet et al.*, 2010]. Among the results of such systems will be the ability to project where and when population growth and climate change will result in adverse effects on water availability and food security, better understanding of carbon sources and sinks, and the potential impacts of hydrological change on biodiversity [*Power et al.*, 1996; *Lovejoy and Hannah*, 2005].

[5] A critical societal need that requires much higher spatial resolutions than are presently available is flood and drought forecasting. At present, global and even regional weather and seasonal climate forecasts are carried out with land surface models that, at best, are relevant to grid sizes or catchments with areas larger (usually much larger) than 100 km^2. Climate change projections at present are applicable to catchments with areas no smaller than about 5000 km^2 (also usually much larger) because of the resolution of global climate models. There is a need for much more highly resolved forecasts and predictions, and while such information is inevitably constrained by the quality of the coupled weather and climate models, it also is presently constrained by the coarse spatial resolution of hydrology and land surface models.

2. The Grand Challenge to Hydrology

[6] We believe that developing a hyperresolution hydrological prediction capability is a "grand challenge for hydrology" because of the significant modeling, computational, and data needs that will be required for global or continental predictions at these spatial resolutions. This challenge is consistent with a call from the Consortium of Universities for the Advancement of Hydrologic Science, Inc. for a community modeling effort, the Community Hydrologic Modeling Platform (CHyMP), to "spur the development of next-generation models that can readily exploit recent advances in computing power and structure, the internet, and access to very high-resolution data" [*Famiglietti et al.*, 2009]. We argue that both the scientific implications and the benefit to society of such an undertaking merit a strong push by the community in this direction. The elements of such a modeling framework will require new approaches and physical process understanding. Though not exhaustive, we outline below what we believe are the six most significant challenges to the development of a hyperresolution hydrological modeling capability.

2.1. Surface and Subsurface Interactions

[7] Hyperresolution global modeling at 1 km^2 or finer, say, to 100 m at continental scales, would allow for much better representation of the effects of spatial heterogeneity in topography, soils, and vegetation on hydrological dynamics at large scales. This in turn will allow representation of processes that are subgrid to the current generation of models, such as slope and aspect effects on surface incoming and reflected solar radiation, and consequent effects on snowmelt, soil moisture redistribution, and evapotranspiration. Higher resolution would also enable better representation of channel processes and would provide indications of inundated areas, water depths in flooded areas, number of people affected, and critical infrastructures potentially at risk.

[8] Implementation of models at these higher resolutions will require more realistic representations of surface water dynamics. In current land surface models (LSMs), overland flow and river routing are often ignored or at best are crudely represented. The major reason for this is not a lack of knowledge and importance of these processes but rather the coarse spatial resolution of LSMs that does not allow accurate representation of, for instance, surface and subsurface water

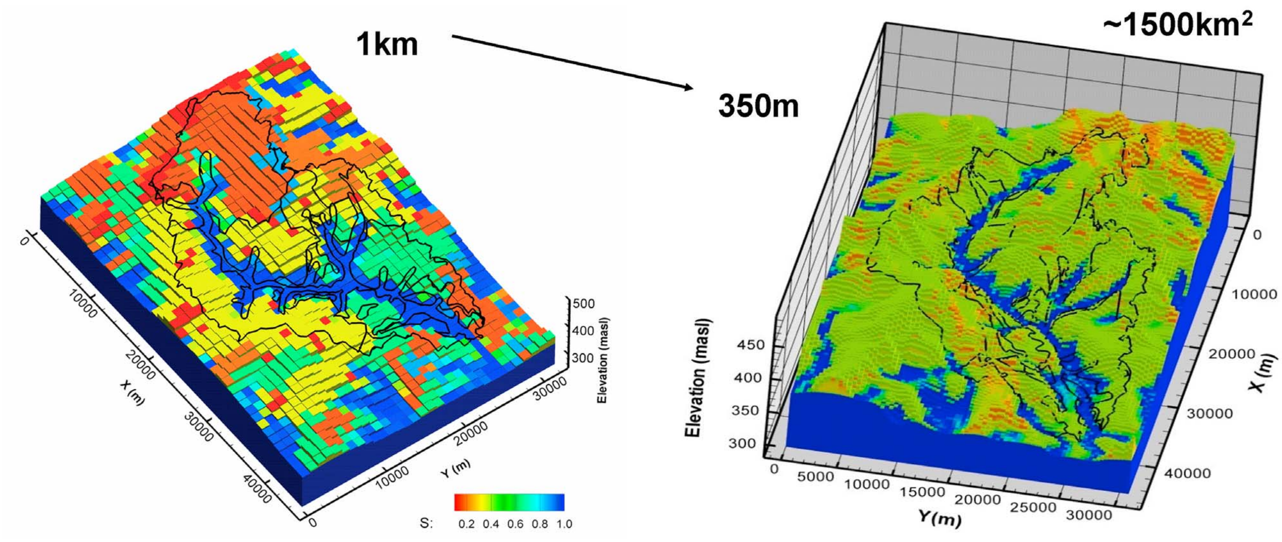

Figure 1. Higher-resolution modeling leads to better spatial representation of saturated and nonsaturated areas, with implications for runoff generation, biogeochemical cycling, and land-atmosphere interactions. Soil moisture simulations on the Little Washita showing the impact that the resolution has on its estimation [*Kollet and Maxwell*, 2008].

