Establishing a Framework for Community Modeling in Hydrologic Science

Report from the
3rd Workshop on a Community Hydrologic Modeling Platform (CHyMP):
A Strategic and Implementation Plan
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Executive Summary

The Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) is continuing a major effort towards the development of a Community Hydrologic Modeling Platform (CHyMP)[1]. A first, scoping workshop was held in March, 2008 [*Famiglietti et al*., 2008, 2009], and identified the need for a substantive, university-led community modeling activity in hydrologic science. A second workshop, *Blueprint for a Community Hydrologic Modeling Platform (CHyMP) Workshop,* further developed the community vision of CHyMP. This 3rd workshop, *A Strategic and Implementation Plan,* was held March 15 – 17, 2011 at the Beckman Center for the National Academies at the University of California at Irvine, to come to community consensus on how to move this vision forward. Sponsored by the National Science Foundation (NSF), the UC Center for Hydrologic Modeling and CUAHSI, the goal of this workshop was to identify concrete steps around several areas related to implementing a community hydrologic modeling effort.

Over 30 participants attended the third workshop (see Table 1), and were invited based on their experience and expertise across a range of aspects of hydrologic modeling. Attendees from the U.S. and abroad represented universities, government labs and federal agencies.

This document provides a detailed report on the finding of the third workshop. A brief workshop report appears as Arrigo et al. [2011].

Findings and Recommendations

The ultimate goal of the CHyMP effort is to establish a community modeling program that enables comprehensive simulation of water anywhere on the North American continent. Such an effort would include connections to and advances in global climate models, biogeochemistry, and efforts of other disciplines that require an understanding of water patterns and processes in the environment. To achieve such a vision will require substantial investment in human and cyber-infrastructure and significant advances in the science of hydrologic modeling and spatial scaling. In the second workshop, the community identified key aspects and recommendations to advance this effort. This third workshop considered explicitly how to implement these recommendations.

Participants agreed that the community is ready to move forward with implementation, and the goal of this workshop was to define a focused effort that could be undertaken immediately. It is recognized that initial implementation of this larger effort can begin with simulation capabilities that currently exist, or that can be easily developed. Discussion centered around four key activities in support of community modeling: benchmarking, dataset evaluation and development, platform

[1] In this report, the 'CHyMP effort" the refers to a group of future investigators, which at present is represented by the report authors and selected workshop participants who currently comprise the CHyMP working group or leadership.

evaluation, and developing a national water model framework. Key findings included:

1) The community is very supportive of the idea of a National Water Model framework, and a community effort is needed to explore what the ultimate implementation of a National Water Model is. A true community modeling effort would support the modeling of "water anywhere" and would include all relevant scales and processes.

2) CHyMP implementation should initially focus on continental scale modeling of water quantity (rather than quality). The goal of this initial model is the comprehensive description of water stores and fluxes in such a way to permit linkage to GCM's, biogeochemical, ecological, and geomorphic models. This continental scale focus allows systematic evaluation of our current state of knowledge and data, leverages existing efforts done by large scale modelers, contributes to scientific discovery that informs globally and societal relevant questions, and provides an initial framework to evaluate hydrologic information relevant to other disciplines and a structure into which to incorporate other classes of hydrologic models.

3) Dataset development will be a key aspect of CHyMP implementation. Our current knowledge of the subsurface is limiting our ability to truly integrate soil and groundwater into large scale models, and to answering critical science questions with societal relevance (i.e. groundwater's influence on climate).

4) The CHyMP workshops and efforts to date have achieved collaboration between university scientists, government agencies and the private sector that must be maintained. CHyMP implementation will focus on establishing working groups that will leverage and maintain this collaboration for maximum scientific and societal benefit.

5) Moving forward, CHyMP implementation should begin with working groups focused initially on an initial version of a National Water Model by establishing current capabilities through benchmarking large-scale models, identifying and enhancing current continental-scale data of important forcing and parameters, and evaluating the cyberinfrastructure needed to support truly integrated hydrologic modeling across the continent.

Introduction

Simulation is a primary tool for the water science community to infer processes controlling water-related phenomena, ranging from streamflow generation, to flooding and drought, landform evolution, and biogeochemical cycling. Historically, scientists have independently developed model code with varying objectives, using a range of computer languages and tested on different data sets.

The net result of this process is the existence of a large number of hydrologic models that are difficult to compare and access. Diversity in approach and in hypotheses is a critical part of a robust and healthy science; yet the lack of comparability of models and performance metrics, and barriers to model accessibility, greatly impede scientific progress. This situation is impeding the advancement of water science relative to other disciplines, like atmospheric science, where a vibrant community-modeling activity has contributed to many key scientific advances over the last several decades.

The objective of the Community Hydrologic Modeling Platform (CHyMP) initiative[2], a grassroots effort begun in 2008, is to build the cyber- and human infrastructure for community-driven, integrated model development and comprehensive dataset compilation, as well as a framework for model distribution, high performance computing access and technical support. The goal of CHyMP is to significantly accelerate the development of advanced hydrological modeling capabilities in order to better equip the community for basic water science discovery and to address complex water issues of the highest priority at regional, national, and international levels. CHyMP is envisioned to be a series projects coordinated through CUAHSI that are designed to build and sustain community modeling in hydrology.

