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Key Points:
- Modeling template formulated using a general set of conservation equations
- Evaluation focuses on flux parameterizations and spatial variability/connectivity
- Systematic approach helps improve model fidelity and uncertainty characterization

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A unified approach for process-based hydrologic modeling: 1. Modeling concept

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Abstract This work advances a unified approach to process-based hydrologic modeling to enable controlled and systematic evaluation of multiple model representations (hypotheses) of hydrologic processes and scaling behavior. Our approach, which we term the Structure for Unifying Multiple Modeling Alternatives (SUMMA), formulates a general set of conservation equations, providing the flexibility to experiment with different spatial representations, different flux parameterizations, different model parameter values, and different time stepping schemes. In this paper, we introduce the general approach used in SUMMA, detailing the spatial organization and model simplifications, and how different representations of multiple physical processes can be combined within a single modeling framework. We discuss how SUMMA can be used to systematically pursue the method of multiple working hypotheses in hydrology. In particular, we discuss how SUMMA can help tackle major hydrologic modeling challenges, including defining the appropriate complexity of a model, selecting among competing flux parameterizations, representing spatial variability across a hierarchy of scales, identifying potential improvements in computational efficiency and numerical accuracy as part of the numerical solver, and improving understanding of the various sources of model uncertainty.

1. Introduction

1.1. The Development of Process-Based Hydrologic Models

Improving process-based hydrologic models requires progress on several fundamental research challenges: (i) defining appropriate equations to simulate the fluxes of water, energy, and momentum for the different subsystems within the model domain; (ii) representing the variability of hydrologic and biophysical processes across a hierarchy of spatial scales; (iii) solving the model equations, including coupling of processes across the different model subdomains; (iv) estimating input data and model parameters; and (v) characterizing model uncertainty. Many of these challenges were articulated by *Freeze and Harlan* [1969] and have captured the attention of the hydrologic research community over the last four decades [e.g., *Beven and Kirkby*, 1979; *Sivapalan et al.*, 1987; *Famiglietti and Wood*, 1994; *Reggiani et al.*, 1998; *Beven*, 2002; *Qu and Duffy*, 2007; *Gupta et al.*, 2008; *Clark and Kavetski*, 2010; *Kollet et al.*, 2010; *Clark et al.*, 2011; *Wood et al.*, 2011; *Montanari and Koutsoyiannis*, 2012].

When faced with the complex and interdisciplinary challenge of building process-based hydrologic models, different modelers often make different decisions at different points in the model development process. These modeling decisions are generally based on several considerations [*Clark et al.*, 2011], including *fidelity* (e.g., what approaches faithfully simulate observed processes), *complexity* (e.g., which hydrologic processes should be represented explicitly), *practicality* (e.g., what is the computational cost of the model simulations; are there sufficient resources to implement the desired modeling concepts), and *data availability* (e.g., is there sufficient data to force and evaluate spatially distributed hydrologic models). Consequently, the hydrologic research community, comprising modelers of diverse background, experience, and modeling philosophy, has historically amassed a wide range of models, which differ in many aspects of their conceptualization and implementation [*Kampf and Burges*, 2007].

The diversity of models has been useful to explore a myriad of scientific and applied questions, across spatial domains from meters to global, and for time periods ranging from single events to centuries. Modern land-surface models provide a detailed representation of many biophysical and hydrologic processes, portraying land-atmosphere feedbacks within century-scale climate simulations [e.g., *Lawrence et al*., 2012]. Hydrologic models are used for a wide range of engineering applications, ranging from flood forecasting [e.g., *Thielen et al*., 2009] to water resource assessments [e.g., *Vano et al*., 2012]. Moreover, at least in principle, the diversity of models provides opportunities to characterize predictive uncertainty arising from different modeling assumptions [e.g., *Butts et al*., 2004].

These advances notwithstanding, the current generation of models has followed a myriad of different development paths, making it difficult for the community to test underlying model hypotheses and identify a clear path to model improvement [*Clark et al*., 2011]. Model comparison studies have been undertaken to explore model differences [*Pitman and Henderson-Sellers*, 1998; *Bowling et al*., 2003; *Smith et al*., 2004; *Rutter et al*., 2009] but have not been able to meaningfully attribute inter-model differences in predictive ability to individual model components because there are often too many structural and implementation differences among the different models considered [e.g., *Koster and Milly*, 1997; *Nijssen et al*., 2003; *Clark et al*., 2011]. Moreover, some model comparison experiments list the models under consideration but do not identify them when reporting the results [e.g., *Duan et al*., 2006]. As a consequence, model comparison studies to date have provided limited insight into the causes of differences in model behavior, and model development has often relied on the inspiration and experience of individual modelers rather than on a systematic analysis of model shortcomings. More broadly, the hydrologic community relies on existing models in its own research, yet inherits these (often poorly documented) model development decisions.

1.2. Unifying Hydrologic Modeling Approaches

The diversity of hydrologic modeling approaches motivates our effort to develop a unified modeling framework to integrate and compare competing modeling approaches. Our basic goal is to enable controlled and systematic evaluation of multiple model representations (hypotheses) of hydrologic processes and scaling behavior [*Clark et al*., 2011].

Our approach to unify different modeling approaches is based on two propositions:

1. Most hydrologic modelers share a common general understanding of how the dominant fluxes of energy and water affect the time evolution of thermodynamic and hydrologic states. For example, consider Figure 1, which illustrates the dominant fluxes for a typical domain used in hydrologic and land-surface models, and compare it to similar diagrams presented in many other modeling papers and textbooks [e.g., *Wigmosta et al*., 1994; *Bonan*, 2002; *Andreadis et al*., 2009; *Lawrence et al*., 2011].
2. The major scientific issues in hydrologic model development are (a) representing spatial variability and hydrologic connectivity throughout the model domain [e.g., *Koster and Suarez*, 1992; *Flügel*, 1995; *Bonan et al*., 2002; *Vivoni et al*., 2004; *Vivoni et al*., 2005; *Maxwell and Kollet*, 2008; *Newman et al*., 2014]; and (b) parameterizing the fluxes of water and energy at the spatial scale(s) of the model discretization [e.g., *Wood et al*., 1988; *Reggiani et al*., 1998; *Beven*, 2006b]. Inter-model differences in spatial configurations and flux parameterizations, while critically important, occur at a lower level in model construction than the formulation of the conservation equations.

Based on these two propositions, a unifying modeling framework can be created by defining a general set of conservation equations for mass and energy, with the capability to incorporate multiple choices for spatial discretizations and flux parameterizations. The framework can be viewed as a design concept for a hydrologic simulation model that is sufficiently flexible, extensible, and modular to encompass a broad range of existing (and potential future) modeling philosophies and strategies.

Formulating the modeling problem in this way recognizes that while the conservation equations are applicable across multiple spatial scales, the associated flux parameterizations typically have very strong scale dependencies [*Mahrt*, 1987; *Reggiani et al*., 1998; *Beven*, 2006b]. Our unified framework provides capabilities to evaluate different representations of spatial heterogeneity and different flux parameterizations, and

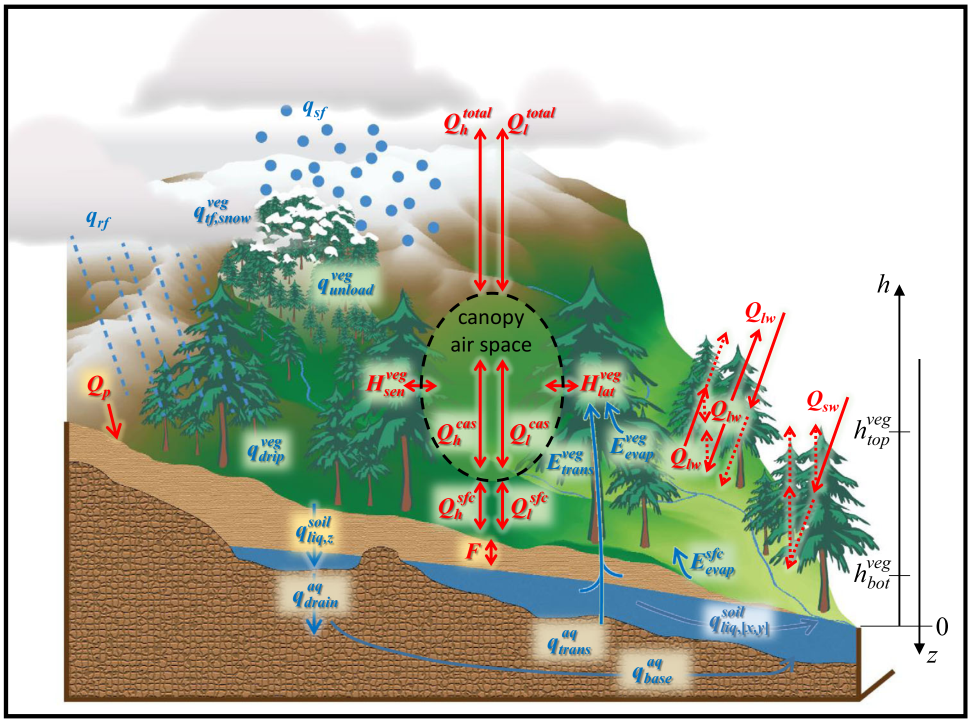

Figure 1. Conceptual depiction of the dominant physical processes at the catchment scale.

therefore tackle the fundamental modeling challenge of simulating the fluxes of water and energy over a hierarchy of spatial scales [*Blöschl and Sivapalan*, 1995; *Seyfried and Wilcox*, 1995; *Giorgi and Avissar*, 1997; *Reggiani et al*., 1998]. The different modeling approaches that can be integrated into the framework include (a) *explicitly* representing spatial heterogeneity through different spatial configurations [*Koster and Suarez*, 1992; *Flügel*, 1995; *Bonan et al*., 2002; *Vivoni et al*., 2004] and different methods to characterize spatial variability in dominant processes and model parameters [*Maxwell and Kollet*, 2008; *Winstral et al*., 2013]; and (b) *implicitly* representing spatial variability below the scale of the model discretization through use of scale-appropriate flux parameterizations [*Beven and Kirkby*, 1979; *Mahrt*, 1987; *Luce et al*., 1999; *Essery et al*., 2008] and/or "effective" model parameter values [*Samaniego et al*., 2010]. Careful scrutiny of these decisions on how to explicitly or implicitly resolve spatial heterogeneity is necessary to pinpoint model weaknesses and improve model fidelity.