and water table slopes that drive surface and subsurface water movement. Instead, these processes, or surrogates for them, are represented with parameterizations that bear only weak relationships to the underlying physics. On the other hand, kinematic wave modeling of surface water within representations of catchment river networks is currently being done [*Bates and De Roo*, 2000]. Potentially, these models can be expanded globally and can be generalized to much higher spatial resolutions, albeit with improved numerical schemes that will be needed to cope with small Courant numbers. More complete representation of the Saint-Venant equations appears to be computationally feasible at hyperresolution but will require more precise channel geometry information. On the other hand, SWOT (planned launch 2019) is expected to provide some of the information that will be required. Flooding of initially dry surfaces is computationally challenging but feasible [e.g., *Hesselink et al.*, 2003]; however, much higher resolution information about channel topography (including small dykes and levees) has to be known at high accuracy for explicit models to provide added value relative to more highly parameterized approaches.

[9] Correct implementations of surface flow in hyperresolution hydrologic models will also require much better representation of the subsurface. Figure 1 illustrates the increased ability to estimate subsurface moisture that results as model spatial resolution increases. The importance of subsurface and surface water dynamics for land surface and land-atmosphere exchanges has been addressed by various studies [see, e.g., *York et al.*, 2002; *Bierkens and van den Hurk*, 2007]. These studies suggest that there exists a strong linkage between the mass, energy, and momentum balances of the subsurface and the land surface, which require integration of what at present are two different paradigms.

[10] The classic LSM community, closely associated with atmospheric sciences, attempts to improve the representation of subsurface–land surface interactions by relaxing the simplifying assumptions associated with the lower boundary condition and its connection to surface water. On the other hand, the classic hydrogeology community attempts to relax the simplifications of the upper boundary (i.e., the land surface) in subsurface flow and transport models, which traditionally has been treated as an oversimplified Neumann boundary condition. Both paradigms require the implementation of additional physics and an associated increase in resolution and spatial scales. *Kollet et al.* [2010] suggest a path forward in the context of coupling groundwater–land surface modeling systems. Essentially, they carried out a parallel modeling study using a 3-D variably saturated flow problem including land surface processes that was solved using from 1 to 16,384 parallel processors. They demonstrated that regional hydrological simulations using $O(10^9)$ unknowns could be solved with reasonable computational effort. This type of computational approach will have application to a broader class of hyperresolution land-atmosphere models.

2.2. Land-Atmosphere Interactions

[11] As in surface-subsurface interactions, our understanding of land-atmosphere interactions is highly limited by the coarse spatial resolutions of current generation models. One example of this limitation is upscaling water energy land-atmosphere feedbacks. The initiation and life cycle of many warm season precipitation events can be markedly influenced by relatively small scale variations in terrain, vegetation, soil moisture, or human structures [cf. *Chow et al.*, 2006]. Because of strong nonlinearity in the life cycle of atmospheric convection (e.g., initiation, cloud growth and decay, diabatic heating, and precipitation) there is a significant potential for relatively small scale (order hundreds of meters) changes in surface flux characteristics that drive larger-scale responses in the atmosphere (order of tens of kilometers). Summer rainfall events provide critical water for ecosystems and agriculture while occasionally generating more extreme responses such as flash floods. Owing to scale-dependent processes, such as the horizontal redistribution of terrestrial water or complex canopy airspace exchanges

[e.g., *Huang et al.*, 2009], improved understanding and prediction of these complex and multiscale feedback interactions between the land surface and atmosphere require hyperresolution land surface modeling. This modeling must satisfy mass and energy conservation constraints and provide meaningful statistical distributions of land surface flux so that the atmosphere can be subjected to turbulence perturbations of realistic structure. Hyperresolution land surface modeling will address one of the key components of this coupled prediction problem that may lead to better weather predictions.