To initiate CHyMP, three workshops on the development of community modeling were held in March 2008 (Famiglietti et al., 2008, 2009), and March 2009 (Famiglietti et al., 2010), and March 2011 (Arrigo, 2011).

The first 'scoping' workshop was limited to a small number of experienced modelers and model users to assess the need for a community modeling effort in hydrology. Participants of the 1st Workshop presented and discussed multiple simulation approaches and scientific problem domains. The group expressed unanimous support for moving forward with a community modeling effort, as well as for the development of an integrated, national-scale water model.

The goal of the 2nd Workshop was to engage the broader community to identify the scope, form and requirements of the community modeling activity, and to identify

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the key science goals that would ultimately drive the development of the platform components. Important findings were that:

- CHyMP should build upon existing platforms or integration software, such as those under development by the Community Surface Dynamics Modeling System (CSDMS), the Earth System Modeling Framework (ESMF), or the NASA Land Information System (LIS);
- The broader community was wholly supportive of the development of a community National Water Model (NWM).
- A critical recommendation that also emerged from the 2nd Workshop was for the CHyMP effort to take a leadership role in establishing a Hydrologic Modeling Community of Practice to establish a set of 'best modeling practices' for a range of issues regarding coding, component model interface structure, and input and output formatting and standards
- Workshop participants agreed that a standardized set of benchmarks and metrics to help define model performance would be a welcome contribution that would likely raise the bar in the hydrologic modeling community by holding it to an agreed upon set of standards.

The 3rd CHyMP Workshop: A Strategic and Implementation Plan, funded by the National Science Foundation and the UC Center for Hydrologic Modeling, brought together over 30 participants (Table 1) from universities, government agencies, and the private sector to focus on defining steps to begin implementing CHyMP.

Before the workshop, participants were asked to review a draft white paper organized around the findings and recommendations of the second workshop. In approaching implementation, the white paper recognized the central idea that building the necessary framework for hydrologic modeling that can integrate a set of interacting components with comprehensive datasets, both from multiple scientific domains and over a range of scope and scales, like advanced climate models, requires a community effort.

While the CHyMP effort can be informed by the atmospheric and climate modeling communities' experience with community modeling, there are some distinct and unique challenges that emerge when considering hydrologic modeling as a community effort. The atmospheric science community's Weather Research and Forecasting model (WRF) has a clear and concise objective (it is a "mesoscale numerical weather prediction system" (http://www.wrf-model.org/index.php)) and thus benchmarks can be designed that assess prediction improvement. Hydrologic modeling is a multi-purpose endeavor. From the second workshop, it was found that the broader community was supportive of the idea of development of a community National Water Model (NWM). However, moving toward implementation requires the community to better define what such a model would look like. The third workshop approached this challenge by identifying the ultimate goal of a NWM: comprehensive simulation of water anywhere on the North American continent. This would ultimately include quantity and quality, surface and subsurface, pore scale to continental processes. Successful implementation of this ultimate vision is dependent on identifying strategic and effective short term steps, as well as longer range plans.

Key Steps toward Implementation

The ultimate goal of CHyMP is a community modeling effort that enables comprehensive simulation of water anywhere on the North American continent. This would enable connections to and advances in global climate models, biogeochemistry, and efforts of other disciplines that require an understanding of water patterns and processes in the environment. To achieve such a vision will require substantial investment in human and cyber-infrastructure and significant advances in the science of hydrologic modeling and spatial scaling. In the second workshop, the community identified key aspects and recommendations to advance this effort. This third workshop considered explicitly how to implement these recommendations.

Participants agreed that the community is ready to move forward with implementation, and the goal of this workshop was to define a focused effort that could be undertaken immediately. It is recognized that initial implementation of this larger effort can begin with simulation capabilities that currently exist, or that can be easily developed. Discussion centered around four key activities in support of community modeling: benchmarking, dataset evaluation and development, platform evaluation, and developing a national water model framework.

The National Water Model (NWM) as framework

In recognition of the immediate focus of this workshop, participants further discussed and agreed on the concept of a "National Water Model" introduced during the second CHyMP workshop. From the second workshop report [Famiglietti et al. 2010]:

"A National Water Model will provide a framework for simulating all the major features of the natural (i.e. snow and ice, permafrost, frozen ground, lakes, wetlands, rivers, floodplains, soil moisture, groundwater, evaporation, transpiration, infiltration, percolation, runoff generation, streamflow) and human (reservoir storage, surface water conveyance, irrigation, surface and groundwater withdrawals, etc.) components of the water cycle, in an integrated manner and at high spatial-temporal resolution. The framework will readily accommodate data from CUAHSI Water Data Services for model calibration and validation; and as well as relevant remotely-sensed data, e.g. for precipitation, surface water, vegetation, surface temperature, snow, soil moisture and groundwater. The multiple potential model uses and stakeholders, as well as space-time scales of application (including upscaling, downscaling and telescoping resolution) were clearly recognized, and viewed as a significant, but tractable research challenge."

The National Water Model (NWM) concept evolved during the workshop as the basis for an initial continental-scale exerciseunder CHyMP. The NWM is a framework to drive the community towards comprehensive, continental-scale simulation of important natural and human-driven water processes over North America. As an initial step, the NWM is envisioned as providing continental scale simulation of the distributed stores, fluxes and flowpaths of water. Focusing on "getting the water right," at this scale, provided a context to evaluate possible benchmarking strategies and data needs, and provides a "zero-order" model against which community needs can be evaluated and prioritized. Additionally, this zero-order model provides the basis on which to incorporate regional scale models and codes, and to explore what data are necessary to truly model the full hydrologic cycle anywhere.

A viable path to early implementation of a National Water Model could be to utilize existing large-scale land-atmosphere models and integrated groundwater-surface water models, particularly those that are designed to use high performance computers. Several existing national-scale modeling efforts were discussed to examine different approaches to implementing an initial NWM framework and identify steps to evolve the processes and capabilities toward comprehensive simulation. Capabilities already exist to simulate certain aspects of national hydrology, with clearly defined objectives, and these efforts need to built upon where possible.

The National Hydrologic Prediction System (Lettenmaier and Wood, 2011) was designed to "provide ensemble forecasts of hydrologic variables and products that form the basis for improved water management, flood forecasting and drought assessment, forecasting and recovery." To meet this specific objective, the NHPS combines ensemble climate model predictions, state variable and initial condition data assimilation and the Variable Infiltration Capacity model (VIC) to create seasonal and near real time streamflow, soil moisture, snow water equivalent, and runoff data. Continental scale simulation of VIC is possible, and the NHPS experience in merging East and West forecasting systems and the extensive validation processes done can inform the CHyMP effort.

The USGS is developing a national hydrologic model to assess how the nation's watershed will respond to climate and land use change. The USGS framework [Hay et al. 2011] uses national spatial data for model input, and can incorporate output from other models (such as GCM climate simulations) and a gridded water balance model, and multiple resolution watershed models. Similar to the NHPS, this project has a specific predictive objective; in this case it is designed to produce outputs of water availability, time and structure of flow. Elements of the USGS framework of incorporating multiple models, providing coupling and access to data, and the ability to execute at multiple resolutions were all taken as important elements to consider in a NWM framework.

Both of these projects represent national scale efforts to produce hydrologic outputs with an emphasis on producing forecasts or predictions of surface water, and can be described as relying on macro-scale land surface models.

An alternative to large-scale land surface models are a class of "integrated" models (e.g. InHM (Jones et al. 2008) , PIHM (Qu and Duffy, 2007), Parflow (Maxwell and Miller 2005)) that couple both surface and subsurface processes and seek full 3D representation of relevant hydrologic processes. HydroGeoSphere (Therrien et al., 2005) was presented as an example of how this type of physically based model can potentially be scaled up for national applications. HPC advances now make the vision of implementing truly integrated modeling at continental scale potentially viable.

The NWM concept illustrates the scientific challenges of scope and scale that further development of a community modeling effort will address. Many grand science challenges in hydrology typically involve understanding processes that are fundamental at small scales, but that have critical implications to society at larger scales. Thus, a NWM is envisioned as a framework that allows continental scale simulation (such as the current NHPS) of the full hydrologic cycle (i.e. surface and subsurface (such as PIHM or HydroGeoSphere)) but also incorporates multiple codes and models that act over regional or watershed scales, with the ultimate ability to "telescope" down to an area and scale of interest (as is being explored by USGS). This is analogous to the development of atmospheric science models, and the advancement of nested grids, but requires different implementation for hydrologic models. Current simulation capabilities require significant trade-offs between simplified representations of parameters and processes over large areas in distributed land surface models, or more accurate representations that are limited to small areas or require heroic amounts of data and processing to reach continental scale. These trade-offs limit progress on critical scientific challenges. A true national water model will include regional and local codes and allow fundamental exploration of how small scale processes scale and important checks on the larger scale simulations. Fundamental research on methodologies for upscaling observations to the model grid scale, and for downscaling model output to local scales, and the ability to incorporate and couple regional models into larger scale simulations, is needed.

Implementation

The initial implementation of a National Water Model will provide an accessible, transferable modeling framework that allows for variable domain resolution, or 'telescoping' to regions where higher spatial resolution is required, incorporate local or regional codes, and will enable significant advances in the science of spatial scaling. The participants recommend beginning with the current suite of models (including those discussed at the workshop as well as other efforts) that can be run at continental scale as prototype "version zero" models, and working within existing efforts to identify key data gaps, advantages and disadvantages of existing approaches through benchmarking and simulation experiments, and to evaluate the cyberinfrastructure needed to achieve true comprehensive, integrated modeling of the surface and subsurface.

Building on existing efforts will be critical for success. CHyMP workshops have achieved collaboration between university scientists, government agencies and the private sector that must be maintained. Existing efforts across government agencies (e.g. USGS, NCAR, NASA) on national and continental scale modeling and data acquisition and integration represent important opportunities for new partnerships and for maintaining and leveraging collaborations that enable maximum scientific and societal benefit.

An important component of a future CHyMP effort should be to take a leadership role in assembling the required data and identifying the key problem sets, questions and existing modeling approaches to distribute to the modeling community to participate in initial exercises that will assess the current state of continental scale models to assemble an initial implementation of the NWM, which will be refined and expanded over time. Calibrated regional and watershed scale models should be used as important benchmarks for the large scale models, and the framework should be developed with ultimate integration and telescoping capabilities in mind.

It is recognized that the NWM may not emerge as "a single model," but instead provides a coherent framework for assessing the needed data, research, and actions required to advance community modeling in hydrology.

Benchmarking and Community of Practice

A key finding of previous CHyMP workshops was the support for development of a Community of Practice (CoP) for hydrologic modeling, which would support more systematic documentation and evaluation of hydrologic models. An important aspect of such evaluation is model performance, e.g. comparison of model results to observed data using some algorithm. While performance indicators are widely used in climate modeling, it is far more complex to develop a uniform set of performance indicators for hydrologic modeling.

The critical difference is the diverse objectives of hydrologic models. Different models focus on different aspects of water movement in the environment depending upon whether the objective is flash flood prediction, nutrient cycling or channel morphometry. Simple prediction metrics (e.g. validating model discharge against a set of stream gages) may be useful in some cases, but might obscure the focus on understanding how the model is representing underlying processes. At the same time, if CHyMP is going to lead a national modeling effort, there is a need to select a set or sets of objectives and to develop appropriate performance indicators.

The hydrologic community needs to agree on a set of performance indicators for *all important classes of water models*, representing processes for pore to continent. These indicators can be used to both assess the predictive capabilities of models, and to gain insights into how to improve them. The workshop reviewed several ongoing efforts to establish performance indicators within the hydrology and climate communities and discussed ways to leverage and build upon these efforts within the hydrologic community.

Intercomparison

Model intercomparison studies are one way to assess our current state and understanding of hydrologic models, and are designed to explore how different parameterizations and computational approaches amongst models affect performance, and to assess the sensitivity of models to certain parameterizations. The atmospheric and weather prediction communities have a history of large scale intercomparison exercises (e.g. The Project for Intercomparison of Land Surface Parameterizations (PILPS, Henderson-Sellers et al. 1995) an ongoing effort that has over 30 land surface modeling groups participating in various phases and experiments, with the ultimate goal of better parameterization of the continental surface in pursuit of better climate models and predictions , the Distributed Model Intercomparison Project (Smith et al. 2004), organized by NOAA and which focuses on streamflow and water resources predictions, and various efforts under the Global Energy and Water Cycle Experiment (GEWEX, Dirmeyer et al. 2006). This type of exercise can inform how the hydrologic community might design a community effort to compare different computational approaches on modeling hydrologic processes. The Framework for Understanding Structural Errors (FUSE, Clark et al. 2008), is an example of a project meant to examine structural differences specifically in hydrologic models by systematically comparing and combining components from different hydrologic models comparing results to validation data.

In the atmospheric sciences, idealized cases are often used to test and understand differences between models (e.g. Jablonowski and Williamson, 2006). The integrated surface-subsurface hydrologic modeling community adopted this approach in a recent workshop (Maxwell, 2011a) that brought together several modeling groups around a set of idealized, simple hydrologic analyses. The results have been used to compare general capabilities and to identify aspects that could lead to improved performance.

One outcome of the workshop is that a community of practice should focus on such intercomparison studies to systematically compare the differences between different model and computational approaches, and to advance our scientific knowledge of how physical processes are represented in fully 3D models. This activity is important to the entire community, and has distinct benefits from benchmarking, discussed below. Intercomparison studies should be organized as part of CHyMP around different classes of models, and should start with simple, idealized cases that can elucidate fundamental differences in and effects of model structures and approaches in physically based models.

Benchmarking

In contrast to intercomparison, model benchmarking evaluates models against a set of metrics to assess the accuracy and progress of each model. Assuming that the initial focus of the CHyMP effort is to advance a National Water Model, a benchmarking exercise will be necessary to set and meet performance standards, to measure progress, and to inform the continued development and refinement of continental scale simulation. Currently, there are no community-accepted standards or benchmarks for hydrologic models. Models are "accepted" by the hydrologic community through publication in the literature, and often models are published with author-defined validation and evaluation metrics. To coalesce around a community effort, a system of meaningful benchmarks needs to be defined for continental-scale simulation. Such an exercise would advance the development of the NWM and provide a blueprint for expanding benchmarking exercises around other classes of hydrologic models.

Several ongoing benchmarking exercises that are largely being led from the atmospheric science community can provide a structure and governance model for benchmarking as part of a community hydrologic modeling initiative. NASA's Land Information System, which integrates observations, models and applications, and is being used by a number of agencies (Kumar et al. 2006). The LIS uses a four-level benchmarking process for its different components:

Level 0: Internal self-consistency.
Level 1: Observed fluxes and states.
Level 2: Relationships between fluxes and states.
Level 3: Uncertainty assessment.

Such a process can and should be adopted by the hydrologic community. Particularly, there is a need for the hydrology community to require documentation beyond the 0-1 levels (e.g. validation against stream flow gages). In hydrology, more meaningful insight is gained by examining higher level moments of stores and fluxes: rather than focus on validating at a few (or even many) gages, can a continental scale model reproduce the spatial structure and temporal patterns of hydrologic fields, such as monthly patterns of surface soil moisture relative to a benchmark blended observational-remote sensing soil moisture product? How do models partition between evaporation and drainage, and how sensitive is other model output to this partitioning? How sensitive are particular fluxes within different models to the initial soil moisture state? Evaluating these higher level benchmarks will not only advance and measure the advance in the simulation capabilities of the modeling community, but also, if we design the appropriate benchmarks, enhance the value of the model output to other modeling communities, and increase the confidence when coupling large scale simulation models to other hydrologic models.

Another example of a benchmarking project is the International LAnd Model Benchmarking (ILAMB, Randerson et al. 2009). ILAMB is a systematic effort to design benchmarks around land models focusing on carbon cycle, ecosystem, surface energy and hydrological processes that can be applied to global climate models. Several aspects of the project, including the goals of supporting design and development of new open source software for modeling benchmarking and intercomparison, and to strengthen linkages between the experimental, monitoring, remote sensing and climate modeling communities to advance the development of new model tests and measurement programs.

CHyMP efforts around benchmarking could both tie in to ILAMB data sets and experiments, as well as be informed by the ILAMB project's experience in developing a comprehensive benchmarking project. A central difference between ILAMB and CHyMP is again the overall objective. ILAMB focuses on land surface models (e.g. similar to VIC) in support of global climate modeling while CHyMP envisions a fully coupled surface and subsurface water simulation model as the NWM.

Implementation

The need to carefully define benchmarking exercises around stated objectives should be an important motive for future CHyMP efforts. The hydrologic community needs benchmarking exercises established for all important classes of water models, representing processes for pore to continent. Several attendees at the workshop had participated in individual model intercomparison studies, and future efforts need to be organized around clear objectives and criteria: a benchmark for a continental scale model that is used to inform predictions might be designed around ability to simulate patterns or features observed in continental scale fields or large basins, while an intercomparison study seeking insight as to how computational approaches affect the performance of a specific class of model might focus on simulating simple, idealized cases and evaluate metrics such as internal consistency and relationships between store and fluxes within the model(s).

CHyMP projects should build on past intercomparison and current benchmarking exercises to begin implementing benchmarking that will advance the goal of continental scale simulation of water, and serve as a framework for comprehensive benchmarking across model classes. The framework of a National Water Model provides a template for these activities. Focusing initially on continental scale models to begin benchmarking efforts will provide a model for other working groups around other model classes, as well as inform the other aspects of CHyMP (e.g. identifying needed data sets, identifying core processes to be included in continental scale modeling, and setting performance standards to measure progress on goals).

A benchmarking initiative should be established by organizing a group around current continental scale models, both land-atmosphere models and possibly integrated ground water –surface water models that can be scaled up using HPC. This effort should coordinate with other large-scale model benchmarking efforts, and should start by bringing current modelers together to establish and agree on an initial set of benchmarks. CUAHSI should provide logistical and coordination support for this initial group and seek funding to execute a benchmarking workshop where participants can identify key variables and data sets needed for benchmarks, and select a set of benchmarks and/or test cases to execute. The results will inform further development of the NWM and the execution of the exercise will provide a framework to organize other modeling groups, including: watershed models, subsurface flow and transport, surface water hydrodynamics, and pore scale flow and transport.

Dataset Development

Central to the development of national water modeling framework, the ability to apply models anywhere and execution of meaningful benchmarking exercises is the quality and completeness of the hydrologic – hydrogeologic data available. This is especially critical for comparing land surface model approaches and fully coupled surface –subsurface models over different domains. Many models are applied and calibrated over limited scopes or regions. The ability to test the transferability of different model approaches can be limited by data availability: data can be hard to access, of different form, or may not exist for all the parameters and forcing data necessary for a certain model.

To advance community modeling, we need to establish a community database that contains key datasets for describing spatial distributions of hydrologic parameters and forcing data. Table 2 describes an attempt by workshop participants to assemble the current state of hydrologic data sets necessary to support hydrologic modeling over the North American continent. An important community effort is necessary to assess the completeness and options for each data theme, as well as identifying the most prominent gaps in supporting multipurpose and multiscale modeling over the continent. For example, while the extent of the IAEA Global Network of Isotopes in Rivers in the Water Isotope data in Table 2 is global, there are approximately 800 point locations and only 10s of sites over the United States. Thus, the ability to assess our ability to "model anywhere" and validate with this data is limited. Weather data, on the other hand, have complete coverage but there are different data sources or products, and at different resolution. Other data, such as the NHD+ data set for streams, is largely well accepted, accessible, and considered complete by our community.

A true community database for hydrologic modeling would require identification of all important parameters and forcing data for each class of hydrologic models.

Systematic evaluation of the form, completeness and resolution of available data from Table 2 would identify the spatial scope on which different models or classes of models could currently be run, and provide an initial metric of how close the community is to "modeling anywhere." Assembling and making available such a database is a necessary first step in implementing model benchmarking and intercomparsion community-wide. Benchmarks identified by working group may inform data gathering and assembling priorities, and providing common data that can be used by models is necessary to evaluate models on equal footing. It is recognized that there are many detailed questions that arise when considering Table 2 deeply: what about forcing where multiple data sets are available? How are derived or modeled products or parameters included and what metadata or information need be provided with them? How and by whom should such data be assembled into a community resource? This requires community evaluation and contribution to defining standards for such a database as part of the CHyMP effort.

Similar to evaluating initial continental scale models in the National Water Model Framework, Table 2 provides a "version zero" sense of where we are now in observing and characterizing the comprehensive North American hydrologic environment. Because of the differences in model requirements, data availability and completeness, this "version zero" limits the ability to truly benchmark and compare classes of models across the North American continent, and contributes to the lack of comprehensive, systematic evaluation accompanying published hydrologic models. CHyMP workshop participants identified the lack of continental scale subsurface information – continental soil depth and hydrostratigraphy – as the top community priority to address in assembling data. While various sources and studies on the subsurface exist, CHyMP workshop participants expressed frustration at the lack of accessibility (data that are not available to the community, data that are in paper format, interpreted data without corresponding raw data and/or metadata) of subsurface information, and the amount of effort required to assemble data for even small studies or regions, and the lack of coordination among these different efforts.

The lack of national comprehensive 3D subsurface data significantly limits our current ability to address fundamental questions in modeling and hydrologic science. Any true community, continental-scale model will need to model the coupled surface – subsurface system. Our ability to test the applicability of the current state of the art multi-physics approaches to surface water-groundwater models (e.g. ParFlow, PIHM, etc.) across the continent is limited by the availability of data, particularly the subsurface. Several in our community (e.g. Duffy et al. 2011, Maxwell 2011b) have shown that with advances in high-performance computing, these models can be parameterized in significant detail at the continental scale, but a key limiting factor is the availability of parameter values and the cyberinfrastructure needed to deliver these data (Duffy et al. 2011).

One motivation for community modeling effort in hydrology is to advance the current state of hydrologic models to address pressing science questions and to advance our current knowledge of terrestrial hydrology in a way that provides knowledge essential to integrating hydrology better into other fields and modeling communities. An effort around advancing our knowledge and characterization of the subsurface informs some of the grand challenges in understanding large scale hydrology and land-atmosphere interaction, including a fundamental questions with long reaching consequences across disciplines and society: Does groundwater matter to climate? In many land-atmosphere models, surface soil moisture is uncoupled from groundwater flow. How accurate is this representation? As we learn more about low frequency climate variability and the complexity of our global climate and hydrologic system, examining this fundamental question with the best available models and with accurate and comprehensive data could yield potentially critical knowledge to hydrology, atmospheric science, global climate studies, and society.

Implementation

Dataset development is a critical activity that will support development of the National Water Model Framework and the Benchmarking exercises necessary to advance the science. Consideration of the current state of our knowledge about our continental or global hydrologic environment yields several gaps that the community recognizes is limiting our pursuit of fundamental science questions and true community modeling advances. Initiating activities that enhance the current state as defined in Table 2 will have far reaching and important consequences. CUAHSI should organize and develop a working group to evaluate and expand Table 2 and to manage technical aspects of developing a comprehensive modeling database for community use. This group could build off the CUAHSI – HIS system, and should focus on evaluating current sources of data, and compiling the readily available data, and prioritizing future improvements in resolution and scope for different data. These recommendations should be transmitted to the community and an important component of CHyMP should be to organized collaborations between academics, federal agencies, and the private sector to leverage available resources and expertise to meet these needs.

It is clear that a focused, large scale effort is needed to meet the challenge of characterizing the subsurface. This is limiting truly integrated hydrologic modeling across our continent, as well as our ability to understand fundamental questions about the coupled global hydrologic and climate system. Workshop participants strongly recommend that CUAHSI organize a working group to address this challenge, and seek substantial funding to assemble existing data across the various forms and sources, and execute a large scale effort where data do not exist. Given the scope of the challenge, and the broader importance, this type of effort requires substantial community support.

Platform Development

To make significant progress on our scientific understanding of the hydrosphere's comprehensive interactions with the lithosphere, biosphere and atmosphere, a community modeling platform is needed to improve access to the broad and diverse range of advanced capabilities to simulate hydrologic processes that are community has developed. A variety of modeling platforms are currently available that may meet many of the needs of the water modeling community. These platforms should be evaluated with the goal of leveraging and complementing existing approaches. Several workshop participants involved in designing, evaluating and adopting modeling platforms provided insight as to how platform evaluation could be approached as part of CHyMP.

The Community Surface Dynamics Modeling System (CSDMS) is an NSF funded project that that provides a community-built and freely available suite of integrated, ever-improving software models and modules for earth surface processes, including hydrology. CSDMS adopted a Common Component Architecture (CCA) framework which allows modelers to contribute their individual codes, which are then integrated as components into the framework. CSDMS has computational resources for model simulations, and couples models that bridge critical process domains, as well as providing many open source tools.

In adopting the framework for CSDMS, developers underwent a long exercise of deciding on needed functionalities, examining different platforms and frameworks, and systematically evaluating each one in light of critical and desirable functionality. CHyMP's platform evaluation effort should follow a similar path.

The ultimate vision resulting from the workshops is a community water-modeling platform that will provide a state-of-the-art tool that is fully integrated with high performance computing and electronic datasets to provide the best available simulations of water-related processes anywhere in North America. This tool should have at its heart advanced numerical techniques for simulating multiple, coupled processes across discrete, telescoping meshes. A suite of tuned numerical methods (e.g. finite element, finite difference, finite volume, lattice Boltzmann) would be available to provide the best approach for any given problem, and to provide a test bed for developing and sharing optimal solution methods. The modeling platform would consolidate basic requirements for developing geometries, generating meshes and rendering graphical output, which are common to all models, but that currently must be reproduced by each new model that is developed.

CHyMP workshops have identified key functionalities to achieve this vision:

- Ability to simulate physics associated with flow and storage of all terrestrial water (ground water, vadose zone, streams, rivers, wetlands, lakes, snow/ice, etc.).

- Spatial scales from 10^{-1}m to 10^{6} m, and time scales from 10^{0}s to 10^{10}s.
- Ultimately provide the framework for simulating physical/chemical/biological processes involving water, including mass transport, biogeochemical reactions, erosion/deposition, porous media deformation, heat conduction and convection.
- Enable clear model linkages for simulating interactions with ecosystems, including the natural and built environments.
- Simulate interaction of terrestrial water with atmosphere and oceans.
- Seamless access to parameter data required to represent locations on North American continent with best currently available resolution.
- Assimilation of remotely sensed and in situ observations
- Ability to calibrate model parameters based on observations.
- Ability for users to modify functions, coupling, processes, etc.
- Enable access to simulation capabilities through web browser.
- Ability to document the model development workflow and make that information available to others.
- Provide transparent access to high performance and high-throughput computing.
- Visualization techniques to facilitate interpretation.

In addition, several at the workshop stressed the need for the platform functionality to extend beyond research capability into useful societal functions. The National Weather Service's Community Hydrologic Prediction System (CHPS) and The Department of Energy's Advanced Simulation Capability for Environmental Management (ASCEM) are two examples of modeling platforms that include functionality important to operational and regulatory use. CHyMP should carefully consider both the model developer community and the potential applications and users of hydrologic models and hydrologic modeling output in designing or selecting a model platform.

Implementation

It was clear from the workshop that several existing platforms may serve some of the needs of the hydrologic community. The clearest recommendation is the need to establish core and desired functionality against which to evaluate current platforms or new platform development. A working group should follow from this workshop that examines in more detail the functional requirements established from the workshop and evaluates current platforms against this functionality. CHyMP should also consider whether a new platform is necessary.

Moving Forward: Key Findings and Recommendations for Implementing CHyMP

The CHyMP workshops have demonstrated community support for a coordinated modeling effort in hydrology. True progress can only be made by a sustained effort. Datasets must grow to enable the development of integrated models across scales, not just at the national scale. Furthermore, the models must evolve to accommodate links to related disciplines such as climate, ecology, biogeochemistry and agriculture, while the datasets must evolve to support model growth. This workshop demonstrated the breadth of work being done across hydrology that can be harnessed and leveraged into CHyMP, and well as identified critical areas where new efforts must be initiated and supported. The key findings that emerged were:

- The community is supportive of the idea of a National Water Model framework, and a community effort is needed to explore what the ultimate implementation of a National Water Model is.
- A true community modeling effort would support the modeling of "water anywhere" and would include all relevant scales and processes.
- A community of practice which documents best practices, and provides a framework for developing code and performance standards for hydrologic models would accelerate the advancement of modeling.
- The lack of subsurface data is seen as a severe limitation to answering critical science questions with societal relevance (i.e. groundwater's influence on climate) and to achieving fully integrated hydrologic modeling at a national scale.
- To make progress, CHyMP must leverage the many efforts being done across the broad spectrum of hydrology, many of which incorporate novel and recent advances in numerical methods and high performance computing.
- The CHyMP effort has been successful in galvanizing the community around the grand vision of community modeling, but most focus on establishing ways to harness this interest and provide mechanisms for the community to truly work together.

During the CHyMP workshops, the concept of a National Water was supported by the participants, and in this third workshop, the goal of simulation on a national scale was identified as a clear objective. A key strategy adopted by the workshop was to focus on current capabilities as a way to assess needs, prioritize activities, and recommend steps forward. To implement CHyMP, the workshop recommends:

- **Focusing on continental scale data and models** to evaluate our current capabilities, and prioritizing improving resolution and completeness with time.
- **Establishing an initial Implementation Working Group** around current large scale models. This working group would be open to any model that can currently be run at national and continental scale. This would be an

important first step to understanding what the “version zero” is of a working national water model. Participants in the group must be willing to share their codes, and will identify the data sets and resolution they are using in their models. The working group would identify data sets and a suite of benchmarks or simulations for initial benchmarking exercises. CUAHSI should support organization of this group. A benchmarking workshop would be held to present project results and discuss lessons learned. This activity should be completed with 12 – 18 mos. and will serve as a blueprint for establishing working groups around other classes of models.

- **Begin comprehensive dataset evaluation and compilation for a community modeling database.** A Data Working Group should be formed to evaluate current data sources and prioritize improvements or additions. This group should work with the Implementation Working Group to identify the data large scale modelers are using, as well as with the CUAHSI – HIS program, and guide the technical development and delivery of the data to the user community. This activity should be implemented immediately.
- **Form a Platform Evaluation Working Group** that both considers currently available platforms and explores new paradigms for achieving the functionality needed to implement CHyMP.
- **Leveraging existing efforts within federal agencies and encourage collaboration** between university efforts and agencies. Particularly, CHyMP should leverage the experience and expertise of USGS, NASA, and NWS national and continental scale efforts.
- **Pursuing development of national 3D hydrostratigraphy information.** This was seen as the top priority in terms of dataset development by the attendees of the CHyMP workshop. The expertise of the USGS, university researchers who have assembled information from various sources, and others need to be harnessed in a collaborative effort.

This workshop identified clear actions to move community modeling forward, many of which can and should be implemented almost immediately, because they build on current data, models or initiatives. CHyMP has been successful in organizing academics, federal agencies and those in the private sector to bring together their expertise, and envision the path forward. To make true progress, CUAHSI must work to facilitate the execution of that vision.

Table I: Participants at 3rd CHyMP workshop

Participants			
Bhatt	Gopal	Pennsylvania State University	
David	Cedric	UTexas	
Detwiler	Russ	UCI	
Fan-Reinfelder	Ying	Rutgers University	
Galluppi	Ken	RENCI	
Gochis	Dave	NCAR	
Goodal	Jon	Univesity of South Carolina	
Hay	Lauren	USGS	
Hill	Mary	USGS	
Hyndman	Dave	Michigan State University	
Idaszak	Ray	RENCI	
Kim	Hyungjun	UCI	
Kitinidis	Peter	Stanford University	
Lettenmaier	Dennis	Univeristy of Washington	
Markstrom	Steve	USGS	
Maxwell	Reed	Colorado School of Mines	
Meza	Juan	LBNL	
Mohanty	Binayak	Texas A&M University	
Opitz	Harold	NOAA	
Peckham	Scott	CSDMS	
Peters-Lidard	Christa	NASA Goddard Space Flight Center	
Rasmussen	Todd	University of Georgia	
Sanders	Brett	UCI	
Sudicky	Ed	University of Waterloo	
Valentine	David	San Diego Supercomputer Center	
Weiland	Frederiek Sperna	Deltares	
Welles	Edwin	Deltares USA	
CUAHSI and CHyMP leadership			
Arrigo	Jennifer	CUAHSI	
Band	Larry	University of North Carolina	
Famiglietti	Jay	University of California, Irvine	
Hooper	Rick	CUAHSI	
Lakshmi	Venkat	University of South Carolina	
Murdoch	Larry	Clemson University	

UCI postdocs, grad students, administrative and technical staff			
Aghakouchak	Amir	UC Irvine	
Anderson	Ray	UC Irvine	
Bijoor	Neeta	UC Irvine	
Castle	Stephanie	UC Irvine	
Gallien	Timu	UC Irvine	
Kim	Byunghyun	UC Irvine	
Lo	MinHui	UC Irvine	
Schubert	Jo	UC Irvine	
Reager	JT	UC Irvine	
Wilkens	Jennifer	UC Irvine	

Table 2. Important datasets for parameterizing large-scale models of water-related processes.

Theme	Parameters	Source
Soils	Soil type, hydraulic conductivity, mineralogy	SSURGO, STATSGO http://soildatamart.nrcs.usda.gov/
Streams	Reach location, elevation, flow	NHDPlus http://www.horizon-systems.com/nhdplus/
Hydrostratigraphy	Sediment or rock type, composition, hydraulic conductivity, specific storage	Scattered sources
Groundwater	Hydraulic head, composition	Scattered sources
Topography	Elevation	NED, ASTER http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/NED http://asterweb.jpl.nasa.gov/content/03_data/01_Data_Products/release_DEM_relative.htm
Bathymetry	Elevation	Scattered sources http://www.ngdc.noaa.gov/mgg/greatlakes/greatlakes.html
Land cover	Categories of land use at different times	NLCD http://www.epa.gov/mrlc/nlcd-2006.html
Species	Range of species	GAP http://www.nbii.gov/portal/server.pt/community/gap_home/1482
Ecosystem		MODIS, CDIAC http://modis-atmos.gsfc.nasa.gov/ECOSYSTEM/index.html http://cdiac.ornl.gov/epubs/ndp/ndp017/ndp017.html
Weather	Precipitation, wind speed, temperature, humidity	NAAR, RIST http://www.esrl.noaa.gov/psd/data/gridded/data.narr.html#levels http://www.ars.usda.gov/Research/docs.htm?docid=3251
Water isotopes	^{18}O, ^{2}H, ^{3}H	IAEA; GNIP; GNIR; MIBA http://www-naweb.iaea.org/napc/ih/index.html

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