In this two-part paper, we develop a unified modeling methodology, the Structure for Unifying Multiple Modeling Alternatives (SUMMA, pronounced 'sū-mə), based on the two propositions defined above, for the model domain extending from the top of the vegetation to the base of active groundwater (i.e., the Earth's Critical Zone) [*Anderson et al*., 2008]. The collective understanding of the connectivity of fluxes and state variables presented in Figure 1 allows us to formulate general conservation equations for water and energy in different model subdomains (here, soil, snow, the vegetation canopy, and the canopy air space). From a model development perspective, the conservation model equations and their numerical solution form the "structural core" of the model. Different modeling approaches can then be implemented within the structural core, enabling a controlled and systematic analysis of alternative modeling options, and providing insight for future model development.

1.3. Organization and Scope

We present our contributions in two related papers. This first paper introduces the general approach used in SUMMA, detailing the spatial organization and model simplifications, and describing how different representations of multiple physical processes can be combined within a single modeling framework. The second paper [*Clark et al.,* 2015] specifies the conservation equations used in the initial implementation of SUMMA, and presents example applications for several research catchments throughout the western USA. Our intent for the first paper is to advance a general methodology for application of the method of multiple working hypotheses in hydrologic and land-surface models (i.e., define a general master modeling template from which existing models can be constructed and new models derived). Our intent for the second paper is to provide a specific initial implementation of this methodology for a broad range of biophysical and hydrologic processes, including radiation transfer through the vegetation canopy, within-and below-canopy turbulence, canopy interception, canopy transpiration, snow accumulation and ablation, and runoff generation.

The remainder of this first paper is organized as follows. In section 2, we summarize key modeling requirements that motivate development of the SUMMA framework. In section 3, we introduce the SUMMA concept, including the spatial organization and model simplifications, how different representations of multiple physical processes can be combined within a single modeling framework, and how this modeling system can be used to tackle major hydrologic modeling challenges. The model development is kept very general to accommodate multiple physical processes representations within a single modeling framework. Based on this development, in section 4 we discuss the ways in which SUMMA can unify different approaches to hydrologic modeling, as well as some important model limitations. Finally, in section 5 we summarize and point to uses of SUMMA to guide model development and understand differences among hydrologic models.

2. Current Capabilities and Modeling Needs

Several frameworks have been developed to systematically evaluate hydrologic modeling alternatives. For example, in the subfield of rainfall-runoff modeling, the Framework for Understanding Structural Errors (FUSE) provides a choice between different process parameterizations for soil hydrology, including different parameterizations for the fluxes of surface runoff, vertical percolation, evaporation, and baseflow [*Clark et al*., 2008], the SUPERFLEX framework allows experimenting with model structures based on combinations of reservoirs and transfer functions [*Fenicia et al*., 2011], and the Catchment Modeling Framework (CMF) enables formulating alternative hypotheses of catchment behavior [*Kraft et al*., 2011]. As more comprehensive examples, the Joint UK Land Environment Simulator (JULES) and the Noah-MP models support different options for a range of biophysical and hydrologic processes [*Best et al*., 2011; *Niu et al*., 2011; *Essery et al*., 2013]. Other examples of multiple-hypothesis frameworks are the Modular Modeling System (MMS) designed to integrate different options for the model components used in catchment hydrology (e.g., different soil models) [*Leavesley et al*., 2002], MODFLOW designed to integrate different options for groundwater modeling [*Harbaugh et al*., 2005; *Foglia et al*., 2013], the Cold Regions Hydrologic Model (CRHM) designed to integrate different options to simulate fluxes of energy and water in cold regions [*Pomeroy et al*., 2007], and WRF-Hydro designed to couple lateral flow functionality and river routing routines to the land component of numerical weather prediction models [*Gochis et al*., 2013]. These modeling methodologies provide, to varying degrees, the ability to experiment with alternative model representations (hypotheses) of hydrologic systems. This flexibility allows hydrologists to more systematically follow the method of multiple working hypotheses [*Clark et al*., 2011] and facilitates a more controlled approach to model evaluation and improvement.

The development of modeling methodologies that support multiple working hypotheses is, however, still in its nascence, and (as yet) has not provided the systematic approach that is needed for model evaluation and improvement. The major requirements to enable systematic model analysis are:

1. *Capabilities to experiment with different representations of spatial variability and hydrologic connectivity*. Many of the modeling frameworks just described provide multiple process parameterizations only within a fixed spatial architecture. For example, FUSE is limited to spatially lumped structures and Noah-MP is limited to a semi-tile grid structure. It is therefore desirable to develop modeling frameworks that support (a) different spatial resolutions; (b) different spatial configurations, e.g., grids and Hydrologic Response Units (HRUs); and (c) different representations of the lateral fluxes of water across model elements, including lateral flow through the soil matrix.
2. *Inclusion of a broad range of dominant biophysical and hydrologic processes, with multiple options for individual processes*. Many of the modeling frameworks are limited in scope. For example, FUSE is restricted to rudimentary representations of the rainfall-runoff process and JULES and Noah-MP are focused

primarily on land-atmosphere fluxes. To generalize approaches from multiple models, it is necessary to formulate a common "structural core" that has sufficient flexibility to integrate equations for a broader range of environmental processes. This enables investigating issues of model complexity—for example, which processes should be represented explicitly—as well as evaluating the suitability of alternative representations of individual physical processes.

3. *Clean separation of the model equations from their numerical solution*. In many current models, the specification of the model equations is intertwined with their numerical solution. This complicates assessment of different physical representations and makes it difficult to evaluate alternative numerical methods [*Clark and Kavetski*, 2010]. To address this limitation, the hypothesized model equations should be articulated before numerical approximations (such as treating fluxes sequentially) are applied. Programmatically, this can be implemented by designing separate subroutines to calculate individual fluxes across control volumes and their derivatives with respect to the relevant model state variables. This modular approach maximally separates the model physics from the numerical solution, as the subroutines to calculate the different flux terms and derivatives can be called by different numerical solvers. The modular approach is also more scalable, as additional subroutines can be developed and integrated with minimal impact on the overall program architecture.
4. *Flexibility to adjust model parameters*. Many current process-based models treat uncertain parameter values (e.g., time decay in snow albedo) as fixed physical constants. This imposes very strong constraints on model behavior [*Mendoza et al*., 2015] and prevents an examination of the interplay between the choice of model parameters and the choice of process parameterizations. The strong constraints imposed by fixed model parameters may be obvious to the original model developers, but perhaps less obvious to future model developers and users. Exposing parameter values to model users addresses this issue, and can enable more comprehensive characterization of uncertainties in model simulations.

More generally, requirements 1–4 lead to highly modular and flexible modeling systems. Although this may seem to be a trivial implementation detail, most current modeling frameworks do not provide the flexibility to isolate and investigate individual modeling decisions. For example, the model building blocks in MMS and CRHM have a very coarse level of granularity (e.g., a complete soil hydrology model, or a complete snow model, with process representations intertwined with their numerical solution), and it is difficult to attribute differences in model behavior to specific modeling decisions. Fine grain modularity facilitates experimenting with both different physical representations and different numerical solvers.

We contend that a modeling framework meeting requirements 1–4 will provide a platform for comprehensively and rigorously evaluating differences among process representations in existing hydrological models, and for supporting future model development and improvement.

3. The SUMMA Concept

3.1. Model Domain

SUMMA's model domain extends from the atmosphere above the vegetation canopy to the river channel and includes the dominant biophysical and hydrologic processes for many regions of the world (Figure 1). We simulate *thermodynamics*, i.e., the storage and flux of energy, and *hydrology*, i.e., the storage and transmission of water (in all of its phases). For thermodynamics, we simulate the heat balance of the vegetation canopy, the canopy air space, snow, and soil, as affected by the radiative fluxes through the vegetation canopy, within-canopy and below-canopy turbulent heat transfer, and energy fluxes throughout the snow and soil. For hydrology, we simulate the water balance of the vegetation, snow, and soil, as affected by the fluxes of interception and unloading (or drip) of snow (or rain) from the vegetation canopy, snowfall, snow melt, and sublimation, vertical and lateral transmission of liquid water through snow and soil, the storage and transmission of water in the shallow subterranean aquifer, and transpiration, canopy evaporation, and ground evaporation.

3.2. Spatial Variability and Lateral Fluxes of Water

A fundamental model development decision is the representation of spatial variability and lateral water fluxes. *Todini* [1988] grouped spatially distributed hydrologic models into two broad classes. The first class of models is distributed "integral" models, defined as a spatial assemblage of one-dimensional column models, connected by a digital river network and/or nested within a larger basin/grid, with no lateral fluxes

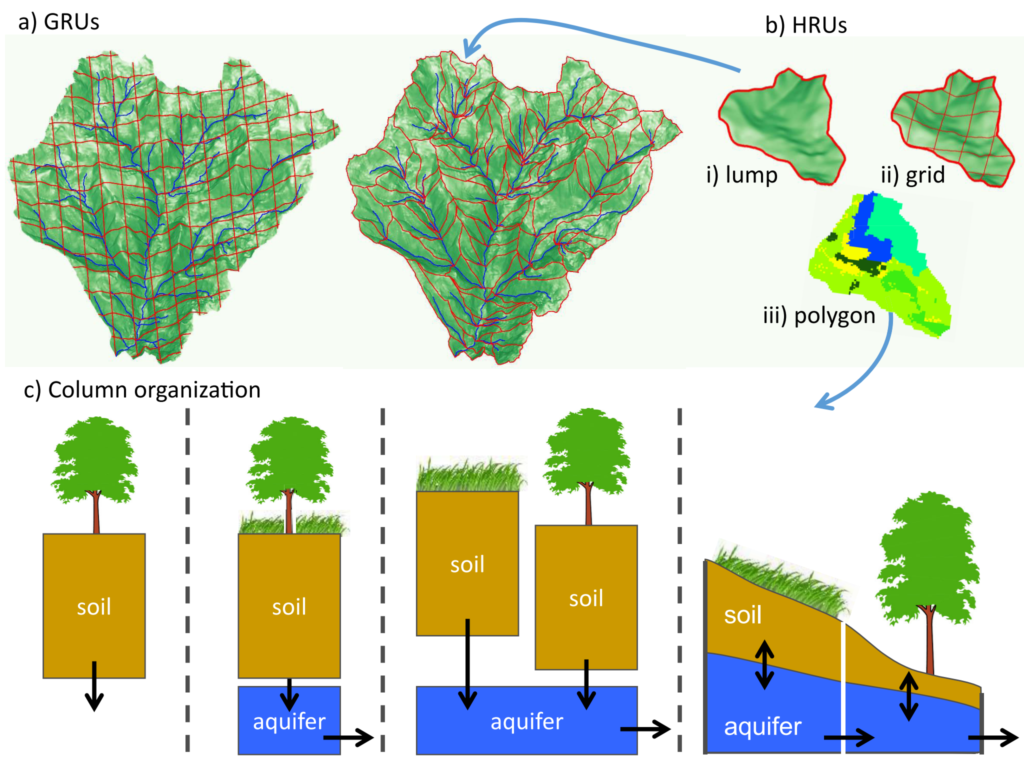

Figure 2. Spatial organization of SUMMA, showing: (a) GRUs (grid or polygon), (b) HRUs (single unit, grid, polygon), and (c) the connection among soil columns and the aquifer. The horizontal footprint of each vertical soil column corresponds to a single HRU, and there can be multiple soil columns (HRUs) embedded within a GRU. In the polygon HRU example (Figure 2b-iii) the riparian HRU was delineated using the Height Above the Nearest Drainage (HAND) index [*Gharari et al*., 2011; *Nobre et al*., 2011] and the remaining hillslope areas were delineated into HRUs by first dividing the basin into flow planes and then identifying hydrologically similar areas (considering radiation loading, topographic sheltering, and vegetation type). Multiple configurations of GRUs and HRUs are possible, which may be optionally connected or disconnected, representing spatial variability across a hierarchy of scales.