[12] Among the ways in which these land-atmosphere interaction challenges might be met is through fully coupled (land-atmospheric-ocean) hyperresolution global models or regional atmospheric models coupled to a hyperresolution land model. Unfortunately, at present both pathways are presently infeasible computationally. Current high-resolution regional coupled models, say. at 2 or 3 km resolution, suffer from the usual representations of homogenous land surfaces (or parameterized heterogeneity) within the grid and would benefit from better representations of the surface at hyperresolutions of, say, 50 to 100 m. Given the mixing in the atmosphere, having a coarser atmosphere overlying a finer land surface representation still yields great benefits in predictions related to biogeochemical fluxes, wetlands, and other manifestations of land surface heterogeneity that are subgrid to the atmospheric model. In regions like the United States, there are merged precipitation radar, in situ gauge data sets at 1–2 km spatial scales that could be used to force off-line hyperresolution land models that would offer much better initial land conditions for the regional models or could provide the turbulent heat fluxes and surface temperatures that can be used as the boundary conditions for large-eddy simulations.

[13] Hyperresolution land surface models, run off-line with high-resolution forcings, will be particularly challenging in terms of the exchange of mass, energy, and momentum from the land surface to the atmosphere. Currently, these exchanges are parameterized using similarity approaches, e.g., Monin-Obukhov, which are based on assumed logarithmic wind profiles and associated stability characteristics of the lower atmosphere. These are purely one-dimensional vertical transfer schemes; lateral transport is not included. There is no horizontal scale attached to these schemes a priori, and the validity depends on the homogeneity of the land surface, i.e., the roughness elements. Resolving variability or heterogeneity at hyperresolution will require advances beyond the similarity approaches and the associated homogeneity assumptions; new transfer schemes will need to include lateral transfer of mass, energy, and momentum that will connect to atmospheric models as lower boundary conditions.

2.3. Water Quality

[14] Representation of water quality at regional to continental scales is in its infancy, and attempts to do so in general are much less sophisticated than are hydrologic representations in global land surface models [*Vörösmarty and Meybeck*, 2004]. More sophisticated models based on physical and biochemical principals exist, e.g., the integrated catchment suite of models at the catchment scale for nitrogen, ammonia, phosphorus, carbon, metals, and sediments [see, e.g., *Whitehead et al.*, 1998a, 1998b]. Such models are presently limited to application to relatively small catchments. Nonetheless, the beginnings of frameworks that could lead to global water quality modeling exist. For instance, some of the current global-scale models resolve the vertical soil heat balance, making it possible to calculate temperatures for runoff components. This information could be combined with surface energy balance representations for river segments to calculate surface water temperature. Surface water temperature, along with water flows and soil moisture predictions from a hyperresolution hydrological model, could be used to drive biogeochemical and water quality modules. Such process-based, dynamic models could be used to address key chemical and ecological issues affecting rivers, lakes, estuaries and oceans. This could include eutrophication causing excessive algal growth, point and diffuse pollution in rivers, contamination of groundwater and lake systems, and metal release.

[15] Furthermore, generalization of hyperresolution land models could allow representation of important processes related to carbon fluxes such as the recycling of carbon to the atmosphere as CO_2. *Richey et al.* [2002] have estimated that 0.5 Gt of carbon per year is outgassed from stream surfaces in the Amazon basin, an amount that is an order of magnitude larger than the export to the ocean via the channel system. Because much of the total surface area is made up of relatively small streams (see Figure 2), accounting for this term, which appears to be substantial relative to other global sources of carbon (and roughly balances terrestrial uptake of carbon in the Amazon basin) requires much more detailed representation of stream channel systems, and their dynamics, than is done by any current land surface model. Hyperresolution hydrological models would provide a construct for representing these processes, which combine biogeochemistry and surface and subsurface moisture fluxes, and cannot realistically be represented in current generation land surface models.

[16] Linking hydrologic stores and fluxes with the nitrogen cycle (specifically, the simulation of redox-sensitive species that affect water quality) is a challenging task that would be aided by hyperresolution models. The redox conditions that affect the coupled soil carbon-nitrogen cycles can change dramatically as soils become saturated. Human activity has increased the loading of fixed nitrogen onto land [*Vitousek et al.*, 1997], which in turn affects both aquatic and terrestrial ecosystems. Assessing how much of the fixed nitrogen loaded onto the land surface is transported to surface waters requires quantification of the mass of nitrogen that is denitrified. Hyperresolution models will allow for the resolution in time and space of zones with high soil moisture, where denitrification occurs. Still, since the relationship between redox conditions in soils and soil moisture is highly nonlinear, mean soil moisture resolutions even at $>O(100\text{ m})$ may not be sufficient to accurately predict nitrification rates, especially when there are significant topographic heterogeneities. Hence, statistical techniques that rely on high-resolution land surface elevations may have to be invoked for this purpose to determine the frequency of high saturated zones within a grid and, in turn, the estimation of denitrification rates as a function of soil chemical properties, temperature, and saturation.