between the individual columns. Distributed integral models are widely used in the land-surface modeling community [e.g., *Best et al*., 2011; *Lawrence et al*., 2011; *Niu et al*., 2011] as well as in the surface water hydrology community [e.g., *Nijssen et al*., 2001; *Koren et al*., 2004; *Hay et al*., 2006]. The second class of models is distributed "differential" models, which explicitly simulate the lateral fluxes of water among model elements [e.g., *Wigmosta et al*., 1994; *Beven and Freer*, 2001; *VanderKwaak and Loague*, 2001; *Ivanov et al*., 2004; *Qu and Duffy*, 2007; *Kollet and Maxwell*, 2008; *Simunek et al*., 2008]. The type of distributed modeling approach has a major impact on the estimated basin-average evapotranspiration and runoff.

SUMMA is organized using a flexible hierarchical spatial structure, based loosely on the approach of *Kouwen et al*. [1993]. This hierarchical structure consists of a collection of Grouped Response Units (GRUs) within the spatial extent of the model domain (Figure 2a), and a collection of Hydrologic Response Units (HRUs) within each GRU (Figure 2b). The GRUs and HRUs are defined as follows:

1. *Grouped Response Units*. The key characteristics of the GRUs are: (i) the GRUs can be of any shape (e.g., grids or subcatchments); (ii) the area of each GRU must be spatially contiguous; (iii) the GRUs can be of any size (in principle); and (iv) the computations for each GRU are performed separately, and total runoff from each GRU, including base flow from the GRU aquifer, is routed through the river network.
2. *Hydrologic Response Units*. A GRU is composed of one or more HRUs. The key characteristics of the HRUs are: (i) similar to the GRUs, the HRUs can be of any shape and size, but there is no longer the restriction that HRUs are spatially contiguous (e.g., an HRU can lump together hydrologically similar areas from different parts of the landscape); (ii) the meteorological forcing data can vary across the HRUs, as opposed to the approach in *Kouwen et al*. [1993] where all HRUs within a given GRU receive the same meteorological input; and (iii) we include the option for lateral subsurface flow among HRUs (see Figure 2c).

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The spatial organization of SUMMA into GRUs and HRUs enables comprehensive evaluation of different methods to represent spatial variability and lateral flow. This can be accomplished in three ways. First, SUMMA supports different spatial configurations in terms of the size and shape of model elements (Figures 2a and 2b). Second, SUMMA supports different methods to represent the lateral flux of water across the model domain, including approaches that *explicitly* represent the fluxes of water between soil columns and approaches where multiple soil columns drain to a conceptual subterranean aquifer (Figure 2c). SUMMA can accommodate complex topographical structures (e.g., multiple noncontiguous hillslope HRUs flowing into a riparian HRU; Figure 2b-iii) and can be configured to simulate lateral subsurface flow between multiple HRUs arranged along representative hillslope(s) (i.e., GRUs) connected to the river network [*Fan and Bras*, 1998; *Troch et al*., 2002]. Third, SUMMA supports different methods to represent spatial variability in meteorological forcing and model parameters. For example, in terms of model forcing data, spatial variability in snowfall can be explicitly represented using spatially variable multipliers, and hence account for processes such as nonhomogeneous snow accumulation and drifting [e.g., *Luce et al*., 1998; *Winstral et al*., 2013]. This comprehensive representation of spatial variability and hydrologic connectivity is critical to address fundamental questions of scaling behavior of different physical processes, through exploring alternative spatial configurations, including grids and HRUs with different lateral flow parameterizations.

SUMMA can be used to reproduce the spatial organization for a broad range of hydrologic and land-surface models. For example, the structure of nesting multiple HRUs within a GRU can be used to represent multiple vegetation tiles within a model grid box, as used in the mosaic scheme of land-surface models [e.g., *Koster and Suarez*, 1992; *Liang et al*., 1994]. The nesting of HRUs and GRUs can also represent the hierarchal landscape organization in ecohydrologic models, such as the embedding of landscape patches within basins in RHESSys [*Tague and Band*, 2004]. As another example, routing flow from multiple GRUs through the river network can be used to represent the one-way landscape-stream coupling approach used in many different hydrologic and land-surface models [e.g., *Nijssen et al*., 2001; *Bandaragoda et al*., 2004; *Koren et al*., 2004; *Lawrence et al*., 2011]. More generally, the flexibility in defining the size and shape of the GRUs and HRUs (Figures 2a and 2b) and the different options for hydrological connectivity in the soil subdomain (Figure 2c) supports representing both the distributed integral and distributed differential methods to spatially distributed hydrologic modeling.

3.3. Process Representation

The selection of methods to represent physical processes at the HRU scale (i.e., given a particular spatial configuration) is another fundamental model development decision. This involves making choices on (1) model complexity, i.e., which physical processes should be represented explicitly, and, correspondingly, which processes can be ignored or greatly simplified; and (2) process representation, i.e., what modeling approaches should be used to represent the dominant biophysical and hydrologic processes.

SUMMA is implemented using a modular structure to support decisions on model complexity and process representation (Figure 3). The key features of Figure 3 are

1. The flux parameterizations are cleanly separated from the conservation equations; and

2. The formulation of the model equations is cleanly separated from their numerical solution.

This modular structure enables incorporating different model representations of physical processes (in particular, different flux parameterizations) within a common set of conservation equations. For example, as illustrated in Figure 3, the different flux parameterizations for the vertical redistribution of water in the soil profile can include gravity drainage (a flux parameterization common in bucket-style rainfall-runoff models) the Darcy flux parameterization (leading to Richards equation), and extensions to the Darcy parameterization to include macropores (a multidomain implementation of Richards equation). The physical processes summarized in Figure 3 can be organized in different spatial configurations, including model elements of different shape and connectivity (section 3.2).

The clean separation of flux parameterizations from the conservation equations facilitates addressing the key model development decisions in a controlled and systematic way. In particular, SUMMA can be used to evaluate which physical processes should be represented explicitly, and, correspondingly, which processes can be ignored or greatly simplified. As such, this allows SUMMA to cover the continuum from simple bucket-style rainfall-runoff models to more complex physically based models. Evaluating which processes

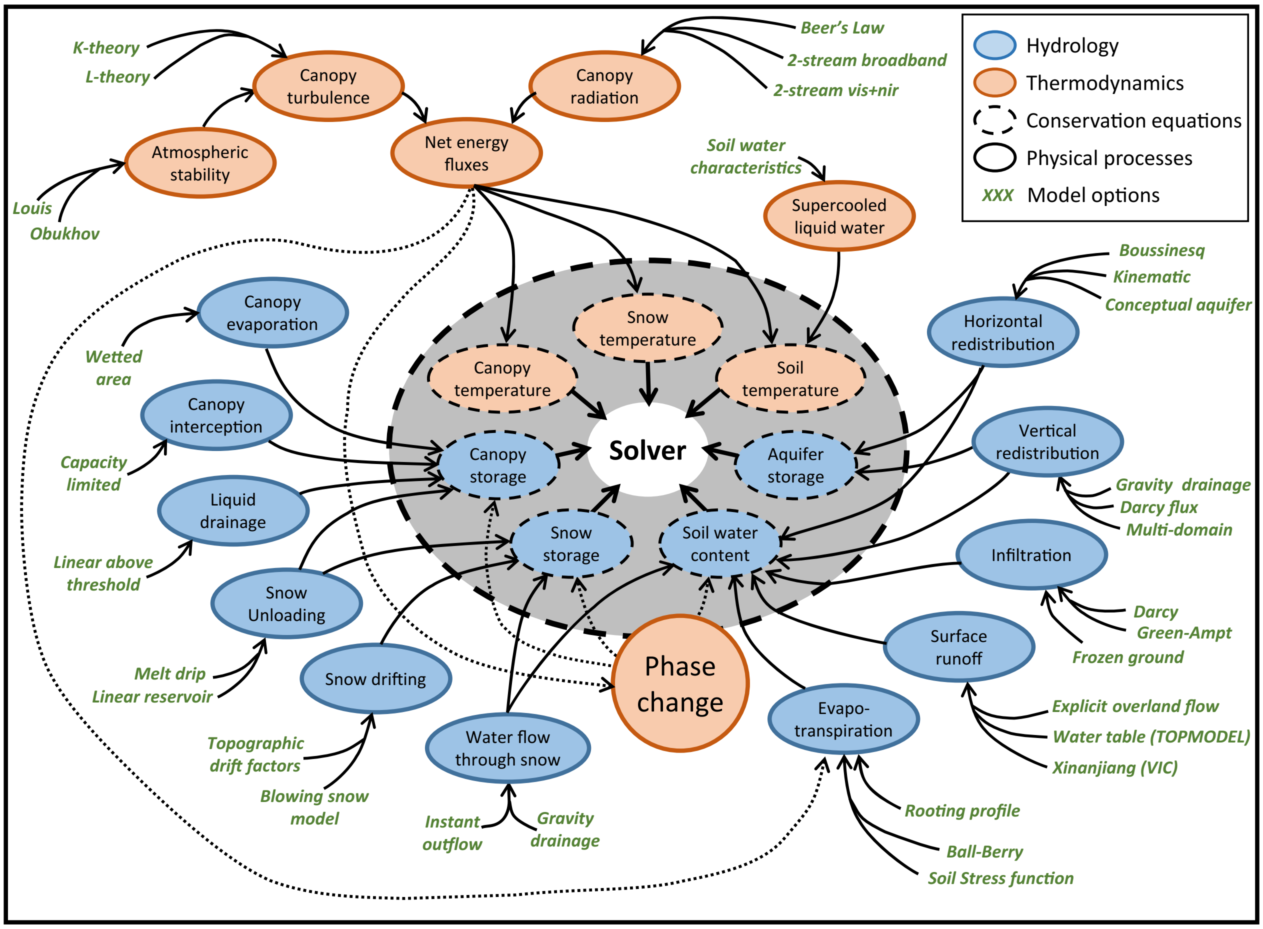

Figure 3. Conceptual diagram illustrating a framework for supporting multiple alternative model options for a range of physical processes, integrated as part of a common numerical solver.