[17] Moving from the catchment scale to regional and continental scales [see *Wade et al.*, 2002a, 2002b] will enable

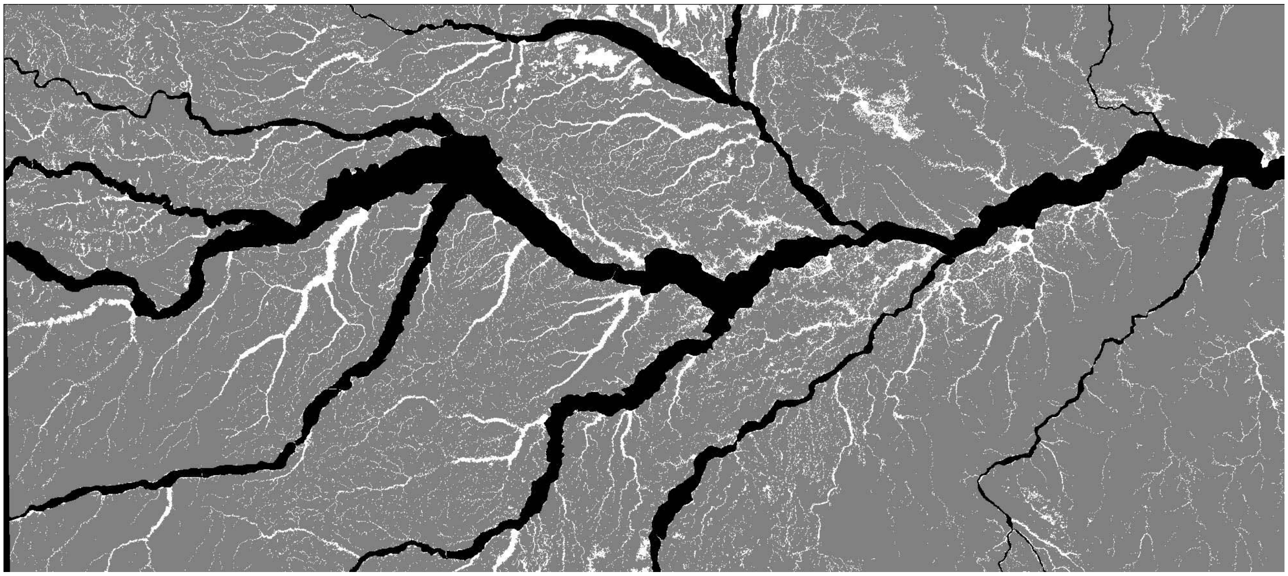

Figure 2. Complex, fine-scale inundation areas of the Amazon River and its tributaries control the CO_2 outgassing during the wet season. The spatial resolutions of current LSMs are unable to accurately simulate inundation dynamics because of limitations in resolution and parameterizations and therefore provide poor estimates of the outgassing. The quadrant extends from 72°W, 0°N to 54°W, 8°S. JERS imagery reprinted from *Hess et al.* [2003], with permission from Elsevier.

a broad range of new problems to be addressed such as the transboundary aspects of pollution control; feedbacks to the climate system; and fluxes of carbon, nitrogen, and phosphorous into coastal and ocean systems. Many biochemical and water quality problems require process-based models to address the dominant modes of behavior, and the models need to be dynamic to adequately address the interactions between state variables, processes, and environmental drivers. These models could build on hyperresolution hydrological models; however, practical issues in both computation, and the manner in which hydrological and physical-chemical processes are represented, remain to be resolved.

2.4. Human Impacts on the Terrestrial Water Cycle

[18] Humans rely heavily on water for survival and well being. As a result, the species has left a large footprint on the terrestrial water cycle. The minimum requirement of water for human survival is about 5 L/d, corresponding to about 10 km^3/yr globally for the current global population. Actual water consumption is orders of magnitude larger; estimates range from about 4000–6000 km^3/yr, or about 10% of global runoff [*Döll*, 2009]. To meet these needs, about 7000 km^3 of reservoir storage has been constructed globally. Most current generation land surface models do not represent the effects of these manipulations of the terrestrial water cycle at all, and those that do, do so only crudely. Furthermore, vegetation has strongly been altered by agricultural development, grazing, and forest harvest, to the extent that only a small percentage of the global land area remains unaffected. Artificial drainage by pipes or canals accelerates subsurface runoff, with strong effects on solute transport, e.g., of nutrients. Man-made dams and reservoirs have also significantly altered river discharge and evaporation, affecting sediment transport and freshwater ecosystem well-being [*Vörösmarty et al.*, 2003; *Döll et al.*, 2009]. Urban areas, although representing a relatively small part of the global land area (and hence not represented at all in most current land surface models), strongly affect the water cycle by reducing infiltration and groundwater recharge and greatly increasing runoff, especially runoff peaks.