should be represented explicitly can be accomplished through model simplification [*Watson et al*., 2013], where one could exclude some of the conservation equations and physical processes defined in Figure 3 (i.e., exclude some state variables) and replace them with much simpler approximations. For example, when exploring the representation of evapotranspiration, it is possible to reproduce the structure of traditional bucket-style rainfall-runoff models by replacing the relevant thermodynamic calculations with empirical methods for estimating the energy forcing for evapotranspiration (e.g., estimates of potential evapotranspiration). At a finer level of granularity, it is also possible to exclude representations of specific physical processes (e.g., neglecting lateral flow between soil columns). Conversely, following the approach of *Sivapalan et al*. [2003], SUMMA can be used to systematically increase model complexity.

The capability to incorporate multiple flux parameterizations within a common set of conservation equations enables users to understand the impact of different modeling assumptions on model behavior. In particular, SUMMA can be used to systematically evaluate different parameterizations of the same process, along with different model parameter values, based on extensive comparison with multivariate process observations. This allows modelers to identify process parameterizations that are consistent with both theoretical expectations and observed data. More generally, analysis of model simulations of internal states and fluxes can help detect compensatory effects of model errors, help to identify specific reasons for model weaknesses, and help to understand uncertainties in individual model components (e.g., see *Clark et al*. [2011] and the debate between *Beven et al*. [2012] and *Clark et al*. [2012]).

The flexibility in implementing multiple modeling approaches in SUMMA also offers practical advances in characterizing model uncertainty. For example, previous multimodel studies have been constrained by the large efforts required to apply multiple but distinct hydrologic models for the same data sets. Consequently, many multimodel studies are restricted to a small model ensemble [e.g., *Butts et al*., 2004; *Mitchell et al*., 2004; *Vano et al*., 2012]. Such practical constraints can be alleviated in frameworks such as SUMMA because it becomes logistically straightforward to generate a large number of model structures/configurations to be used in the multimodel ensembles, through a permutation of the large number of supported model options. Most importantly, the large number of possible permutations in SUMMA (both in modeling options and parameter values) can provide a much more extensive and detailed coverage of the model hypothesis space [*Beven*, 2006a; *Clark et al*., 2011], and hence a much more robust portrayal of model uncertainty than the typical "small ensemble" multimodel applications.

3.4. Numerical Solution

Another fundamental model development decision is the method(s) used to solve—or, more commonly, approximate—the model equations. The spatial organization and spatial approximations used in SUMMA make it possible to solve the model equations independently for each HRU, resulting in a relatively low dimensional state space (e.g., fewer than 20 state variables per HRU). Note that SUMMA is not currently configured as a full 3-D model. From a numerical perspective, this simplifies the structure of the model equations and their numerical solution.

The key decisions on numerical implementation for such low dimensional systems include the vertical discretization of the model equations, the use of operator-splitting approximations (i.e., the sequential solution of different physical processes), and choice of the solution method in the different model subdomains. These numerical decisions are often based on accuracy-efficiency trade-offs. For example, a fixed-step noniterative solution of the moisture-based form of Richards' equation is used as a cost-cutting measure to reduce run times in the Community Land Model [e.g., *Oleson et al*., 2010]. The impacts of numerical implementation on the performance of large complex hydrologic models are poorly understood (in particular, the operator splitting approximations and the simplifications made for individual processes), and there is a need to evaluate how different numerical approximations affect the solution accuracy and computational efficiency.

The modularity of SUMMA provides scope to experiment with different numerical solvers. In developing and implementing SUMMA, its structural core (the inner circle in Figure 3) is deliberately separated from the different physics options (the outer branches in Figure 3). While to-date we have implemented a single numerical solver, the same model physics routines can be called from different numerical solvers. This enables experimentation with a range of different approximation methods, including explicit schemes, implicit schemes, different operator-splitting approximations, and different adaptive time-stepping strategies. Such flexibility in the choice of numerical solver (e.g., similar to the approach used by *Clark and Kavetski* [2010] for traditional bucket-style rainfall-runoff models) enables systematic assessments of the impact of the numerical solution on model simulations. The focus on improving the structural core of SUMMA parallels the development paradigm in more complex models, e.g., numerical weather prediction and climate models [e.g., *Held and Suarez*, 1994], where efforts are focused on improving the "dynamical" core used to solve the flow equations [e.g., *Klemp et al*., 2007].

3.5. Software Implementation

Different modeling groups have used different approaches to implement alternative process representations within a single model software framework [*Clark et al*., 2011]. Key considerations include both the granularity of process integration (i.e., the size of the model building blocks) and the type of process integration (i.e., how the model building blocks are assembled). The size of the model building blocks can range from (1) individual modeling decisions, e.g., an individual flux parameterization [*Clark et al*., 2008; *Fenicia et al*., 2011; *Niu et al*., 2011; *Essery et al*., 2013]; (2) the dominant physical processes for a given subdomain, e.g., a snow model integrated as part of a hydrologic modeling system [*Leavesley et al*., 2002; *Pomeroy et al*., 2007]; and (3) entire models, e.g., a complete land surface model, integrated as part of a multimodel framework [*Kumar et al*., 2006].

Different methods for assembling model building blocks include (1) simple "wrappers" to provide appropriate software interfaces between different model components [e.g., *Leavesley et al*., 2002; *Pomeroy et al*., 2007; *Werner et al*., 2013]; (2) more complex "couplers" to control the execution and time evolution of a complex model by synchronizing and controlling the flow of data between the various model components [e.g., *Craig et al*., 2011]; and (3) integrating new modeling capabilities into the master model code base [e.g., *Cherkauer et al*., 2003; *Maxwell and Miller*, 2005; *Lawrence et al*., 2011; *Niu et al*., 2011]. The specific approach used to combine process representations depends on the intended purpose of the model and other considerations.

Our intent in developing SUMMA is to foster a controlled and systematic approach to model evaluation and improvement. To this end, the software implementation of SUMMA provides modeling alternatives at a fine level of granularity (e.g., at the level of individual modeling decisions, such as individual flux parameterizations [*Clark et al.,* 2015], with alternative modeling approaches integrated into the master model code base. Specifically, we formulate separate modules to calculate fluxes across the boundaries of model control volumes and the derivative of the net flux with respect to the relevant model state variables. Multiple modeling options are included within the individual modules, and the flux terms and derivatives from the different modules are combined as part of the numerical solver. This modular approach to software implementation provides flexibility both in the selection of different modeling options for physical processes and in the selection of the numerical solver.

4. Discussion

4.1. Unifying Different Approaches to Process-Based Hydrologic Modeling

SUMMA is designed to provide a unifying modeling framework that both encompasses existing approaches to process-based hydrologic modeling and facilitates the exploration of new modeling approaches. Here we summarize how SUMMA addresses three common contrasts in modeling typologies: (1) parsimonious bucket-style rainfall-runoff models versus physically explicit models; (2) lumped models versus distributed models; and (3) hydrologic models versus land-surface schemes.

1. *Parsimonious bucket-style rainfall-runoff models versus physically explicit models*. The SUMMA framework enables systematically examining which physical processes should be represented explicitly to meet specific objectives, and which processes can be ignored or greatly simplified. Specifically, some of the flux terms in the conservation equations can be set to zero, and some of the conservation equations can be omitted from the model and replaced with simpler parameterizations (e.g., parameterizations of potential evapotranspiration instead of explicitly simulating the thermodynamic state of the system; temperature-index parameterizations of snow melt instead of explicitly simulating all snow-atmosphere energy fluxes). These capabilities enable investigating models covering the spectrum from parsimonious bucket-style rainfall-runoff models to more physically explicit models, and exploring model complexity issues in a controlled way.
2. *Lumped models versus distributed models*. The SUMMA framework provides the flexibility to define the size and shape of model elements across a hierarchy of spatial scales, as well as different options to represent lateral subsurface flow in the soil subdomain. This enables representing both lumped hydrologic models as well as a myriad of different approaches for spatially distributed hydrologic modeling.
3. *Hydrologic models versus land surface models*. The *raison d'etre* of land surface models is to simulate land-atmosphere fluxes (historically focusing on biophysical processes) and the *raison d'etre* of hydrologic models is to simulate streamflow (historically focusing on hydrologic processes). While this distinction has become less clear-cut over time, land surface models still have more emphasis on biophysical processes such as within and below-canopy turbulence, whereas hydrologic models have more emphasis on hydrologic processes such as runoff generation mechanisms. SUMMA includes a broad range of biophysical and hydrologic processes, and can represent the dominant processes included in most hydrologic models and land-surface schemes. The SUMMA modular design is also extensible, allowing the modeler to add processes and/or process representations not currently included.

More generally, SUMMA encompasses process representations and spatial organizations used across a broad range of process-based hydrologic models. A noteworthy application of SUMMA is to select specific physics options and spatial configurations that reproduce the structure and behavior of existing models (the practice of "model mimicry"). The ability to reproduce existing models is valuable because the parameterizations in such models often embody the results from important (albeit often under-reported) investigations and modeling experiments. Therefore, the more flexible and systematic SUMMA framework can be used to construct reference (benchmark) cases in structured model comparison experiments, and/or as starting points for subsequent model refinement. Importantly, applications of model mimicry can expose specific reasons for inter-model differences that were hidden in previous model inter-comparison projects.

4.2. Relationships With Alternative Modeling Blueprints

SUMMA can help reconcile different philosophical approaches to process-based hydrologic modeling, including the seemingly competing approaches of "physically explicit" models and "conceptual" models, and the related dichotomy between "bottom-up" and "top-down" approaches.

Physically explicit models attempt to explicitly represent all dominant processes, typically by starting with partial differential equations (PDEs) describing conservation of mass/energy and supplementing them with closure relationships estimated at the small scale (or laboratory scale). This approach to model development is frequently referred to as the bottom-up approach because it involves spatial integration of the small scale equations. In practice, the integration is invariably carried out numerically over discrete grids. Models based on the bottom-up approach are often referred to as "distributed physically based" models [*Binley et al.*, 1989a, 1989b; *Grayson et al.*, 1992a, 1992b; *Wigmosta et al.*, 1994; *VanderKwaak and Loague*, 2001; *Ivanov et al.*, 2004; *Loague et al.*, 2006; *Rigon et al.*, 2006] and, more recently, "integrated physical hydrology" models [*Maxwell et al.*, 2014a, 2014b]. *Freeze and Harlan* [1969] provided one of the earliest and arguably the most influential and commonly used blueprint for developing physically explicit models, using systems of coupled PDEs.

There are two distinct challenges in implementing the bottom-up approach [*Freeze and Harlan*, 1969]: (i) it is difficult or impossible to obtain sufficiently high resolution spatial data on the physical characteristics of the model domain, especially the storage and transmission properties of soils; and (ii) numerical implementation on high resolution spatial mesh may be computationally infeasible. As a consequence, the bottom-up approach is often applied with grid/data resolutions that are too coarse to accurately represent the small-scale spatial heterogeneity and its effects on fluxes at larger spatial scales. For example, applications of Richards equation with horizontal grid resolution of the order of 1 km for a continental-scale domain [*Maxwell et al.*, 2014a] do not fully represent the strong topographic controls on subsurface flow in mountainous regions and do not account for subgrid-scale heterogeneities in soil properties and vegetation. Conversely, applications with horizontal grid resolution of the order of meters are only currently feasible for relatively small domains [*Kollet et al.*, 2010] and require soil data at spatial resolutions that are impractical given current observational capabilities. Most applications of the bottom-up approach do not extensively experiment with different flux parameterizations, in particular, to implicitly reflect the effects of subgrid-scale heterogeneities.

In contrast, conceptual models attempt to represent the aggregate effects of dominant processes on some integrated response of interest (e.g., catchment-scale streamflow). These models do not attempt to use detailed physical equations and instead lump multiple physical processes into a few "effective" mathematical functions [e.g., *Burnash et al.*, 1973; *Lindström et al.*, 1997; *Perrin et al.*, 2003]. These models use weak constraints (e.g., "mass balance," "flow increases with storage," etc.) and require the modeler to choose specific flux functions based on mathematical convenience (i.e., an educated guess), or based on previous studies, or by iteratively fitting model predictions to observed data in the particular location of interest [e.g., *Ambroise et al.*, 1996; *Clark et al.*, 2008; *Bulygina and Gupta*, 2011; *Fenicia et al.*, 2014]. This approach is often referred to as top-down model development [*Klemes*, 1983; *Dooge*, 1986; *Sivapalan et al.*, 2003], and forms the basis for the alternative blueprint for hydrologic modeling presented by *Beven* [2002].

Top-down modeling can be viewed as an attempt to directly define large-scale flux equations (closure relationships) that implicitly represent the aggregate impact of subgrid scale heterogeneities, and hence avoid the requirement for high resolution spatial data and the need for expensive numerical integration. The quest to define large-scale flux equations was the main motivation for developing the Representative Elementary Watershed (REW) approach [*Reggiani et al.*, 1998]. As noted above, these closure relationships are seldom obtained by formal analysis of the small-scale equations (although see *Reggiani et al.* [1998] and *Zehe et al.* [2006]). Instead, these functions are often selected from a range of quite simple a priori options (often power laws relating storage and discharge) and/or on the basis of fitting quantities of interest such as streamflow at the catchment outlet. Top-down modeling often produces models with predictive abilities comparable or higher than the predictive abilities of bottom-up models—at a fraction of the computational effort and data requirements [e.g., *Smith et al.*, 2013]. However, such models are often criticized as "physically unrealistic"—for example, such models may not correctly represent the distinct flow generation processes that combine into the response of interest [*Ebel and Loague*, 2006], and such models are unlikely to provide a robust basis for extrapolations such as those needed for predictions in ungauged basins and for predictions of the effects of climate change [*Hrachowitz et al.*, 2013].

The bottom-up and top-down perspectives need not be mutually exclusive. SUMMA unifies these competing modeling philosophies by combining the quest for physical detail (as in the bottom-up approach) with the quest to develop/improve parameterizations that implicitly reflect the effects of subgrid-scale heterogeneities on grid-average fluxes (as in the top-down approach). In the SUMMA approach, we apply physically explicit conservation equations to describe the time evolution of thermodynamic and hydrologic states (where community agreement exists), and accommodate multiple representations of spatial variability, connectivity and flux parameterizations (reflecting community disagreements).

4.3. Advancing Current Model Development Paradigms

Our emphasis on identifying suitable model representations of spatial variability, connectivity and fluxes is shared in most hydrologic model development efforts. For example, the derivation of the REW approach [*Reggiani et al.*, 1998; *Reggiani and Rientjes*, 2005] formally distinguishes between (1) the application of physically explicit conservation equations within physically meaningful control volumes versus (2) the development of scale-appropriate parameterizations of fluxes across the boundaries of the control volumes. Many other model development efforts seek to identify scale-appropriate flux parameterizations. Examples include attempts to define new flux parameterizations suitable for use at larger spatial scales [e.g., *Mahrt*, 1987; *Essery et al.*, 2008]; statistical-dynamical modeling approaches which parameterize grid-average fluxes based on subgrid spatial variability in model state variables [e.g., *Beven and Kirkby*, 1979; *Moore and Clarke*, 1981; *Wood et al.*, 1992; *Koren et al.*, 1999; *Luce et al.*, 1999]; and schemes that attempt to improve simulations of grid-average fluxes through multiple flux calculations over a given model control volume, such as separate stomatal resistance calculations for sunlit and shaded leaves in order to properly scale evapotranspiration from the leaf scale to the canopy scale [e.g., *Wang and Leuning*, 1998; *Dai et al.*, 2004], and separate energy balance calculations for snow-covered and snow-free areas [e.g., *Takata et al.*, 2003; *Swenson and Lawrence*, 2012].

SUMMA provides substantial flexibility in evaluating competing modeling approaches. First, SUMMA allows for flexibility in the representation of spatial variability—the control volumes used in SUMMA can be defined based on hydrologic similarity (e.g., using HRUs) [*Vivoni et al.*, 2004; *Newman et al.*, 2014] and/or using high-resolution grids [*Wigmosta et al.*, 1994]; where the HRUs and grids can be nested to provide simulations that span multiple spatial scales. Second, SUMMA provides flexibility in the use of different methods to represent the hydrologic connection of spatial elements across the landscape [*Beven and Freer*, 2001]. We do not require that the flux parameterizations be based on spatial gradients in model state variables (section 3.3)—SUMMA explicitly allows for both gradient-based [*Freeze and Harlan*, 1969] and spatially averaged flux formulations [*Reggiani et al.*, 1999]. Third, SUMMA can accommodate newly hypothesized flux parameterizations, facilitating the exploration of model representations of heterogeneity and scaling behavior [*Dooge*, 1986; *Reggiani et al.*, 1998; *Sivapalan*, 2005; *Beven*, 2006b; *Kirchner*, 2006; *McDonnell et al.*, 2007; *Troch et al.*, 2009].

More generally, SUMMA is intended as a tool to *enable* systematic development and testing of hydrologic modeling alternatives. SUMMA (in itself) does not provide a framework to derive flux parameterizations that represent nonlinear and hysteretic behavior and the impact of subgrid heterogeneities on grid-average fluxes. Rather, we recognize that improvements in model fidelity require a tool that can isolate and evaluate individual processes within a model, in order to minimize the number of differences between alternative model configurations so that it is possible to attribute differences in model behavior to individual modeling decisions. Improvements in model fidelity also require a tool that can evaluate how interlinked physical processes combine to produce the system-scale response at larger spatial scales. SUMMA enables decomposing land surface models into a set of testable components (constituent hypotheses), and using multivariate and multiscale data to systematically evaluate individual model hypotheses and their interactions.

4.4. Limitations

SUMMA has several important limitations, both in terms of the scope of the initial implementation and in terms of the overall modeling concept.

The initial implementation of SUMMA (described in the companion paper) is limited to the terrestrial water and energy fluxes shown in Figure 1. SUMMA does not currently include terrain effects on the radiation balance, vapor transport within snow and soil, horizontal transport of snow associated with avalanching or drifting, storage and fluxes of carbon and nitrogen, and does not currently explicitly represent depression storage, wetlands and lakes, major aquifers, and losses from the stream to the aquifer. It is straightforward to extend SUMMA to include additional physical processes. This can be done both through expanding model couplings (e.g., coupling with a groundwater model) and/or through expanding the current set of state equations.

A more general limitation is that we approximate the soil subdomain as a set of hydrologically connected multilayer vertical columns (connected through lateral subsurface flow), and do not attempt a full 3-D representation of the model domain [e.g., *Kollet and Maxwell*, 2006; *Loague et al*., 2006]. Specifically, the lateral flow among soil columns is included as a source/sink term in the conservation equation for soil hydrology. This approach offers flexibility to experiment with a broad range of modeling approaches—for example, these spatial approximations for the soil subdomain are used in a number of existing catchment hydrology models [e.g., *Wigmosta et al*., 1994; *Beven and Freer*, 2001; *Troch et al*., 2003]. The simpler spatial discretization employed here has previously been demonstrated to reproduce the behavior of 3-D variably saturated flow models [*Paniconi et al*., 2003], and we plan to further investigate differences with full 3-D representations of subsurface flow in future model work (e.g., using the set of benchmarks described by *Maxwell et al*. [2014b]).

5. Conclusions

This paper describes a unified framework for hydrological modeling, designed to enable a systematic implementation and evaluation of alternative modeling approaches for process representation, and the identification of specific causes of model weaknesses. The proposed approach, which we term the Structure for Unifying Multiple Modeling Alternatives (SUMMA), is based on the community understanding of how the dominant fluxes of energy and water affect the time evolution of thermodynamic and hydrologic states. The framework is centered on the structural core, which comprises the general conservation equations for the hydrologic and thermodynamic state variables within the model domain, and general algorithms for their numerical solution. Different process representations and different spatial configurations can be integrated into the structural model core, which enables users to decompose the modeling problem into the individual decisions made as part of model development and evaluate different "fine grain" model development decisions in a systematic and controlled way.

SUMMA can facilitate progress toward answering the following fundamental modeling questions and challenges: (1) which physical processes should be represented explicitly in different environmental settings, and, correspondingly, which processes can be ignored or greatly simplified; (2) what modeling approaches should be used to represent the dominant biophysical and hydrologic processes at the spatial scale of the model discretization; (3) how should the spatial variability of physical processes be represented across a hierarchy of spatial scales, including the complexity of the spatial linkages (hydrologic connectivity) across the landscape; (4) what algorithms should be used to solve the model equations; and (5) how can we provide insights into the sources of model uncertainty. The companion paper describes the initial implementation of SUMMA for key biophysical and hydrologic processes, and provides example applications that begin to address some of these fundamental modeling challenges.

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References

Ambroise, B., K. Beven, and J. Freer (1996), Toward a generalization of the TOPMODEL concepts: Topographic indices of hydrological similarity, *Water Resour. Res.*, *32*(7), 2135–2145, doi:10.1029/95WR03716.

Anderson, S. P., R. C. Bales, and C. J. Duffy (2008), Critical zone observatories: Building a network to advance interdisciplinary study of Earth surface processes, *Mineral. Mag.*, *72*(1), 7–10, doi:10.1180/minmag.2008.072.1.7.

Andreadis, K. M., P. Storck, and D. P. Lettenmaier (2009), Modeling snow accumulation and ablation processes in forested environments, *Water Resour. Res.*, *45*, W05429, doi:10.1029/2008WR007042.

Bandaragoda, C., D. G. Tarboton, and R. Woods (2004), Application of TOPNET in the distributed model intercomparison project, *J. Hydrol.*, *298*(1), 178–201, doi:10.1016/j.jhydrol.2004.03.038.

Best, M. J., et al. (2011), The Joint UK Land Environment Simulator (JULES), model description—Part 1: Energy and water fluxes, *Geosci. Model Dev.*, *4*(3), 677–699, doi:10.5194/gmd-4–677-2011.

Beven, K. (2002), Towards an alternative blueprint for a physically based digitally simulated hydrologic response modelling system, *Hydrol. Processes*, *16*(2), 189–206, doi:10.1002/hyp.343.

Beven, K. (2006a), A manifesto for the equifinality thesis, *J. Hydrol.*, *320*(1–2), 18–36, doi:10.1016/j.jhydrol.2005.07.007.

Beven, K. (2006b), Searching for the Holy Grail of scientific hydrology: Q(t) = H((S)under-left-arrow, (R)under-left-arrow, Delta t)A as closure, *Hydrol. Earth Syst. Sci.*, *10*(5), 609–618, doi:10.5194/hess-10-609-2006.

Beven, K., and J. Freer (2001), A dynamic TOPMODEL, *Hydrol. Processes*, *15*(10), 1993–2011, doi:10.1002/hyp.252.

Beven, K., P. Smith, I. Westerberg, and J. Freer (2012), Comment on "Pursuing the method of multiple working hypotheses for hydrological modeling" by M. P. Clark et al., *Water Resour. Res.*, *48*, W11801, doi:10.1029/2012WR012282.

Beven, K. J., and M. J. Kirkby (1979), A physically based, variable contributing area model of basin hydrology, *Hydrol. Sci. Bull.*, *24*, 43–69, doi:10.1080/02626667909491834.

Binley, A., J. Elgy, and K. Beven (1989a), A physically based model of heterogeneous hillslopes.1. Runoff production, *Water Resour. Res.*, *25*(6), 1219–1226, doi:10.1029/WR025i006p01219.

Binley, A., K. Beven, and J. Elgy (1989b), A physically based model of heterogeneous hillslopes. 2. Effective hydraulic conductivities, *Water Resour. Res.*, *25*(6), 1227–1233, doi:10.1029/WR025i006p01227.

Blöschl, G., and M. Sivapalan (1995), Scale issues in hydrological modelling: A review, *Hydrol. Processes*, *9*, 251–290, doi:10.1002/hyp.3360090305.

Bonan, G. (2002), *Ecological Climatology: Concepts and Applications*, 678 pp., Cambridge University Press, Cambridge, U. K.

Bonan, G. B., S. Levis, L. Kergoat, and K. W. Oleson (2002), Landscapes as patches of plant functional types: An integrating concept for climate and ecosystem models, *Global Biogeochem. Cycles*, *16*(2), 1021, doi:10.1029/2000GB001360.

Bowling, L. C., D. P. Lettenmaier, B. Nijssen, J. Polcher, R. D. Koster, and D. Lohmann (2003), Simulation of high-latitude hydrological processes in the Torne-Kalix basin: PILPS phase 2(e) - 3: Equivalent model representation and sensitivity experiments, *Global Planet. Change*, *38*(1–2), 55–71, doi:10.1016/S0921-8181(03)00005-5.

Bulygina, N., and H. Gupta (2011), Correcting the mathematical structure of a hydrological model via Bayesian data assimilation, *Water Resour. Res.*, *47*, W05514, doi:10.1029/2010WR009614.

Burnash, R., R. Ferral, and R. McGuire (1973), A generalized streamflow simulation system—Conceptual modeling for digital computers, report, Joint Fed. and State River Forecast Cent., Sacramento, Calif.

Butts, M. B., J. T. Payne, M. Kristensen, and H. Madsen (2004), An evaluation of the impact of model structure on hydrological modelling uncertainty for streamflow simulation, *J. Hydrol.*, *298*(1), 242–266, doi:10.1016/j.jhydrol.2004.03.042.

Cherkauer, K. A., L. C. Bowling, and D. P. Lettenmaier (2003), Variable infiltration capacity cold land process model updates, *Global Planet. Change*, *38*(1–2), 151–159, doi:10.1016/s0921-8181(03)00025-0.

Clark, M. P., and D. Kavetski (2010), Ancient numerical daemons of conceptual hydrological modeling: 1. Fidelity and efficiency of time stepping schemes, *Water Resour. Res.*, *46*, W10510, doi:10.1029/2009WR008894.

Clark, M. P., A. G. Slater, D. E. Rupp, R. A. Woods, J. A. Vrugt, H. V. Gupta, T. Wagener, and L. E. Hay (2008), Framework for Understanding Structural Errors (FUSE): A modular framework to diagnose differences between hydrological models, *Water Resour. Res.*, *44*, W00B02, doi:10.1029/2007WR006735.

Clark, M. P., D. Kavetski, and F. Fenicia (2011), Pursuing the method of multiple working hypotheses for hydrological modeling, *Water Resour. Res.*, *47*, W09301, doi:10.1029/2010WR009827.

Clark, M. P., D. Kavetski, and F. Fenicia (2012), Reply to comment by K. Beven et al. on "Pursuing the method of multiple working hypotheses for hydrological modeling," *Water Resour. Res.*, *48*, W11802, doi:10.1029/2012WR012547.

Clark, M. P., et al. (2015), A unified approach for process-based hydrologic modeling: Part 2. Model implementation and example applications, *Water Resour. Res.*, *51*, doi:10.1002/2015WR017200.

Craig, A. P., M. Vertenstein, and R. Jacob (2011), A new flexible coupler for earth system modeling developed for CCSM4 and CESM1, *Int. J. High Performance Comput. Appl.*, *26*, 31–42, doi:10.1177/1094342011428141.

Dai, Y., R. E. Dickinson, and Y.-P. Wang (2004), A two-big-leaf model for canopy temperature, photosynthesis, and stomatal conductance, *J. Clim.*, *17*(12), 2281–2299, doi:10.1175/1520-0442(2004)017<2281:atmfct>2.0.co;2.

Dooge, J. C. I. (1986), Looking for hydrologic laws, *Water Resour. Res.*, *22*(9S), 46S–58S, doi:10.1029/WR022i09Sp0046S.

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

Ebel, B. A., and K. Loague (2006), Physics based hydrologic response simulation: Seeing through the fog of equifinality, *Hydrol. Processes*, *20*(13), 2887–2900, doi:10.1002/hyp.6388.

Essery, R., P. Bunting, J. Hardy, T. Link, D. Marks, R. Melloh, J. Pomeroy, A. Rowlands, and N. Rutter (2008), Radiative transfer modeling of a coniferous canopy characterized by airborne remote sensing, *J. Hydrometeorol.*, *9*(2), 228–241, doi:10.1175/2007JHM870.1.

Essery, R., S. Morin, Y. Lejeune, and C. B. Menard (2013), A comparison of 1701 snow models using observations from an alpine site, *Adv. Water Resour.*, *55*, 131–148, doi:10.1016/j.advwatres.2012.07.013.

Famiglietti, J. S., and E. F. Wood (1994), Multiscale modeling of spatially variable water and energy balance processes, *Water Resour. Res.*, *30*(11), 3061–3078, doi:10.1029/94WR01498.

Fan, Y., and R. L. Bras (1998), Analytical solutions to hillslope subsurface storm flow and saturation overland flow, *Water Resour. Res.*, *34*(4), 921–927.

Fenicia, F., D. Kavetski, and H. H. G. Savenije (2011), Elements of a flexible approach for conceptual hydrological modeling: 1. Motivation and theoretical development, *Water Resour. Res.*, *47*, W11510, doi:10.1029/2010WR010174.

Fenicia, F., D. Kavetski, H. H. G. Savenije, M. P. Clark, G. Schoups, L. Pfister, and J. Freer (2014), Catchment properties, function, and conceptual model representation: Is there a correspondence?, *Hydrol. Processes*, *28*(4), 2451–2467, doi:10.1002/hyp.9726.

Flügel, W. A. (1995), Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Bröl, Germany, *Hydrol. Processes*, *9*, 423–436, doi:10.1002/hyp.3360090313.

Foglia, L., S. Mehl, M. Hill, and P. Burlando (2013), Evaluating model structure adequacy: The case of the Maggia Valley groundwater system, southern Switzerland, *Water Resour. Res.*, *49*, 260–282, doi:10.1029/2011WR011779.

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

Gharari, S., M. Hrachowitz, F. Fenicia, and H. H. G. Savenije (2011), Hydrological landscape classification: Investigating the performance of HAND based landscape classifications in a central European meso-scale catchment, *Hydrol. Earth Syst. Sci.*, *15*(11), 3275–3291, doi:10.5194/hess-15–3275-2011.

Giorgi, F., and R. Avissar (1997), Representation of heterogeneity effects in earth system modeling: Experience from land surface modeling, *Rev. Geophys.*, *35*(4), 413–437, doi:10.1029/97RG01754.

Gochis, D. J., W. Yu, and D. N. Yates (2013), The WRF-Hydro model technical description and user's guide, version 1.0., 120 pp. [Available at http://www.ral.ucar.edu/projects/wrf_hydro/.]

Grayson, R. B., I. D. Moore, and T. A. McMahon (1992a), Physically based hydrologic modeling: 1. A terrain-based model for investigative purposes, *Water Resour. Res.*, *28*(10), 2639–2658, doi:10.1029/92WR01258.

Grayson, R. B., I. D. Moore, and T. A. McMahon (1992b), Physically based hydrologic modeling, 2. Is the concept realistic?, *Water Resour. Res.*, *28*(10), 2659–2666, doi:10.1029/92WR01259.

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

Harbaugh, A. W., E. R. Banta, and M. C. Hill (2005), *MODFLOW-2000, the US Geological Survey Modular Ground-Water Model: User Guide to Modularization Concepts and the Ground-Water Flow Process*. U.S. Geological Survey. Open-File Report 00-92, 121pp.

Hay, L. E., M. P. Clark, M. Pagowski, G. H. Leavesley, and W. J. Gutowski (2006), One-way coupling of an atmospheric and a hydrologic model in Colorado, *J. Hydrometeorol.*, *7*(4), 569–589, doi:10.1175/JHM512.1.

Held, I. M., and M. J. Suarez (1994), A proposal for the intercomparison of the dynamical cores of atmospheric general circulation models, *Bull. Am. Meteorol. Soc.*, *75*(10), 1825–1830, doi:10.1175/1520-0477(1994)075<1825:APFTIO>2.0.CO;2.

Hrachowitz, M., et al. (2013), A decade of Predictions in Ungauged Basins (PUB)—A review, *Hydrol. Sci. J.*, *58*(6), 1198–1255, doi:10.1080/02626667.2013.803183.

Ivanov, V. Y., E. R. Vivoni, R. L. Bras, and D. Entekhabi (2004), Catchment hydrologic response with a fully distributed triangulated irregular network model, *Water Resour. Res.*, *40*, W11102, doi:10.1029/2004WR003218.

Kampf, S. K., and S. J. Burges (2007), A framework for classifying and comparing distributed hillslope and catchment hydrologic models, *Water Resour. Res.*, *43*, W05423 doi:10.1029/2006WR005370.

Kirchner, J. (2006), Getting the right answers for the wrong reasons, *Water Resour. Res.*, *42*, W03S04, doi:10.1029/2005WR004362.

Klemes, V. (1983), Conceptualization and scale in hydrology, *J. Hydrol.*, *65*, 1–23, doi:10.1016/0022-1694(83)90208-1.

Klemp, J. B., W. C. Skamarock, and J. Dudhia (2007), Conservative split-explicit time integration methods for the compressible nonhydrostatic equations, *Mon. Weather Rev.*, *135*(8), 2897–2913, doi:10.1175/MWR3440.1.

Kollet, S. J., and R. M. Maxwell (2006), Integrated surface-groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model, *Adv. Water Resour.*, *29*(7), 945–958, doi:10.1016/j.advwatres.2005.08.006.

Kollet, S. J., and R. M. Maxwell (2008), Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model, *Water Resour. Res.*, *44*, W02402, doi:10.1029/2007WR006004.

Kollet, S. J., R. M. Maxwell, C. S. Woodward, S. Smith, J. Vanderborght, H. Vereecken, and C. Simmer (2010), Proof of concept of regional scale hydrologic simulations at hydrologic resolution utilizing massively parallel computer resources, *Water Resour. Res.*, *46*, W04201, doi:10.1029/2009WR008730.

Koren, V., J. Schaake, K. Mitchell, Q. Y. Duan, F. Chen, and J. Baker (1999), A parameterization of snowpack and frozen ground intended for NCEP weather and climate models, *J. Geophys. Res.*, *104*(D16), 19,569–19,585, doi:10.1029/1999JD900232.

Koren, V., S. Reed, M. Smith, Z. Zhang, and D. J. Seo (2004), Hydrology Laboratory Research Modeling System (HL-RMS) of the US National Weather Service, *J. Hydrol.*, *291*(3–4), 297–318, doi:10.1016/j.jhydrol.2003.12.039.

Koster, R. D., and P. C. D. Milly (1997), The interplay between transpiration and runoff formulations in land surface schemes used with atmospheric models, *J. Clim.*, *10*(7), 1578–1591, doi:10.1175/1520-0442(1997)010<1578:TIBTAR>2.0.co;2.

Koster, R. D., and M. J. Suarez (1992), Modeling the land surface boundary in climate models as a composite of independent vegetation stands, *J. Geophys. Res.*, *97*(D3), 2697–2715, doi:10.1029/91JD01696.

Kouwen, N., E. Soulis, A. Pietroniro, J. Donald, and R. Harrington (1993), Grouped response units for distributed hydrologic modeling, *J. Water Resour. Plann. Manage.*, *119*(3), 289–305, doi:10.1061/(ASCE)0733-9496(1993)119:3(289).

Kraft, P., K. B. Vaché, H.-G. Frede, and L. Breuer (2011), CMF: A hydrological programming language extension for integrated catchment models, *Environ. Modell. Software*, *26*(6), 828–830, doi:10.1016/j.envsoft.2010.12.009.

Kumar, S. V., et al. (2006), Land information system: An interoperable framework for high resolution land surface modeling, *Environ. Modell. Software*, *21*(10), 1402–1415, doi:10.1016/j.envsoft.2005.07.004.

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

Lawrence, D. M., K. W. Oleson, M. G. Flanner, C. G. Fletcher, P. J. Lawrence, S. Levis, S. C. Swenson, and G. B. Bonan (2012), The CCSM4 land simulation, 1850–2005: Assessment of surface climate and new capabilities, *J. Clim.*, *25*(7), 2240–2260, doi:10.1175/JCLI-D-11-00103.1.

Leavesley, G. H., S. L. Markstrom, P. J. Restrepo, and R. J. Viger (2002), A modular approach to addressing model design, scale, and parameter estimation issues in distributed hydrological modelling, *Hydrol. Processes*, *16*(2), 173–187, doi:10.1002/hyp.344.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges (1994), A simple hydrologically based model of land-surface water and energy fluxes for General Circulation Models, *J. Geophys. Res.*, *99*(D7), 14,415–14,428, doi:10.1029/94JD00483.

Lindström, G., B. Johansson, M. Persson, M. Gardelin, and S. Bergström (1997), Development and test of the distributed HBV-96 hydrological model, *J. Hydrol.*, *201*(1), 272–288, doi:10.1016/s0022–1694(97)00041-3.

Loague, K., C. S. Heppner, B. B. Mirus, B. A. Ebel, Q. H. Ran, A. E. Carr, S. H. BeVille, and J. E. VanderKwaak (2006), Physics-based hydrologic-response simulation: Foundation for hydroecology and hydrogeomorphology, *Hydrol. Processes*, *20*(5), 1231–1237, doi:10.1002/hyp.6179.

Luce, C. H., D. G. Tarboton, and K. R. Cooley (1998), The influence of the spatial distribution of snow on basin-averaged snowmelt, *Hydrol. Processes*, *12*(10–11), 1671–1683, doi:10.1002/(SICI)1099-1085(199808/09)12:10/11<1671::AID-HYP688>3.0.CO;2-N.

Luce, C. H., D. G. Tarboton, and K. R. Cooley (1999), Sub-grid parameterization of snow distribution for an energy and mass balance snow cover model, *Hydrol. Processes*, *13*(12–13), 1921–1933, doi:10.1002/(SICI)1099-1085(199909)13:12/13<1921::AID-HYP867>3.3.CO;2-J.

Mahrt, L. (1987), Grid-averaged surface fluxes, *Mon. Weather Rev.*, *115*(8), 1550–1560, doi:10.1175/1520-0493(1987)115<1550:GASF>2.0.CO;2.

Maxwell, R. M., and S. J. Kollet (2008), Quantifying the effects of three-dimensional subsurface heterogeneity on Hortonian runoff processes using a coupled numerical, stochastic approach, *Adv. Water Resour.*, *31*(5), 807–817, doi:10.1016/j.advwatres.2008.01.020.

Maxwell, R. M., and N. L. Miller (2005), Development of a coupled land surface and groundwater model, *J. Hydrometeorol.*, *6*(3), 233–247, doi:10.1175/JHM422.1.

Maxwell, R. M., L. E. Condon, and S. J. Kollet (2014a), Simulation of groundwater and surface water over the continental US using a hyperresolution, integrated hydrologic model, *Geosci. Model Dev. Discuss.*, *7*, 7317–7349. [Available at http://www.geosci-model-dev-discuss.net/7/7317/2014/gmdd-7-7317-2014.pdf.]

Maxwell, R. M., M. Putti, S. Meyerhoff, J. O. Delfs, I. M. Ferguson, V. Ivanov, J. Kim, O. Kolditz, S. J. Kollet, and M. Kumar (2014b), Surface-subsurface model intercomparison: A first set of benchmark results to diagnose integrated hydrology and feedbacks, *Water Resour. Res.*, *50*, 1531–1549, doi:10.1002/2013WR013725.

McDonnell, J., M. Sivapalan, K. Vaché, S. Dunn, G. Grant, R. Haggerty, C. Hinz, R. Hooper, J. Kirchner, and M. Roderick (2007), Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology, *Water Resour. Res.*, *43*, W07301, doi:10.1029/2006WR005467.

Mendoza, P., M. Clark, M. Barlage, B. Rajagopalan, L. Samaniego, G. Abramowitz, and H. V. Gupta (2015), Are we unnecessarily constraining the agility of complex process-based models?, *Water Resour. Res.*, *51*, 716–728, doi:10.1002/2014WR015820.

Mitchell, K. E., D. Lohmann, P. R. Houser, E. F. Wood, J. C. Schaake, A. Robock, B. A. Cosgrove, J. Sheffield, Q. Duan, and L. Luo (2004), The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system, *J. Geophys. Res.*, *109*, D07S90, doi:10.1029/2003JD003823.

Montanari, A., and D. Koutsoyiannis (2012), A blueprint for process-based modeling of uncertain hydrological systems, *Water Resour. Res.*, *48*, W09555, doi:10.1029/2011WR011412.

Moore, R., and R. Clarke (1981), A distribution function approach to rainfall runoff modeling, *Water Resour. Res.*, *17*(5), 1367–1382, doi:10.1029/WR017i005p01367.

Newman, A. J., M. P. Clark, A. Winstral, D. Marks, and M. Seyfried (2014), The use of similarity concepts to represent sub-grid variability in land-surface models: Case study in a snowmelt dominated watershed, *J. Hydrometeorol.*, *15*, 1717–1738, doi:10.1175/JHM-D-13-038.1.

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

Nijssen, B., et al. (2003), Simulation of high latitude hydrological processes in the Torne–Kalix basin: PILPS phase 2(e) - 2: Comparison of model results with observations, *Global Planet. Change*, *38*(1–2), 31–53, doi:10.1016/S0921-8181(03)00004-3.

Niu, G. Y., et al. (2011), The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements, *J. Geophys. Res.*, *116*, D12109, doi:10.1029/2010JD015139.

Nobre, A. D., L. A. Cuartas, M. Hodnett, C. D. Renno, G. Rodrigues, A. Silveira, M. Waterloo, and S. Saleska (2011), Height above the nearest drainage—A hydrologically relevant new terrain model, *J. Hydrol.*, *404*(1–2), 13–29, doi:10.1016/j.jhydrol.2011.03.051.

Oleson, K. W., et al. (2010), Technical description of version 4.0 of the Community Land Model, *NCAR Tech. Note NCAR/TN-478+STR* 257, National Center for Atmospheric Research, Boulder, Colorado, USA.

Paniconi, C., P. A. Troch, E. E. van Loon, and A. G. Hilberts (2003), Hillslope storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes: 2. Intercomparison with a three dimensional Richards equation model, *Water Resour. Res.*, *39*(11), 1317, doi:10.1029/2002WR001730.

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

Pitman, A. J., and A. Henderson-Sellers (1998), Recent progress and results from the project for the intercomparison of landsurface parameterization schemes, *J. Hydrol.*, *212*(1–4), 128–135, doi:10.1016/S0022–1694(98)00206-6.

Pomeroy, J. W., D. M. Gray, T. Brown, N. R. Hedstrom, W. L. Quinton, R. J. Granger, and S. K. Carey (2007), The cold regions hydrological process representation and model: A platform for basing model structure on physical evidence, *Hydrol. Processes*, *21*(19), 2650–2667, doi:10.1002/hyp.6787.

Qu, Y. Z., and C. J. Duffy (2007), A semidiscrete finite volume formulation for multiprocess watershed simulation, *Water Resour. Res.*, *43*, W08419, doi:10.1029/2006WR005752.

Reggiani, P., and T. H. M. Rientjes (2005), Flux parameterization in the representative elementary watershed approach: Application to a natural basin, *Water Resour. Res.*, *41*, W04013, doi:10.1029/2004WR003693.

Reggiani, P., M. Sivapalan, and S. M. Hassanizadeh (1998), A unifying framework for watershed thermodynamics: Balance equations for mass, momentum, energy and entropy, and the second law of thermodynamics, *Adv. Water Resour.*, *22*(4), 367–398, doi:10.1016/S0309–1708(98)00012-8.

Reggiani, P., S. M. Hassanizadeh, M. Sivapalan, and W. G. Gray (1999), A unifying framework for watershed thermodynamics: Constitutive relationships, *Adv. Water Resour.*, *23*(1), 15–39, doi:10.1016/S0309-1708(99)00005-6.

Rigon, R., G. Bertoldi, and T. M. Over (2006), GEOtop: A distributed hydrological model with coupled water and energy budgets, *J. Hydrometeorol.*, *7*(3), 371–388, doi:10.1175/JHM497.1.

Rutter, N., et al. (2009), Evaluation of forest snow processes models (SnowMIP2), *J. Geophys. Res.*, *114*, D06111, doi:10.1029/2008JD011063.

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

Seyfried, M., and B. Wilcox (1995), Scale and the nature of spatial variability: Field examples having implications for hydrologic modeling, *Water Resour. Res.*, *31*(1), 173–184, doi:10.1029/94WR02025.

Simunek, J., M. T. van Genuchten, and M. Sejna (2008), Development and applications of the HYDRUS and STANMOD software packages and related codes, *Vadose Zone J.*, *7*(2), 587–600, doi:10.2136/VZJ2007.0077.

Sivapalan, M. (2005), Pattern, process and function: Elements of a unified theory of hydrology at the catchment scale, in Encyclopedia of Hydrological Sciences, edited by M. G. Anderson, pp. 193–219, John Wiley, London.

Sivapalan, M., K. Beven, and E. F. Wood (1987), On hydrologic similarity. 2. A scaled model of storm runoff production, *Water Resour. Res.*, *23*(12), 2266–2278, doi:10.1029/WR023i012p02266.

Sivapalan, M., G. Blöschl, L. Zhang, and R. Vertessy (2003), Downward approach to hydrological prediction, *Hydrol. Processes*, *17*(11), 2101–2111, doi:10.1002/hyp.1425.

Smith, M., et al. (2013), The distributed model intercomparison project—Phase 2: Experiment design and summary results of the western basin experiments, *J. Hydrol.*, *507*, 300–329, doi:10.1016/j.jhydrol.2013.08.040.

Smith, M. B., D. J. Seo, V. I. Koren, S. M. Reed, Z. Zhang, Q. Duan, F. Moreda, and S. Cong (2004), The distributed model intercomparison project (DMIP): Motivation and experiment design, *J. Hydrol.*, *298*(1–4), 4–26, doi:10.1016/j.jhydrol.2004.03.040.

Swenson, S., and D. Lawrence (2012), A new fractional snow-covered area parameterization for the Community Land Model and its effect on the surface energy balance, *J. Geophys. Res.*, *117*, D21107, doi:10.1029/2012JD018178.

Tague, C., and L. Band (2004), RHESSys: Regional hydro-ecologic simulation system-an object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling, *Earth Interact.*, *8*, Paper 1, 1–42, doi:10.1175/1087–3562(2004)8<1:RRHSSO>2.0.CO;2.

Takata, K., S. Emori, and T. Watanabe (2003), Development of the minimal advanced treatments of surface interaction and runoff, *Global Planet. Change*, *38*(1), 209–222, doi:10.1016/S0921–8181(03)00030-4.

Thielen, J., J. Bartholmes, M. H. Ramos, and A. de Roo (2009), The European flood alert system—Part 1: Concept and development, *Hydrol. Earth Syst. Sci.*, *13*(2), 125–140, doi:10.5194/hess-13-125-2009.

Todini, E. (1988), Rainfall-runoff modeling—Past, present, and future, *J. Hydrol.*, *100*(1–3), 341–352, doi:10.1016/0022-1694(88)90191-6.

Troch, P., E. Van Loon, and A. Hilberts (2002), Analytical solutions to a hillslope-storage kinematic wave equation for subsurface flow, *Adv. Water Resour.*, *25*(6), 637–649.

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

Troch, P. A., G. A. Carrillo, I. Heidbüchel, S. Rajagopal, M. Switanek, T. H. Volkmann, and M. Yaeger (2009), Dealing with landscape heterogeneity in watershed hydrology: A review of recent progress toward new hydrological theory, *Geogr. Compass*, *3*(1), 375–392, doi:10.1111/j.1749-8198.2008.00186.x.

VanderKwaak, J. E., and K. Loague (2001), Hydrologic-response simulations for the R-5 catchment with a comprehensive physics-based model, *Water Resour. Res.*, *37*(4), 999–1013, doi:10.1029/2000WR900272.

Vano, J. A., T. Das, and D. P. Lettenmaier (2012), Hydrologic sensitivities of Colorado River runoff to changes in precipitation and temperature, *J. Hydrometeorol.*, *13*(3), 932–949, doi:10.1175/JHM-D-11-069.1.

Vivoni, E. R., V. Y. Ivanov, R. L. Bras, and D. Entekhabi (2004), Generation of triangulated irregular networks based on hydrological similarity, *J. Hydrol. Eng.*, *9*(4), 288–302, doi:10.1061/(ASCE)1084-0699(2004)9:4(288).

Vivoni, E. R., V. Teles, V. Y. Ivanov, R. L. Bras, and D. Entekhabi (2005), Embedding landscape processes into triangulated terrain models, *Int. J. Geogr. Inf. Sci.*, *19*(4), 429–457, doi:10.1080/13658810512331325111.

Wang, Y.-P., and R. Leuning (1998), A two-leaf model for canopy conductance, photosynthesis and partitioning of available energy I:: Model description and comparison with a multi-layered model, *Agric. For. Meteorol.*, *91*(1), 89–111, doi:10.1016/S0168-1923(98)00061-6.

Watson, T. A., J. E. Doherty, and S. Christensen (2013), Parameter and predictive outcomes of model simplification, *Water Resour. Res.*, *49*, 3952–3977, doi:10.1002/wrcr.20145.

Werner, M., J. Schellekens, R. Gijsbers, M. van Dijk, O. van den Akker, and K. Heynert (2013), The Delft-FEWS flow forecasting system, *Environ. Modell. Software*, *40*, 65–77, doi:10.1016/j.envsoft.2012.07.010.

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

Winstral, A., D. Marks, and R. Gurney (2013), Simulating wind-affected snow accumulations at catchment to basin scales, *Adv. Water Resour.*, *55*, 64–79, doi:10.1016/j.advwatres.2012.08.011.

Wood, E. F., M. Sivapalan, K. Beven, and L. Band (1988), Effects of spatial variability and scale with implications to hydrologic modeling, *J. Hydrol.*, *102*(1), 29–47, doi:10.1016/0022-1694(88)90090-X.

Wood, E. F., D. P. Lettenmaier, and V. G. Zartarian (1992), A land surface hydrology parameterization with sub grid variability for general circulation models, *J. Geophys. Res.*, *97*(D3), 2717–2728, doi:10.1029/91JD01786.

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

Zehe, E., H. Lee, and M. Sivapalan (2006), Dynamical process upscaling for deriving catchment scale state variables and constitutive relations for meso-scale process models, *Hydrol. Earth Syst. Sci.*, *10*, 981–996, doi:10.5194/hess-10-981-2006.