[19] The atmospheric focus of most land surface models has resulted in the above effects being mostly ignored aside from land cover change (land cover is prescribed in most models and hence can account for changes in current relative to historical conditions), primarily because the areas affected are modest, and the global land area is only a third the size of the global oceans. However, the manifestations of environmental change, not to speak of the demand for weather and seasonal climate forecasts, is greatest over land, and representation of the key land surface processes arguably deserves more attention than it has been given. Therefore, a hyperresolution hydrologic model needs to include modeling of anthropogenic manipulations of the water cycle such as water withdrawals and consumptive water use by the various water use sectors, large-scale transfers, and reservoirs. The water use sites need to be related to the respective locations of water withdrawals and needs to distinguish groundwater from surface water withdrawals.

[20] To be able to simulate the effect of dams, the location, surface areas, volumes, and operating purposes of reservoirs are required. Such information at present is available only for the largest global reservoirs [*International Commission of Large Dams*, 2003], which constitute about two thirds of global reservoir storage. Additionally, hyperresolution hydrologic models must provide for improved representation of urban hydrology, including the effects of impervious areas on heat flows, infiltration, groundwater recharge, and flooding. The significant challenge in modeling the urban areas at high resolution will be the geometry and functioning of the subterranean man-made infrastructure for drinking water, storm runoff, and sewage. Drinking water is often extracted

(far) away from the actual cities, and storm water runoff and sewage is discharged locally, but its impact is often transported large distances. Representing these effects will require surmounting fundamental data issues. The types of information required, for instance, to define urban drainage networks generally requires spatial resolutions considerably finer than 100 m and is available at present only on a local basis [e.g., *Meierdiercks et al.*, 2010].

2.5. Computational Considerations

[21] Global, hyperresolution modeling will require large, massively paralleled computer resources and solution algorithms that efficiently use these resources. For purposes of this discussion, we characterize such systems as massively parallel clustered computing resources with more than 1000 processors, which are increasingly becoming available to scientists and practitioners. While such systems have been utilized in many Earth science disciplines for decades, the land surface, hydrologic, and hydrogeologic modeling communities have been slow to utilize these computational resources in a formalized fashion. *Kollet et al.* [2010] offer examples of the effective speed-up in computing time for a coupled groundwater–land surface modeling system that uses more than 16,000 processors. In implementing coupled and uncoupled physics-based modeling approaches for hyperresolution modeling, technical problems that arise in parallel computing environments will have to be addressed. Some of these problems are particular to the land surface and subsurface hydrodynamics under consideration and their discretization, including using nested approaches and multiscale process representation, solver infrastructures to obtain solutions to the resulting systems of equations; load balancing of large problems; and input-output handling. Fortunately, many of these problems have been faced, albeit in somewhat different forms, by other fields, so we can draw on a rich history of sophisticated concepts, software libraries, and technical tools that have been tested and applied elsewhere.

[22] Computational algorithms and computer systems will also be needed to merge satellite and ground observations with the terrestrial water cycle model via much more computationally demanding data assimilation procedures. Excluding Greenland and Antarctica, the land area of Earth is approximately 135,000,000 km^2. Depending on the model resolution, this requires a system that can simulate between 10×10^6 (~4 km resolution) and $>100 \times 10^6$ (~1 km resolution) grids on an hourly to daily basis. Furthermore, some satellite data sets are or will be available at much higher spatial resolutions (e.g., NASA's Shuttle Radar Terrain Mapping (SRTM) mission produced near-global (±60° latitude) digital elevation data at sub–100 m grid resolution) and hence greater data rates. For instance, the land downlink for SWOT is expected to process about 1 Tb of data per day. Without advanced numeric algorithms and parallel and cluster computer approaches, the computational demands will clearly be infeasible. Understanding the potential of modern computer hardware for addressing problems of this magnitude is fundamental to making progress on developing a hyperresolution hydrologic system.

2.6. Observations and Data

[23] Hyperresolution hydrologic modeling will entail an unprecedented demand for very high resolution, global land surface characterization data. To support model resolutions at 1 km or finer implies a need for observations of some processes at spatial scales on the order of tens of meters. The HydroSHEDS elevation and hydrography data set [*Lehner et al.*, 2008], based on SRTM mission data, is one state-of-the-art example data set (Figure 3).

[24] While some of these data exist over parts of the global domain (and the challenge therefore is to extend them into unified and consistent global databases), others are nonexistent at present. For example, data on sectoral water withdrawals and water sources exist at country and subnational scales, but subnational information is very difficult to obtain, especially in developing countries. Furthermore, there are major inconsistencies in data categories and other specifics across country boundaries. Existing data as to the location of river dikes are often unreliable, and global DEMs are currently too coarse for this purpose. This will limit implementation of hyperresolution flood inundation forecasts. Global data required to represent water management effects, such as the location of artificially drained areas, water quality data, and subsurface characterization data, are mostly nonexistent at high spatial resolutions. Global soil texture information and related soil hydraulic and thermal properties are also lacking at high spatial resolutions, yet this information critical in improving the modeling of crops; prediction of the dynamics of infiltration and soil water, nonpoint pollution; or landslide potential (among other processes.)

[25] The current era of satellite remote sensing provides unprecedented observations to support some of the needs associated with global hyperresolution hydrological modeling, but there is a clear need for improvements in sensor resolution and the development of advanced downscaling methodologies. Hydrologists can now obtain routine estimates of evaporation and land surface temperature from thermal infrared sensors, precipitation from active and passive microwave sensors, surface soil moisture and snow water equivalent from passive microwave sensors, and snow-covered area using both visible and microwave sensors [*Schmugge et al.*, 2002]. Planned and recently launched sensors have led to a new suite of hydrologically relevant observations, including improved active and passive microwave-based precipitation on the order of kilometers as part of the Global Precipitation Mission (GPM) and combined active-passive soil moisture retrievals as part of the Soil Moisture Passive Active (SMAP) mission, gravity-based terrestrial water storage from the Gravity Recovery and Climate Experiment (GRACE) whose resolution hopefully will be considerably improved in follow-up missions, active radar sensors that will provide two-dimensional altimetric water levels (from the recently announced NASA–Centre National d'Etudes Spatiales SWOT mission), high-resolution snow water data under the CoReH20 mission, and DESDynl for vegetation structure information that should lead to improved land cover characteristics (e.g., leaf area index phenology) and ecosystem health. The major challenges therefore remain to assess the importance of specific current, planned and to-be-developed measurements, to determine how to process the observations to make them more useful, and to develop appropriate computational assimilation systems where the observations can be merged with the hydrological models. As examples, areas of remote sensing technical developments would include advanced antenna designs that allow for high

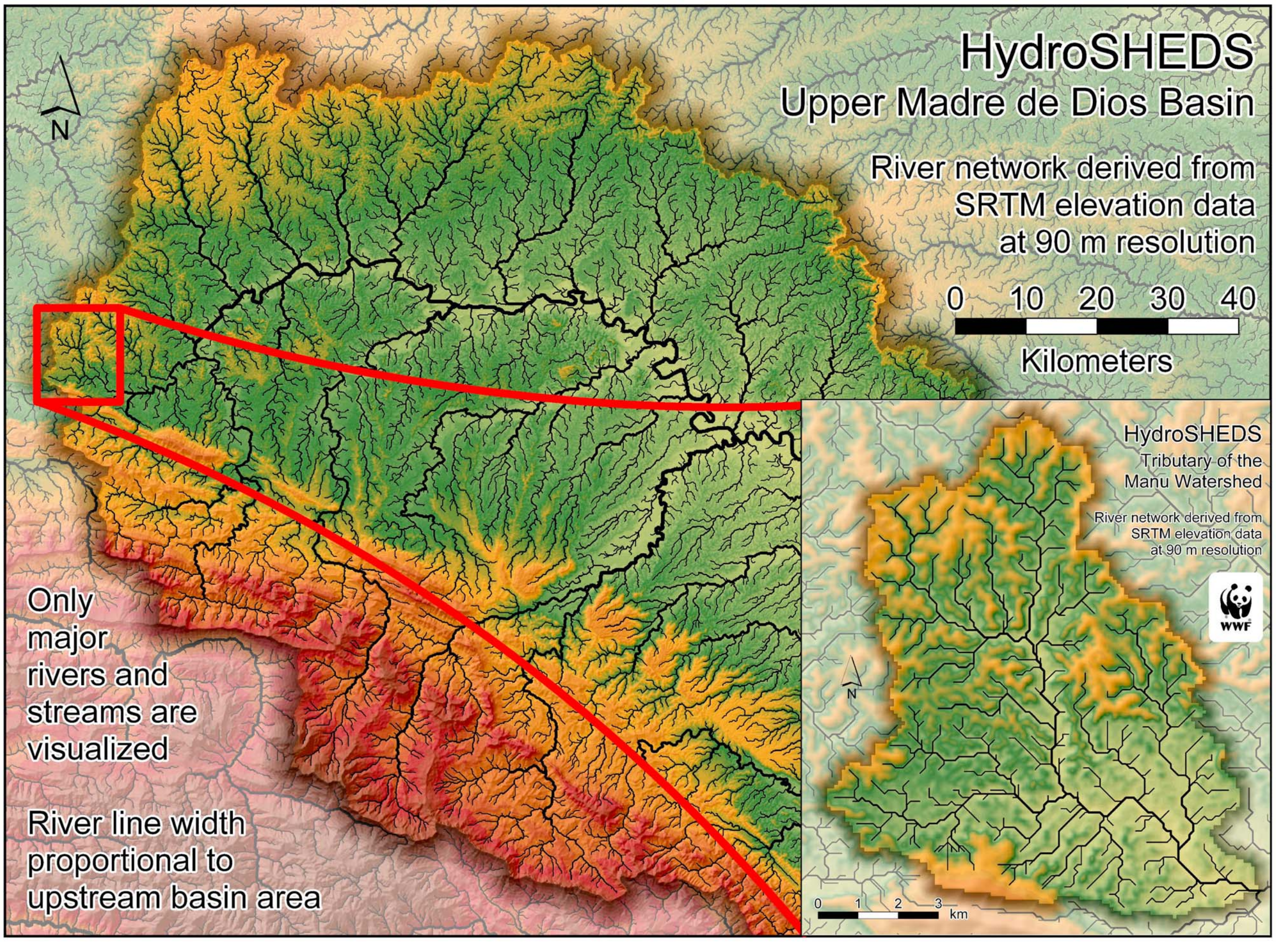

Figure 3. HydroSHEDS, an example of a global data set that will be needed for a hyperresolution hydrologic model. The data set consists of elevation, stream networks, watershed boundaries, drainage directions, and ancillary data layers such as flow accumulations, distances, and river topology at various resolutions from approximately 90 m to 10 km and is based on data from NASA's Shuttle Radar Topography Mission.

spatial resolution while maintaining swath width and advanced geostationary sensors that allow for thermal sensing at scales equivalent to today's polar orbiting thermal sensors. The development of advanced satellite simulation models combined with the called-for hyperresolution land model would allow for quantitative assessment of such potential systems, essentially an advanced Observing System Simulation Experiment (OSSE) framework.

[26] In addition, the development of a global hydrological model should go hand in hand with a reassessment of needs and opportunities for improved in situ observation networks. The assessment should look for instrumentation that produces information that is orthogonal to satellite data [*Fenicia et al.*, 2008] or would help interpret and calibrate satellite data. The type of instruments required could very well include distributed telemetric sensing networks, which are coming of age [*Ritsema et al.*, 2009; *Lehning et al.*, 2009]. The new network technologies are complemented through the use of cost-effective sensors, which, combined with the near ubiquitous presence of Global System for Mobile Communications and general packet radio service communication, allow for collection of data from stations and networks around the world. In addition, several international communications companies have recently shown interest in environmental sensing. This assessment of the in situ network should be part of a comprehensive global OSSE.

3. Call to Action

[27] Hyperresolution land surface modeling would provide a framework for addressing science questions that we are not able to answer with current modeling capabilities. Social benefits would accrue because of improved ability to monitor and predict the Earth's terrestrial water, energy, and biogeochemical cycles. We have discussed the challenges that such an enterprise will face, some of which are daunting. Nonetheless, we believe that the challenge can be met by a concentrated and coordinated effort by the hydrologic community. Such an effort could be initiated by adapting existing models and slowly adding to them and/or replacing them by new constructs. While our vision is to develop a global-scale hyperresolution land modeling capability, we recognize that a nested, multiscale system could represent one pathway forward. Such a "telescoping" potential would allow for

incorporating different processes that may be important in different regions, e.g., urban areas with great detail on impervious runoff areas, detention ponds, and storm drains and wetlands with organic carbon and nitrogen dynamics. Hydrologic models applicable to small catchments already exist at the scales we discuss, so the challenge is to increase the domain to the large regional, continental and global scales and to develop the fine-scale process parameterizations, data sets, and computational resources for these scales. The work can and should make use of test beds, some of which have already been proposed by the community for developing the parameterizations that link water-energy-biogeochemical processes. Many individual researchers are involved in projects that relate to hyperresolution modeling in one way or another; however, unification of these efforts is lacking.

[28] We call for the international hydrologic community and the hydrological science support infrastructure to endorse an effort to build a hyperresolution hydrologic modeling framework that will lead to a better understanding of the global terrestrial water, energy, and biogeochemical cycles and the anthropogenic impacts on the system. Similar community initiatives have been successful in the recent past. For example, the call to apply our science to understand the hydrologic response in ungauged basins [*Sivapalan*, 2003] led to the International Association of Hydrological Sciences Project for Ungauged Basins (PUB), which has developed into robust, wide-ranging, and mostly self-organizing research groups and projects addressing a variety of hydrologic science problems relevant to PUB. On the U.S. national scale, the Consortium of Universities for the Advancement of Hydrologic Science, Inc., has a more structured collaborative activity, including formal governance, a board of directors, and a director, but more importantly, science activities that include development of a research and test bed plans and funded research projects. One activity, the proposed Community Hydrologic Modeling Platform (CHyMP), is synergistic to the call here for the development of a hyperresolution LSM.

[29] Three areas where assistance is needed from hydrologic science research and infrastructure programs to move our vision forward are as follows.

[30] 1. Enhanced access to massively parallel computing infrastructure on a sustained basis is needed. Such infrastructure exists and is widely used by other engineering and physical science communities. The access must be accompanied by research support so knowledge and expertise in these resources are part of student-based hydrologic research. It can be argued that establishing this expertise would be in the scientific interests of many countries.

[31] 2. Infrastructure to support the data needs of the initiative is also needed. This is more complicated and costly and requires people to help develop and integrate the supporting data sets and to host, maintain, and disseminate the data. These needs would presumably require a dedicated center or effort appended to an existing center.

[32] 3. Programmatic support for the underlying research that would allow the effort to move forward is needed. One end-member for such an effort would be an integrated research effort with the goals of designing a modular structure for such a hyperresolution modeling system and identifying the hydrological processes to be represented and their parameterizations, numerical solutions, and structure within a massively parallel computing environment. This approach would follow the development path for the Weather and Research Forecast (WRF) model [*Michalakes et al.*, 2001; *Skamarock et al.*, 2005]. This was an international, multi-institutional research and development effort, led by the National Center for Atmospheric Research, that resulted in an advanced mesoscale forecast and data assimilation system that is finding wide use both in research and operationally. Potentially, a high-resolution land surface model, as called for in this paper, could follow this path given institutional leadership. The other end-member would be an ad hoc community effort along the lines of PUB, where self-organizing groups focus on aspects of the science plan, or, similarly, the effort to develop the Common Land Model (CLM) [*Dai et al.*, 2003]. The CLM effort brought together many land modeling researchers to develop a new LSM by synthesizing previous advances and introducing new improvements with the goal of incorporating the new model into the NCAR Community Climate System Model, a much narrower goal than is envisioned here. Our assessment is that the WRF development path could be a successful approach and that the PUB model works best for specific science issues and could be an element of a larger development effort but that the CLM approach would probably suffer from lack of focus, funding, and organization.

[33] We have argued in this opinion paper that the hydrology community needs a hyperresolution land surface model to address the water problems facing society. We strongly believe that addressing this need, as described here, will ultimately lead to a more informed and aware society that can sustain the water needs of the future.

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M. F. P. Bierkens and R. P. H. van Beek, Department of Physical Geography, Utrecht University, PO Box 80115, NL-3508 TC Utrecht, Netherlands.

E. Blyth, Centre for Ecology and Hydrology, Wallingford OX10 8BB, UK.

A. de Roo, Institute for Environment and Sustainability, European Commission Joint Research Centre, Via E. Fermi 2749, T.P. 261, I-21027 Ispra, Italy.

P. Döll, Institute of Physical Geography, Goethe University Frankfurt, PO Box 111932, D-60054 Frankfurt am Main, Germany.

M. Ek, Environmental Modeling Center, National Centers for Environmental Prediction, 5200 Auth Rd., Rm. 207, Suitland, MD 20746-4304, USA.

J. Famiglietti, UC Center for Hydrologic Modeling, University of California, Irvine, CA 92697-4690, USA.

D. Gochis, Research Applications Laboratory, National Center for Atmospheric Research, Boulder, CO 80304, USA.

P. Houser, Department of Geography and GeoInformation Science, George Mason University, Fairfax, VA 22030, USA.

P. R. Jaffé, J. K. Roundy, J. Sheffield, T. J. Troy, and E. F. Wood, Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544, USA. (efwood@princeton.edu)

S. Kollet, Meteorological Institute, Bonn University, Auf dem Huegel 20, D-53121 Bonn, Germany.

B. Lehner, Department of Geography, McGill University, Burnside Hall, 805 Sherbrooke St. W, Montreal, QC H3A 2K6, Canada.

D. P. Lettenmaier, Department of Civil and Environmental Engineering, University of Washington, Box 352700, Seattle, WA 98195-2700, USA.

C. Peters-Lidard, Hydrological Sciences Branch, NASA Goddard Space Flight Center, Code 614.3, Greenbelt, MD 20771, USA.

M. Sivapalan, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA.

N. van de Giesen, Department of Water Management, Delft University of Technology, Stevinweg 1, NL-2628 CN Delft, Netherlands.

A. Wade, School of Human and Environmental Science, University of Reading, Whiteknights, Reading RG6 6DW, UK.

P. Whitehead, School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK.