15 Forest Hydrology Modeling: Processes, Methods and Example Models

H.E. Golden[1]*, D.M. Amatya[2] and G. Sun[3]

[1]Office of Research and Development, Center for Environmental Measurement and Modeling, US Environmental Protection Agency, Cincinnati, Ohio, USA; [2]Santee Experimental Forest, Southern Research Station, USDA Forest Service, Cordesville, South Carolina, USA; [3]Eastern Forest Environmental Threat Assessment Center, USDA Forest Service, Research Triangle Park, North Carolina, USA

Abstract

This chapter provides a brief overview of why and how forest hydrological models are applied to answer important global research and management questions. It steps through physical functions that most forest hydrological models represent, how to best select the model for a particular goal, and how to think about model parameterization and calibration. Finally, a suite of example forest hydrology models focused on different model domains (i.e. plots, watersheds, groundwater and coupled surface–subsurface) are discussed.

15.1 Introduction

Characterizing and quantifying interactions among components of the forest hydrological cycle is complex and usually requires a combination of field monitoring and modeling approaches (Weiler and McDonnell, 2004; National Research Council, 2008). In the past decade, integrated watershed management approaches have required improved understanding of soil, vegetation, and water quality and quantity responses to disturbances such as wildland fires (Hallema *et al.*, 2018; Beyene *et al.*, 2021; Paul *et al.*, 2022; Povak *et al.*, 2022) and climate change (Zema and Lucas-Borja, 2022; Zhang *et al.*, 2022), as well as practices such as urban forestry (Department of Environmental Resources, 1999), green infrastructure (Ercolani *et al.*, 2018; Coville *et al.*, 2020), forest thinning (Lundquist *et al.*, 2013; Sun *et al.*, 2022) and reforestation (Li *et al.*, 2018; Peña-Arancibia *et al.*, 2019). Modern forest hydrological models are important tools for testing related hypotheses, understanding hydrological processes, filling knowledge gaps and synthesizing forest experimental data (Sun *et al.*, 2011; Komatsu and Kume, 2020). Sun *et al.* (2023) provided a recent, concise, integrative overview of the status of forest hydrological modeling.

A well-calibrated and verified model that incorporates the general principles of forest hydrology can supplement field measurements (e.g. Hydrograph Separation Program, HYSEP; Sloto and Crouse, 1996; Barlow *et al.*, 2015). In turn, these measurements can provide data to improve a model and its performance, particularly when long-term data become available (Tian *et al.*, 2012a; b). Forest hydrology models

*Corresponding author: golden.heather@epa.gov

 Forest Hydrology: Processes, Management and Assessment (eds Leon J. Bren *et al.*)
DOI: 10.1079/9781800625310.0015

can also simulate water quantity and quality in forested watersheds (i.e. catchments) and larger river basin scales with limited recorded measurements, such as stream discharge (Sivapalan, 2003), groundwater levels and evapotranspiration (ET) (Sun *et al*., 2011). Many forest hydrology models can also quantify forest biogeochemical cycling as well as surface-water quality in watersheds (DeWalle, 2003; Amatya *et al*., 2013; Nelitz *et al*., 2013), and all in response to modern pressures such as climate change and urbanization.

However, improved models that project the hydrological responses to forest management practices are needed (Amatya *et al*., 2011; Vose *et al*., 2011; Tian *et al*., 2012b; Komatsu and Kume, 2020). This requires a suite of approaches, incorporating decades of research, on the response of processes regulating hydrological dynamics to forest management (Jones *et al*., 2009; Buttle, 2011; Tian *et al*., 2012b). Forest hydrology models are a necessity to project beyond current hydrological conditions and from young stands to forests with full canopied watersheds (e.g. quantifying the effects of forest site preparation, forest growth and silvicultural techniques on the hydrological cycle). This involves simulating changes in components of the forest or the forest watershed's water balances, including runoff, ET, snow accumulation/melt, melting permafrost and the cumulative effects of these changes on stream, river and lake processes (Beckers *et al*., 2009; Sun *et al*., 2011; Tian *et al*., 2012a). Projecting such shifts in the forest hydrological cycle requires numerical modeling methods because of their ability to conduct time-stepped simulations of specific hydrological processes within a given domain and to scale data to broader spatial extents using physically or process-based approaches (National Research Council, 2007).

This chapter provides a brief overview of forest hydrological modeling for answering important global research and management questions. Many hundreds of hydrological models have been applied globally across multiple decades to represent and predict forest hydrological processes (Beckers *et al*., 2009; Amatya *et al*., 2013; Nelitz *et al*., 2013), and these have been comprehensively discussed in a recent review paper (Sun *et al*., 2023). The focus of this chapter is to highlight a sampling of these process-based models and approaches. We specifically focus on 'forest hydrology models': physically based simulation tools that quantify compartments of the forest hydrological cycle. Physically based models can be considered those that describe the conservation of mass, momentum and/or energy (Beckers *et al*., 2009). While we provide minimal emphasis on empirical modeling methods (those that use measured data to derive relationships between variables, e.g. linear regression models), these approaches can be embedded within physically based models.

We focus on the watershed scale, which includes multiple drainage areas ranging across various orders of magnitude (e.g. 0.1–1000 km^2), based on Golden *et al*. (2014) and consistent with Wei and Zhang (2011). Temporal scales of each model are associated with the time step the modeler selects to solve the governing equations within the model based on the specific processes of interest, typically hourly for streamflow hydrograph predictions and flow rates in urban settings, daily for most hydrological applications, monthly for forested and/or large-scale ecosystem models, and annually for the transient groundwater flow models.

15.2 Model Functionality and Complexity

Forest hydrology models can range in both functionality and complexity. Each model's functionality and complexity results, in part, from the hydrological processes embedded in the model's structure, the mathematical equations representing these processes, and how the spatial extent of the model domain is discretized (Beckers *et al*., 2009). These models also include the interactions among processes and across scales (Clark *et al*., 2017). Most models simulate, at minimum, a basic water balance that includes moisture inputs (e.g. rainfall, snow and/or snowmelt) and water flux outputs via ET including canopy and soil/understory evaporation and runoff as a combination of surface and subsurface flows (Fig. 15.1).

How the water balance and water fluxes are simulated and what are required as model inputs vary widely based on how models describe the hydrological processes at different spatial/temporal scales. Typically, many models consider

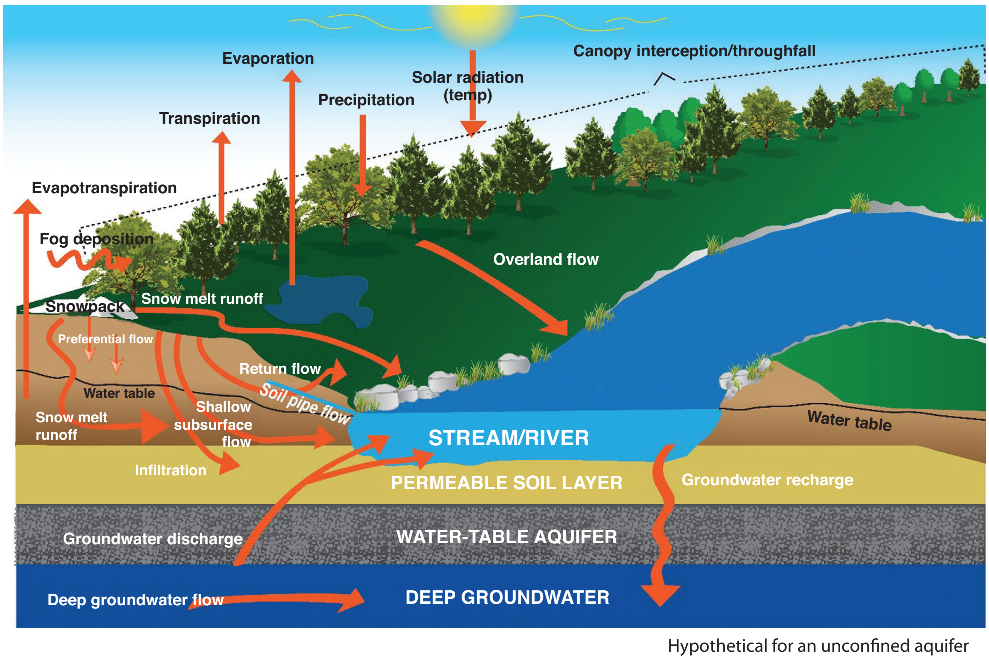

Fig. 15.1. Processes that can be modeled with forest hydrology simulation tools.

the forest ecosystem as mature (e.g. static), while other select models (e.g. DRAINMOD-FOREST; Tian *et al.*, 2012a) explicitly simulate forest physiological and phenological dynamics and how these dynamics affect a forest stand's water balance. Some models simulate the interactions among the soil, vegetation and atmosphere that affect the soil moisture dynamics and water-use efficiency of vegetation in forests (e.g. PnET-N-DNDC simulations of N_2O and NO emissions from forest soils; Li *et al.*, 2000; Stange *et al.*, 2000). Simulated outputs are diverse across models as well, but generally include peak flow, low flow, total streamflow/water yield, ET, and/or changes in soil moisture or groundwater table elevations over time.

15.2.1 Rainfall–runoff functions

The initiation of overland flow or subsurface flow in models that include rainfall–runoff dynamics on hillslope and river channels (i.e. 'watershed models') occurs when a threshold soil moisture level, such as soil field capacity, is reached. Each model calculates a threshold value and runoff-generating processes differently. Forest hydrology models will typically represent one (but sometimes more than one) of these runoff-generating processes, which might include variable source area (VSA) dynamics (e.g. TOPMODEL, Beven and Kirkby, 1979), the USDA Natural Resources Conservation Service curve number method (e.g. Soil and Water Assessment Tool, Neitsch *et al.*, 2011), Green-Ampt infiltration processes (e.g. Hydrologic Simulation ProgramFORTRAN (HSPF)), Hooghoudt's equation for subsurface drainage and Kirkham's equation for ponding conditions for shallow water table and drainage rates (e.g. DRAINMOD-FOREST, Tian *et al.*, 2012a), soil moisture response function (e.g. Visualizing Ecosystems for Land Management Assessment (VELMA), Abdelnour *et al.*, 2011), three-dimensional finite difference or linear reservoir approach for saturated zones, the two-dimensional Richard's equation or two-layer water balance models (e.g. MIKE SHE, Graham and Butts, 2005; Distributed Hydrology Soil Vegetation Model (DHSVM), Wigmosta *et al.*, 1994) or soil moisture balance

(Water Supply Stress Index (WaSSI), Sun *et al.*, 2011) approaches, depending on the temporal scale of simulation. Additional details on these processes are covered in associated chapters in this volume.

For forest hydrology models that explicitly simulate rainfall–runoff processes, runoff may be initiated in the model of interest via infiltration-excess runoff (Horton, 1933), saturation-excess overland flow (Dunne and Black, 1970), including VSA dynamics, or a combination of both overland flow types. Subsurface storm flow (Hursh and Brater, 1941), including preferential flows, may also be implemented in the model's water balance routine, as well as return flows (i.e. flow that travels through the shallow subsurface before reissuing to the land surface). Surface depressional storage capacity, Manning's overland surface runoff coefficient, land slope, and other landscape and surface/ litter vegetation characteristics are then used to store or route the excess rainfall after soil saturation to the nearest stream.

15.2.2 Evapotranspiration functions

To effectively model forest hydrological responses to changes in climate, management, fires and other land cover practices, ET must be simulated. Evapotranspiration of a forest ecosystem is the sum of canopy, soil, water litter and understory vegetation surface evaporation, as well as stand transpiration, and is a major component of the forest hydrological cycle (Sun *et al.*, 2016; Komatsu and Kume, 2020; Sun *et al.*, 2023). Plot and watershed models typically estimate subdaily, daily or monthly potential (as the upper limit of ET; Jovanovic and Israel, 2012) via one (or more) of three basic ET formulas: empirical Hamon (Hamon, 1963), energy-based Priestley–Taylor (Priestley and Taylor, 1972) and/or the fully process-based Penman–Monteith (McNaughton and Black, 1973), in order of their complexity. Recently, some traditionally non-forest watershed-scale models have used the ET process and ET-related parameters embedded in these formulations to expand representations of the forest hydrological cycle across commonly used watershed models (e.g. Soil and Water Assessment Tool (SWAT),Haas *et al.*, 2022a, b). Komatsu and Kume (2020) have provided a thorough background of how forest hydrologists have modeled ET through time.

15.2.3 Model parameterization

Depending on the study or management objectives, the complexity of the model and the forest composition, the number and breadth of parameters required to simulate key processes may vary substantially. In addition to several previously mentioned soil and runoff related parameters, parameters related to simulation of forest ET may include rooting depth and distribution, leaf area index, canopy density, canopy structure and interception capacity, stomatal or canopy conductance, and other biophysical characteristics including those that represent the understory type/species (additional details are included Chapter 3, this volume). A recent review of current hydrological models indicated that ET is not well quantified for forested watersheds due to lack of data related to vegetation-specific parameters (Sun *et al.*, 2023). Overall, a key modeling challenge is the availability and quality of spatially explicit data to help put values on model parameters (Clark *et al.*, 2017).

Anthropogenic processes may also be incorporated into the functionality of many forest hydrological models. Some models can project variations in hydrological processes in response to climate change, management scenarios, wildfire, insect and disease outbreaks, and shifts in land cover/land use. For example, studies have applied modeling approaches to project the effects of forest harvesting and management on peak flows in British Columbia (e.g. Whitaker *et al.*, 2003; Thyer *et al.*, 2004), portions of South America (Bathurst *et al.*, 2011; Birkinshaw *et al.*, 2011), China (Sun *et al.*, 2006; Cao *et al.*, 2021), north-western USA (Stednick, 2008; Abdelnour *et al.*, 2011; Yan *et al.*, 2021) and forest management practices in California (Cristea *et al.*, 2014), among others. In a synthesis study, Amatya *et al.* (2013) outlined eight criteria for an ideal forest hydrology model that can describe the impacts of forest fertilization on southern US forested landscapes.

15.2.4 Balancing model functionality and complexity

Model functionality and complexity go hand in hand: typically, the greater number of functions the model simulates, the more complex the model (Golden *et al.*, 2017). Forest hydrology models can vary considerably in complexity from simple empirical models (not discussed here) to process-based models that cover a range of low (Forest Hydrology Model (ForHyM), Arp and Yin, 1992) to medium (VELMA, Abdelnour *et al.*, 2011) to highly complex (e.g. HydroGeoSphere, Brunner and Simmons, 2012; MIKE SHE, Graham and Butts, 2005) hydrological representations: that is, from simple bucket-type models to models that implement multiple soil–water interactions and transport processes. Model complexity can also vary with spatial scale: highly complex and computationally intensive models often function best at finer spatial scales; as the spatial scale expands, the resolution of the modeled system necessarily needs to coarsen to decrease computational demands.

Forest hydrology process-based studies coupled with modeling approaches have most commonly been approached from a small watershed scale (National Research Council, 2008) using paired-watershed approaches (Von Stackelberg *et al.*, 2007) starting as early as 1909–1928 in North America (Bates and Henry, 1928). However, more recent studies have expanded their spatial scales toward the scale of management (e.g.large watersheds, regions, nations, globally) and have used generalizing principles derived from finer-scale studies.

Models can be discretized in different ways based on the model structure, the spatial scale of interest, and the management or research question. Typically, models are spatially discretized in one of three ways: lumped, semi-distributed or fully distributed. Spatially lumped models represent the model domain as one unit, without any heterogeneity in its characteristics (e.g.all soils and land cover are the same throughout the domain). Semi-distributed models carve the watershed into similarly functioning units, such as hydrological response units (similar combinations of land cover, soils and slope) (Neitsch *et al.*, 2011), field management units, subbasins or finite difference grids. Fully distributed models have varying parameters and processes across the model domain (Kampf and Burges, 2007; Arnold *et al.*, 2016). Forest hydrology models can also vary temporally, with some operating on a continuous time step (e.g. daily, monthly and/or annually).

15.3 Model Selection

A forest hydrology model is a simplification of reality. This is an important consideration when selecting the appropriate model for the forest hydrological management and/or research question being addressed. The current state of the science remains limited on insights into choosing the most appropriate spatial resolution to represent the hydrological processes of a specific system. Of utmost importance is the development of a perceptual hydrological model of the study area (i.e. a conceptualization of the forested watershed and its hydrological processes) (McMillan *et al.*, 2023), based on tying together information provided by spatial data based on remote sensing (e.g. light detection and ranging (LiDAR), Landsat, moderate resolution imagery spectroradiometer (MODIS)), a Geographic Information System (GIS), monitoring (e.g. precipitation, stream flow, snowpack depths), past modeling efforts and professional knowledge. This will help to: (i) determine the most important hydrological processes of the study area; (ii) select a model that can simulate these dominant processes; and (iii) determine whether the simplifying hydrological assumptions in the chosen model (e.g. spatial discretization – breaking the model into grids or subbasins or another spatial unit – and temporal resolution) is valid for the system (Golden *et al.*, 2017).

When selecting a model, various factors should be considered. For example, a lumped parameter model might be appropriate (compared with a spatially explicit model) where spatial heterogeneity is low or the spatial scale of the study area is broad (e.g. region, national), or there is a combination of the two. Model selection must also consider the management or research questions, the hydrological processes important to those questions and what future projections need to be simulated, such as climate change or forest management scenarios that vary in complexity.

Practical considerations for choosing a forest hydrology model include the modeling objective, input data needs and parameter availability, computational time and cost–benefits of model complexity. For example, most watershed-based forest hydrology models require an accurate digital elevation model and stream network layers as base data for watershed delineation and drainage network configuration, and spatial data on soils and land cover, in addition to measurements of hydrometeorological variables (e.g. precipitation, temperature), ET (e.g. eddy covariance flux, remote sensing), snowpack depths, water-table variations and streamflow measurements at the watershed outlet.

Depending on the study question, additional information may be needed. For example, water-level data from groundwater wells, piezometers and other surface-water features in the watershed (e.g. wetlands, lakes, dams) may be required to parameterize the model and quantify the full water balance. Furthermore, model set-up, implementation and spin-up (the initial period taken for the model to equilibrate) times, as well as the skill level required to execute the model, all increase with model complexity. Therefore, considering the balance of benefits associated with minimizing model uncertainty versus the increased computational intensity costs associated with added model complexity – including spatial, temporal and process complexity – is imperative (Dehotin and Braud, 2008; Clark *et al.*, 2015, 2017).

15.4 Model Diagnostics and Evaluation

Model evaluation needs to be conducted to determine whether a forest hydrology model is characterizing the system appropriately. In the most general sense, model calibration is a process by which model parameters are adjusted so that the simulated model output matches an observed set of data within a predefined acceptable range. Model parameters are often fitted using measured data or calibrated within reasonable ranges, as determined by the system and/or literature values when data are lacking. However, careful consideration of equifinality (Beven, 1993), which describes the process of arriving at the same simulated model output using a variety of different model parameter sets or structures – without knowing which one might be closest to 'reality' – is important.

Traditionally, watershed models are calibrated by varying parameter values so that simulated streamflow closely matches observed stream gauge data at the watershed outlet. However, models can be improved by also calibrating to spatially distributed observed water table depths, soil moisture, ET and other water balance components. In forest hydrology models that incorporate plant growth components, model calibration to measured leaf area index, total biomass, rooting depth and/or ecosystem productivity, alongside hydrological variables, will also improve the model.

Parameter estimation programs (e.g. PEST, Doherty and Johnston, 2003; OSTRICH, Matott, 2005) that generate best-fit parameter sets to match simulated results to observed data and assess accuracy based on one or more objective functions (optimization; Price *et al.*, 2012) should be selected to generate the best-fit parameter set to match simulated results to observed data (Boyle *et al.*, 2003). A multi-objective framework reduces the problems associated with calibrating to local objective function minima and avoids subjectivity and information loss in model acceptability criteria by simultaneously minimizing observed and simulated differences of multiple functions (Doherty and Johnston, 2003; Flerchinger *et al.*, 2012). Arnold *et al.* (2016) recommended a diagnostic approach that looks at signature patterns of behavior in the model outputs to determine which processes, and thus parameters, need further adjustment during calibration. In a companion study, Malone *et al.* (2015) developed parameterization guidelines and considerations for hydrological models. Additionally, McMillan *et al.* (2017) and Yan *et al.* (2023) provided guidelines for hydrological signatures that could be evaluated in this process.

Validation of the model outputs traditionally suggests the successful testing of simulated outputs against observed data using an input data set different from that of the calibration data set. A split-sample approach is one popular example whereby calibration and validation are conducted during a sequential set of years: one continuous set is used for calibration, the other for validation (Klemes, 1986). More recent work detailed obstacles involved in using split-sample approaches and argued for applying full data sets for calibration only, rather than splitting them with model validation (Arsenault *et al.*, 2018).

15.4.1 Uncertainty and sensitivity analysis

Uncertainties in forest hydrology models must be accounted for in some capacity. Model uncertainties can take the form of parameter uncertainties, input data uncertainties, process uncertainties and predictive uncertainties, among others. For example, McMillan *et al.* (2018) categorized hydrological model uncertainties into measurement, derived data, interpolation, scaling, and data management uncertainties. Whatever the focus is, the first step in uncertainty analysis typically involves quantifying simulation output uncertainty by propagating uncertainties throughout the model and generating a probabilistic distribution of simulated outputs. How uncertainties should be handled in hydrological modeling is a debate that has continued for decades (Matott *et al.*, 2009; Pianosi and Wagener, 2016; Herrera *et al.*, 2022), and new developments, such as those in the realm of Bayesian frameworks for uncertainty analyses, have widened the debate (Tasdighi *et al.*, 2018).

Beven and Young (2013) suggested that uncertainties in hydrological models can be aleatory (irreducible) or epistemic (reducible) in nature. Aleatory uncertainties are random and can be treated probabilistically in the model, while epistemic errors are associated with current lack of knowledge of processes operating within the system. Regardless of the form of uncertainties in the model, it is appropriate to detail the assumptions underlying these uncertainties and quantify them, where appropriate and feasible. Sensitivity analysis is one way of estimating the output uncertainties caused by changes in values model parameters. Sensitivity analysis can determine which parameters assert the most quantifiable control over model outputs, that is, the analysis can quantify which model parameters produce a change in simulated outputs based on incremental changes in a parameter values.

15.5 Examples of Forest Hydrology Models

We grouped our example forest hydrology models into three categories, each based on the model's focal domain: (i) plot and watershed models; (ii) groundwater models; and (iii) coupled surface–subsurface hydrology models. Stand-level models are a specific type of plot-scale model. While many models, with varying discretization approaches, can be applied to questions in forest hydrology (Fig. 15.2), here we expound on a handful of these.

Watershed models – also called catchment models or basin-scale models – refer to physically based models that simulate processes contributing to the forest hydrology water balance (e.g. surface and subsurface runoff, ET), including overland and channel routing to a surface-water system. Watershed models use topographically defined watersheds as boundaries and simulate surface and shallow subsurface processes. Unlike groundwater models, watershed models quantify groundwater as part of the watershed's water balance; the groundwater flow equation is not explicitly solved. Therefore, the deep groundwater system is considered a hydrological 'sink.' The contributions of lentic surface-water features such as lakes, ponds and wetlands to the water balance are also often not explicitly simulated.

Some watershed models exemplified here focus heavily on ecosystem processes, such as forest growth and productivity (e.g. DHSVM), while others are more hydrologically focused (e.g. TOPMODEL) without forest stand dynamics included. All watershed models exemplified here include some means of streamflow routing – from conceptual (e.g. all excess runoff is transported to the subbasin outlet to simple time of concentration) to more complex kinematic wave routing, so that streamflow at the watershed outlet can be simulated.

Groundwater models focus on solving groundwater flow equations specifically. Coupled surface–subsurface models (e.g. GSFLOW)

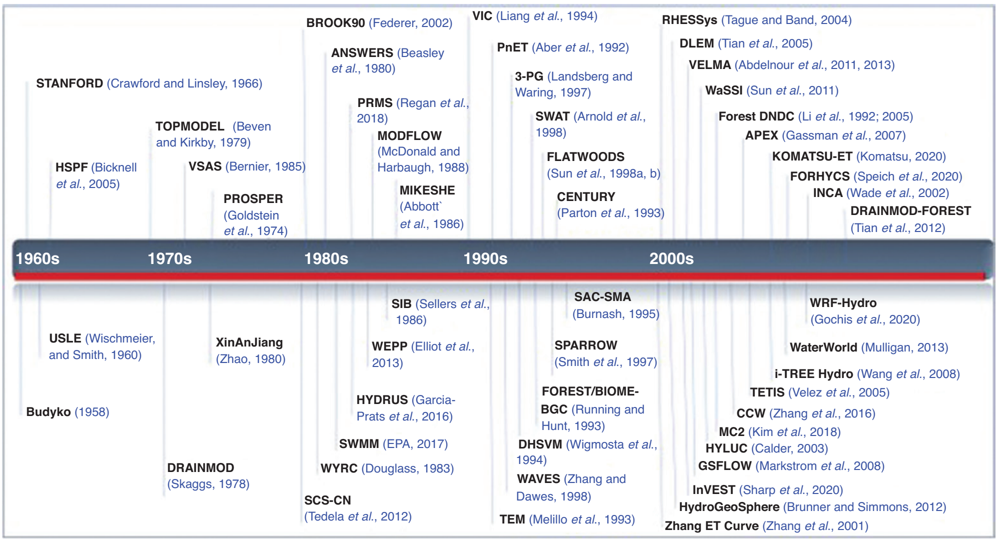

Fig. 15.2. A host of models can be applied to questions related to forest hydrology. We focus on a sample of these models. Modified from Sun *et al*. (2023).

are typically highly complex and involve both process-based surface and subsurface hydrological processes.

15.5.1 Plot and watershed models

PnET-BGC (Gbondo-Tugbawa *et al.*, 2001) and CENTURY (Parton *et al.*, 1993; Parton, 1996) are plot-scale models that simulate forest hydrological processes across a forest stand. PnET is a lumped parameter, monthly or daily time step, and stand-level (more generally called plot-scale) model that quantifies carbon and water dynamics in mature forests. Hydrological processes simulated by the PnET (photosynthetic/ET) model include canopy interception, plant transpiration, macropore flow, lateral flow and deep percolation to the aquifer. CENTURY is a plot-scale terrestrial biogeochemical model that operates at a monthly time step (Parton *et al.*, 1993; Parton, 1996). The model is composed of linked submodels representing forest production, grassland and crop production, soil organic matter and water balance. The simplified water balance submodel simulates monthly evaporation, transpiration, soil water content, snow water content and saturated flow between soil layers.

Several examples of watershed models that can be applied to forest hydrology include ForHyM (Arp and Yin, 1992; Meng *et al.*, 1995), TOPMODEL (Beven and Kirkby, 1979), iTree Hydro (Wang *et al.*, 2008), VELMA (Abdelnour *et al.*, 2011, 2013), Agricultural Policy/Environmental eXtender (APEX, Williams and Izaurralde, 2005; Gassman *et al.*, 2007), Precipitation-Runoff Modeling System (PRMS, Leavesley *et al.*, 1983, 2005), DHSVM (Wigmosta *et al.*, 1994, 2002), BROOK90 (Federer *et al.*, 2003), Variable Infiltration Capacity (VIC, Liang *et al.*, 1994, 1996), Integrated Nitrogen Catchment Model (INCA, Wade *et al.*, 2002), Forest-BGC (Running and Gower, 1991), Regional Hydro-Ecological Simulation System (RHESSys, Band *et al.*, 1993; Tague and Band, 2004) and WaSSI (Sun *et al.*, 2011; Caldwell *et al.*, 2012; Sun *et al.*, 2015). A brief synopsis of each is included below, and additional details are given in Table 15.1.

TOPMODEL is a semi-physically based flexible watershed hydrological mass balance modeling tool that is particularly robust in forested watersheds with shallow soils (Beven and Kirkby, 1979). Flow routing in TOPMODEL is driven by VSA dynamics and includes both saturated flow and infiltration-excess overland flow.

Table 15.1. Example plot-scale and watershed models for forest hydrology applications.

Model[a]	Hydrological approach	Simulation outputs: hydrology	Time steps	Spatial scale	Level of complexity[b]	Appropriate regions of application	Model files publicly accessible	Available online user manual and website[c]
iTree-Hydro	Six main routines for rainfall runoff processes: interception, impervious surface, soils, evaporation and transpiration, routing and pollution; uses time-area delay function or one-parameter diffusion-based exponential function for constructing downstream hydrograph	Streamflow, water balance	Daily	Multi-scale watersheds and plots (i.e. city or parcel)	Medium	Multiple: can be applied to watersheds with different rainfall–runoff mechanisms; recent cold region module development (version 2; Yang *et al.*, 2011)	Yes, by request	Yes; www.itreetools.org/hydro/
PnET (all)	Lumped-parameterized one-dimensional water balance model from canopy to soil	ET, watershed runoff	Daily to monthly	Plot to regional	Low	All forest ecosystem, both upland and lowland	Yes	Yes; www.pnet.sr.unh.edu/
CENTURY	Simplified water balance incorporating evapotranspiration, soil water content and saturated flow	Water routing from landscape with carbon, nitrogen, phosphorus and sulfur loadings	Monthly	Plot	Low	Temperate and tropical forests	Yes	Yes; www.nrel.colostate.edu/projects/century/
TOPMODEL	Semi-distributed rainfall-runoff model; variable source area dynamics but simulates both saturated excess and infiltration excess overland flows; assumes water table follows topography	Various water balance components including streamflow, overland flow (saturated and infiltration excess), subsurface flow, and return flow	Daily	Multi-scale watersheds	Medium	Multiple: typically best in systems with moderate to steep topography and shallow soils	Yes, as an ArcGIS extension, R Statistical Package code or the original code	Yes, in the dynamic TOPMODEL R statistical version: https://cran.r-project.org/web/packages/dynatop/index.html

Continued

Table 15.1. Continued

Model[a]	Hydrological approach	Simulation outputs: hydrology	Time steps	Spatial scale	Level of complexity[b]	Appropriate regions of application	Model files publicly accessible	Available online user manual and website[c]
VELMA	Spatially distributed ecohydrological model; simulates daily infiltration, evapotranspiration and surface/subsurface runoff through four soil layers	Various water balance components including streamflow, overland flow (saturated and infiltration excess), and subsurface flows through four user-defined soil layers	Daily	Multi-scale watersheds	Medium	Multiple: developed in small forested watersheds of Pacific north-west USA but applied/tested elsewhere	Yes	www.epa.gov/water-research/visualizing-ecosystem-land-management-assessments-velma-model
APEX	Curve number method (five options) and Green-Ampt infiltration (four options), subsurface drainage, and five options for PET for ET estimates	Precipitation, snowfall, interception, surface runoff, subsurface flow, snowmelt, irrigation, total water yield, PET, ET	Daily, monthly or annual	Field/small watershed, grid-based	Medium	Upland agricultural and forested fields or watersheds	Yes	Yes; https://epicapex.tamu.edu/ and http://epicapex.tamu.edu/apex/
PRMS	Semi-distributed processed-based rainfall–runoff model for multiple spatial and temporal scales	Various water balance components including evaporation, transpiration, runoff and infiltration, and considers the interaction with the forest/plant canopy, snowpack dynamics and soil hydrological processes	Daily to centuries	Multi-scale watersheds	Medium	Multiple	Yes	Yes; www.usgs.gov/software/precipitation-runoff-modeling-system-prms

Continued

Table 15.1. Continued

Model[a]	Hydrological approach	Simulation outputs: hydrology	Time steps	Spatial scale	Level of complexity[b]	Appropriate regions of application	Model files publicly accessible	Available online user manual and website[c]
DHSVM	Saturation-excess infiltration; Darcy's law for unsaturated and kinematic for saturated subsurface	Surface runoff, snow and snowmelt, soil moisture and ET, streamflow	Subdaily	Watershed	Medium	Applied worldwide across various climate regimes, although originally developed for mountainous terrains	Yes	Yes; www.pnnl.gov/projects/distributed-hydrology-soil-vegetation-model; GITHUB: https://github.com/pnnl/DHSVM-PNNL
BROOK90	One-dimensional water balance with canopy and multi-layer soil profile	Soil water content, overland flow, bypass flow from soil layers, groundwater flow	Daily	Plot	Low	Applied worldwide although designed for forests within north-east USA	Yes	Yes; www.ecoshift.net/brook/brook90.htm
VIC	Grid-cell based water balance with canopy, and three-layer soil profile	Watershed water balance, streamflow with accompanying routing model	Daily to monthly	Regional, global	Medium	Any, as intended to accompany large-scale general circulation models	Yes	https://vic.readthedocs.io/en/master/
INCA	Semi-distributed water balance with canopy, soil and riparian components	Streamflow, watershed water balance	Daily	Watershed	Medium	No limitations; applied extensively in Europe	No, commercial product	www.watres.com/software/INCA/
SWAT	Semi-distributed processed-based rainfall-runoff model for multiple spatial and temporal scales	Streamflow, watershed water balance	Daily	Watershed	Medium	Originally for agricultural watersheds but recent developments to improve forest parameterization	Yes	https://swat.tamu.edu/

Continued

Table 15.1. Continued

Model[a]	Hydrological approach	Simulation outputs: hydrology	Time steps	Spatial scale	Level of complexity[b]	Appropriate regions of application	Model files publicly accessible	Available online user manual and website[c]
WEPP and GeoWEPP	Distributed rainfall runoff and erosion simulation model	Runoff from field and plots, sediment delivery	Multiple	Hillslope and small watersheds (<2.6 km^2)	Medium	Managed forests, roads, wildfire areas	Yes	www.nrcs.usda.gov/resources/tech-tools/water-erosion-prediction-project, https://fargo.nserl.purdue.edu/geowepp/ and https://doc.wepp.cloud/
FOREST-BGC	One-dimensional water balance with forest canopy and soil surface	Outflow, ET	Daily	Watershed to regional	Medium	Any forest watersheds	Yes	https://daac.ornl.gov/OTTER/guides/Runnings_Forest_BGC_Model.html
BIOME BGC	Ecosystem model simulating hydrological across multiple scales based on one-dimensional water balance concepts	ET, soil water, snow depth, outflow	Daily	Multiple scale	Medium	Terrestrial ecosystem consisting of one or multiple biomes	Yes	www.umt.edu/numerical-terradynamic-simulation-group/project/biome-bgc.php
RHESSys	Semi-distributed water balance incorporating TOPMODEL, CENTURY, DHSVM and BIOME BGC	Streamflow, carbon, and nutrient dynamics at watershed outlet and within model components	Daily	Watershed	Medium	Mountainous watersheds	Yes	Yes; http://fiesta.bren.ucsb.edu/~rhessys/
WaSSI	Distributed by HUC-12 watersheds at the continental scale	Water yield, ET, ecosystem productivity, water supply stress index	Monthly	Watershed	Low	Continental	Yes	https://web.wassiweb.fs.usda.gov/

[a]See text for definitions of model names.
[b]Complexity levels refer to the balance of spatial and temporal model discretization, parameterization, and computational burden of the model. ‘High complexity’ means all complexity sources are demanding.
[c]All accessed 13 May 2025.
ET, evapotranspiration; PET, potential evapotranspiration.

iTree Hydro (previously called UFORE-Hydro; Wang *et al.*, 2008) is a physically based, semi-distributed urban forestry hydrological model that simulates runoff volume and water quality across different urban land covers. Simulations in iTree Hydro are at a daily time step and can operate at multiple watershed or plot (i.e. city, parcel) scales. A user can simulate the effects of various urban impervious and vegetation cover scenarios on the urban forest water balance, including interception, ET, infiltration and runoff.

The VELMA model is a fully distributed (i.e. it captures spatial variability in physical properties of a watershed) ecohydrological model initially developed for forested watersheds, particularly in the Pacific north-west USA (Abdelnour *et al.*, 2011; Abdelnour *et al.*, 2013). VELMA can simulate multiple parts of the forest hydrological cycle (e.g. daily infiltration and redistribution, ET, surface and subsurface runoff) using a four-layer soil column structure.

The semi-distributed APEX model (Williams and Izaurralde, 2005; Gassman *et al.*, 2007) was developed to evaluate land management impacts of hydrology, water and soil quality, and vegetation growth and competition in upland watersheds. The forestry version includes rainfall interception by canopy/litter, silvicultural practices and subsurface flow that includes deep percolation and lateral seepage using storage routing and pipe flow equations (Saleh *et al.*, 2004; Williams and Izaurralde, 2005).

PRMS is a semi-distributed processed-based watershed model that simulates components of the water balance, including evaporation, transpiration, runoff and infiltration, and quantifies interactions with the forest/plant canopy, snowpack dynamics and soil hydrological processes (Leavesley *et al.*, 1983; Leavesley *et al.*, 2005). PRMS has been applied across many landscape types and broad spatial scales. At broader spatial scales, PRMS is often calibrated in forested headwaters.

BROOK90 is a one-dimensional process-based hydrologic model that operates on a daily time step and was originally developed for forested watersheds in north-eastern USA (Federer *et al.*, 2003). The model includes components for interception by a single-layer canopy, snow accumulation and melt, direct evaporation from soil and snow, transpiration from a single-layer canopy and multi-layered soil, and multi-layered soil water movement.

DHSVM is a watershed-scale hydrological model that operates at subdaily time steps (Wigmosta *et al.*, 1994; Wigmosta *et al.*, 2002; Perkins *et al.*, 2019). The model is composed of seven modules representing ET, snowpack accumulation and melting, canopy snow interception and release, unsaturated subsurface flow, saturated subsurface flow, surface overland flow and channel flow. DHSVM is frequently applied to evaluate forest management hydrological effects across a variety of physiographical settings (Storck *et al.*, 1998; Bowling and Lettenmaier, 2001; Cristea *et al.*, 2014; Yan *et al.*, 2021; Sun *et al.*, 2022).

The VIC model is a macroscale hydrological model that operates at daily to monthly time steps; it complements global-scale general circulation models used for climate simulations and weather prediction (Liang *et al.*, 1994; Liang *et al.*, 1996). The model includes forest ET, canopy storage, surface and surface runoff, aerodynamic flux, and snow accumulation and melt.

INCA is a semi-distributed process-based watershed model that operates at a daily time step and is popularly used in Western European forested watershed studies (Whitehead *et al.*, 1998a, b; Wade *et al.*, 2002). The INCA hydrological module simulates soil moisture, storage and evaporation, topographic impacts on flow, and streamflow, and can be applied to assess the effects of forest management on watershed-scale hydrology and biogeochemical cycling.

SWAT, a widely used watershed-scale, semi-distributed model (Arnold *et al.*, 1998) originally developed for upland agricultural landscapes, has been tested, modified and updated for its application to large landscapes containing large portions of forest lands (von Stackelberg *et al.*, 2007; Watson *et al.*, 2009; Parajuli, 2010; Amatya and Jha, 2011), and has recently been improved for forested systems (Haas *et al.*, 2022a, b).

The Watershed Erosion Prediction Project (WEPP; Foster and Lane, 1987), its geospatial interface GeoWEPP (Renschler, 2003), and the most recent watershed-scale version (Brooks *et al.*, 2016; Lew *et al.*, 2022) focus on simulating the water balance and sediment delivery in hillslope and small watersheds (<36 km^2), areas within managed forests, along forests with roads and in wildfire areas, as well as rangelands and agricultural systems.

The FOREST-BGC model (Running and Gower, 1991) and its successors, such as the BIOME-BGC model (White *et al.*, 2000) and other BGC family models, are process-based, watershed-scale ecosystem-focused models that can be spatially aggregated and averaged to a per-unit area basis. FOREST-BGC's water balance is simulated at a daily time step and includes evaporation, transpiration, rainfall interception, throughfall, soil moisture, snow water equivalent depth and soil outflow of water.

RHESSys is a semi-distributed hydrological model that operates at a daily time step and is used to simulate mountainous watersheds (Band *et al.*, 1993; Tague and Band, 2004). The hydrological component of the model simulates atmospheric processes and soil hydrological and transport processes including vertical seepage, soil evaporation, lateral flow, and canopy radiative and moisture processes.

Finally, the WaSSI model is a relatively low-complexity, integrated, lumped parameter (limited spatial variations in physical characteristics within a subwatershed), semi-process-based model that solves water balances at broad spatial scales (Fig. 15.3) (Sun *et al.*, 2011, 2015; Caldwell *et al.*, 2012; Liu *et al.*, 2022). It operates on a monthly time step and simulates the full monthly water balance (ET, streamflow, ecosystem productivity and soil moisture storage) for each land cover class at a user-defined watershed scale.

15.5.2 Groundwater models

Groundwater models explicitly simulate groundwater table dynamics and flows, and are needed

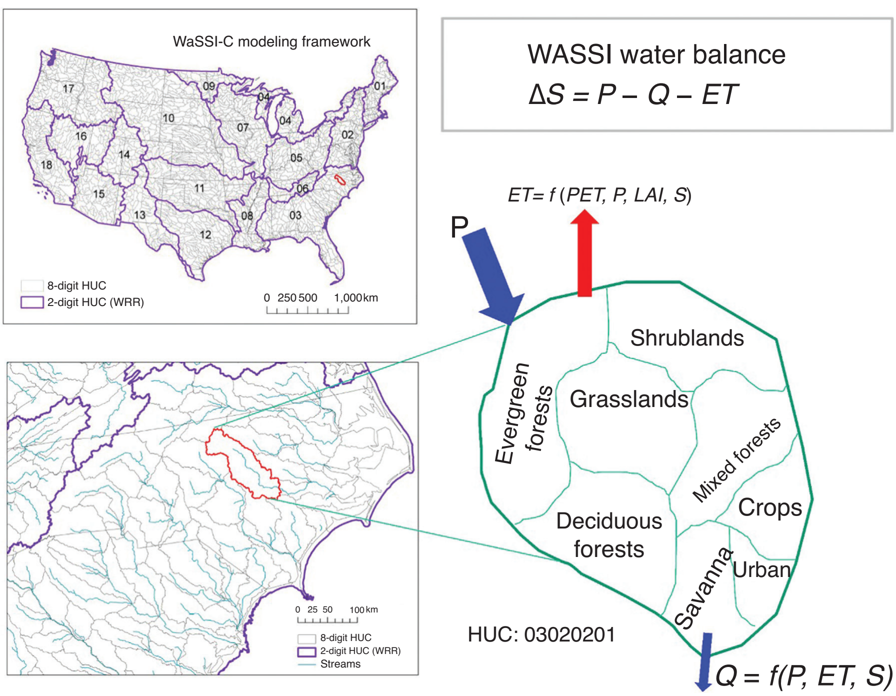

Fig. 15.3. WaSSI: an example of a relatively low-complexity, large-scale ecosystem model that can be applied to forest hydrology management and research questions. *ET*, evapotranspiration; HUC, hydrologic unit code (a watershed identifier); *LAI*, leaf area index; *P*, precipitation; *PET*, potential evapotranspiration; *Q*, watershed runoff; Δ*S*, change in water storage at the watershed scale; WRR, water resource region,

to answer research and management questions related to the movement and transport of subsurface flows and solutes through saturated porous media. Groundwater models are typically bounded by deep subsurface flow networks that reach across multiple watershed boundaries and use the groundwater flow equation (i.e. mass balance and Darcy's law) to estimate deep groundwater transport, which is based on relationships among hydraulic conductivity, specific yield, hydraulic gradient, fluid flow rates and the contributing model domain area. Surface-water flows and features (e.g. lakes, ponds, wetlands, streams, rivers) are not explicitly modeled in groundwater simulations and are considered boundary conditions. Two example groundwater models that could be used for simulating forest hydrological systems with a strong groundwater component are MIKE SHE (Abbott *et al.*, 1986a, b) and DRAINMOD-FOREST (Tian *et al.*, 2012a) (Table 15.2).

The MIKE SHE model (Abbott *et al.*, 1986a, b) is a physically based, fully distributed watershed-scale hydrological modeling system (without streamflow routing unless linked with the MIKE11 module) that was designed to describe the full hydrological cycle in a watershed. The model simulates the hydrological processes of canopy interception, soil evaporation, transpiration, infiltration, overland flow, unsaturated flow in soils, groundwater flow in aquifers and channel flows in rivers.

DRAINMOD-FOREST (Tian *et al.*, 2012a) is a field-scale, fully process-based and integrated model for simulating hydrology, soil carbon and nitrogen cycles, and vegetation growth in lowland forests under various climate conditions and silvicultural practices. Hydrological processes in DRAINMOD-FOREST are simulated on a daily or hourly basis and include ET, rainfall interception, infiltration, subsurface drainage, surface runoff, deep seepage and soil water dynamics in the unsaturated zone.

15.5.3 Coupled surface–subsurface hydrology models

Coupled surface–subsurface hydrology models are highly complex modeling systems that link surface and groundwater models by dividing surface and subsurface flow into different regions or domains, and solve the governing equations in each region using iterative solution methods (e.g. Markstrom *et al.*, 2008) or simultaneously solve the governing equations for surface and subsurface flows (e.g. Panday and Huyakorn, 2004). These models consider feedback among various components of the surface and subsurface water balances (e.g. runoff, groundwater flows and ET) and are thus extremely complex and computationally arduous. Two examples of such models that can be used to address forest hydrological management and research-related questions are HydroGeoSphere (Therrien *et al.*, 2010; Brunner and Simmons, 2012) and GSFLOW (Markstrom *et al.*, 2008) (Table 15.3).

HydroGeoSphere is a fully integrated, physically based numerical model that simulates, at a variety of time steps, coupled-surface (in two dimensions) and subsurface (in three dimensions) hydrological processes so that all primary components of the hydrological cycle are modeled (i.e. overland flow, streamflow, evaporation, transpiration, groundwater recharge, subsurface discharge into surface-water bodies) (Therrien *et al.*, 2010; Brunner and Simmons, 2012; Cornelissen *et al.*, 2014; de Schepper *et al.*, 2015).

GSFLOW is a high-complexity coupled surface–subsurface hydrological model that operates at a daily time step (Fig. 15.4) (Markstrom *et al.*, 2008). The model integrates the surface-water PRMS (Leavesley *et al.*, 1983; Leavesley and Stannard, 1995) and the Modular Groundwater Flow Model (MODFLOW) (Harbaugh *et al.*, 2000; Harbaugh, 2005). PRMS (Table 15.1) simulates land-surface hydrologic processes in ET, runoff, infiltration and interflow, plant canopy interception and storage, and snowpack. MODFLOW is a popular grid-based groundwater flow model that simulates three-dimensional saturated groundwater flow and storage, one-dimensional unsaturated flow, and groundwater interaction with streams.

15.5.4 Emerging modeling methods

Machine learning (ML) is a subfield of artificial intelligence that enables computers to recognize patterns and make predictions, and deep

Table 15.2. Examples of groundwater models for forest hydrology applications.

Model	Hydrological approach	Simulation outputs: hydrology	Time steps	Spatial scale	Level of complexity	Appropriate regions of application	Model files publicly accessible	Available online user manual and website
MIKE SHE	Fully distributed	ET, streamflow, soil moisture content, water table level	Subdaily, daily	Variable	High	All	No; this is a commercial product	Yes; http://www.mikepoweredbydhi.com/products/mike-she (accessed 13 may 2025)
DRAINMOD-FOREST	One-dimensional water balance of canopy, the soil surface and along a soil column	ET, outflow, soil water, seepage, water table level	Subdaily, daily	Field scale	Medium	Lowland	Yes	No

Complexity levels refer to the balance of spatial and temporal model discretization, parameterization and thereby computational burden of the model. High complexity means all complexity sources are demanding.
ET, evapotranspiration.

Table 15.3. Examples of coupled surface–subsurface models for forest hydrology applications.

Model	Hydrological approach	Simulation outputs: hydrology	Time steps	Spatial scales	Level of complexity	Appropriate regions of application	Model files publicly accessible	Available online user manual and website
HydroGeoSphere	Surface domain represented as two-dimensional overland flow; subsurface represented as three-dimensional unsaturated/saturated flow	All primary components of the hydrological cycle are modeled (i.e.overland flow, streamflow, evaporation, transpiration, groundwater recharge, subsurface discharge to surface-water bodies)	Daily to centuries	Multi-scale domains (e.g.plots, watersheds)	High	Multiple	No, this is a commercial product	No, but information can be found at: www.aquanty.com/hydrogeosphere/ (accessed 13 May 2025)
GSFLOW	Coupled surface and groundwater model; PRMS for surface; finite difference equation for subsurface	HRU water balance, streamflow, groundwater dynamics	Daily	Watershed, regional	High	Any	Yes	Yes; http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/GSFLOW.html (accessed 13 May 2025)

Complexity levels refer to the balance of spatial and temporal model discretization, parameterization and thereby computational burden of the model. High complexity means all complexity sources are demanding.
HRU, hydrological response unit; PRMS, Precipitation-Runoff Modeling System.

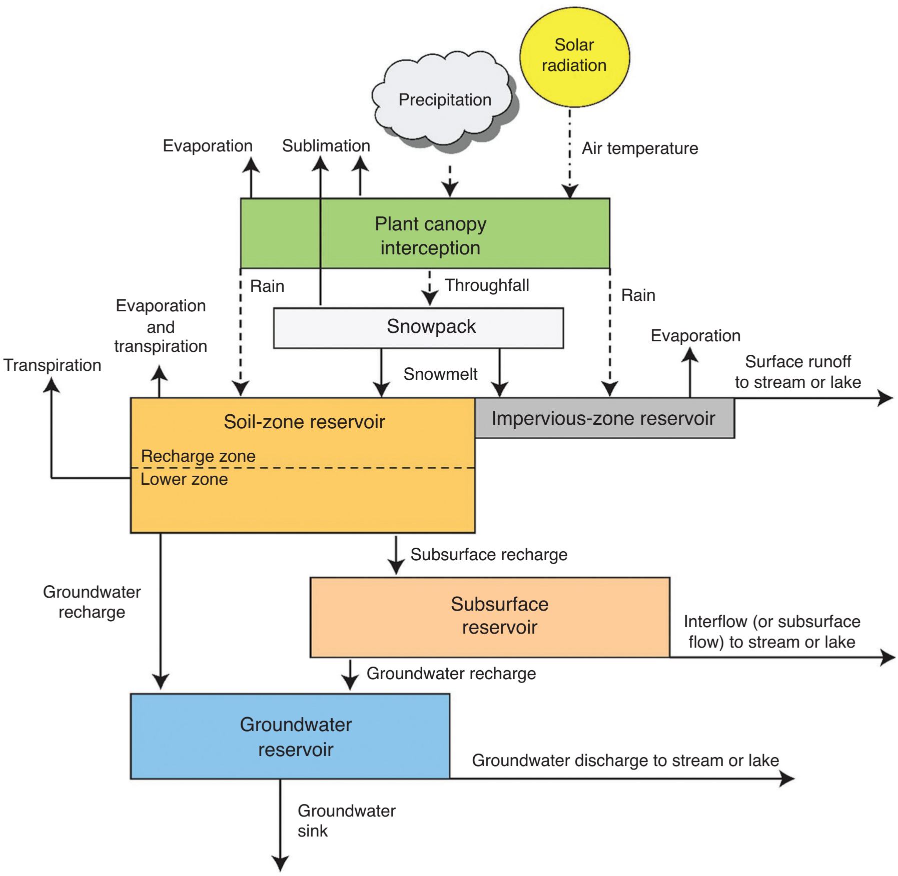

Fig. 15.4. GSFLOW model structure: an example of the complex coupled surface-subsurface modeling system. From Markstrom *et al*. (2008), with permission; S. Markstrom, US Geological Survey, personal communication (2015).

learning (DL) (LeCun *et al*., 2015) is a type of ML that applies neural networks with multiple layers to understand data patterns. While ML has gained popularity in multiple disciplines in the past decades, applications in hydrology span less than a decade (Lange and Sippel, 2020). The specific use of DL in hydrology has been even more recent (Shen, 2018; Shen *et al*., 2018; Gauch *et al*., 2021). However, DL is on a rapid upward trajectory in the hydrological sciences (Shen and Lawson, 2021).

Several ML modeling approaches have recently been applied to test hypotheses and pose questions regarding forest hydrological processes. For example, Schmidt *et al*. (2020) applied a combined neural network approach to estimate forest soil water content across space and time. Random forest applications have also been applied to estimate annual runoff in response to forest losses (Li *et al*., 2020), to predict inundation dynamics and hydroperiods (Riley and Stillwell, 2023), to understand woody wetland loss due to sea-level rise (He *et al*., 2023), to track forest soil moisture dynamics (in comparison with other ML methods; de Oliveira *et al*., 2021) and to transfer output, via a random forest-based tool, from a process-based model focused on forest thinning impacts on snowpack to other nearby forested watersheds (Krogh *et al*., 2020).

The prediction capacity of ML models often matches or goes beyond that of process-based models (Kratzert *et al*., 2019). The downside is that they provide lower interpretability regarding forest hydrological processes. To improve the interpretability of these modeling methods, process-guided DL has been introduced (Willard *et al.*, 2022). In this approach, the processes embedded in a physically based model can 'guide' the ML or DL model toward better process understanding for the modeler. Relatedly, explainable deep learning is another method to better understand drivers and patterns in DL models (Zhi *et al.*, 2024), such as that used to discover mechanisms causing flood patterns across the USA (Jiang *et al.*, 2022). Furthermore, emerging fusions of process-based models with DL methods, such as differentiable process-based models (Feng *et al.*, 2022; Shen *et al.*, 2023) and neural ordinary differential equations (Höge *et al.*, 2022), integrate the power of DL into process-based models for hydrological predictions.

Another major development for forest hydrological modeling has been integrating remotely sensed (satellite and airborne; optical or sensor) data into process-based forest hydrology models to better calibrate and 'capture' forest hydrological processes and related parameters, such as ET, leaf area index, canopy leaf temperature and albedo. Remote sensing enables viewing of large land expanses instantaneously and integrating heterogeneous landscapes at a range of spatial resolutions (Sass and Creed, 2011). Use of data such as remotely sensed ET from MODIS (Mu *et al.*, 2011) can be directly integrated into watershed ecohydrology models to improve their accuracy (Rajib *et al.*, 2018).

Overall, the rapid development of supercomputing, accessible 'big' spatial and temporal data stored – and being computed – across multiple cloud-based platforms, and remote-sensing technology is changing how we think about, and model, forest hydrological systems. However, distributed watershed forest hydrological modeling, which allows detailed representations of forest hydrological processes, has not kept pace: the developments have remained stable for over a decade since 2010 (Sun *et al.*, 2023). Therefore, given recent technological advances in data availability and computing platforms, there is still much room for growth in efficient forest hydrological modeling, potentially with reduced prediction uncertainties.

15.6 Conclusions

Forest hydrology models are important tools for developing a clearer understanding of the dominant hydrological processes of a forest stand or watershed (i.e. catchmen) and the process-based hydrological responses to future forest impacts, such as silvicultural practices, implementation of management activities and climate change, on water resources and other ecosystem services. These models can vary widely in complexity; therefore, clarity regarding research or management questions in addition to the conceptual hydrological model of the forest stand or watershed is imperative for model selection. Model evaluation, including uncertainty and sensitivity analyses, is a primary approach to determine whether hydrological processes of interest and/or importance in the modeled system are well characterized, ultimately reporting output variables of interest with quantified prediction uncertainties. With technological and high-speed computing developments in recent years, future forest hydrology modeling work will move further toward incorporating innovative remote sensing, ML, and geophysical and biogeochemical methods for improved parameterization and process understanding. Furthermore, empirical methods (e.g. tracer and isotopic studies for hydrograph separation) and statistical approaches should continue to be integrated into mechanistic modeling structures. Finally, the development of new, simplified, but physically based models might be most appropriate in some forested systems (Sidle *et al.*, 2011), improving our general understanding and guiding forest management.

15.7 Disclaimer

The views expressed in this chapter are those of the authors and do not necessarily represent the views or policies of the US Environmental Protection Agency and the US Department of Agriculture Forest Service.

References

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J. (1986a) An introduction to the European Hydrological System – Systeme Hydrologique European, "SHE", 1: History and philosophy of a physically-based, distributed modelling system. *Journal of Hydrology* 87, 45–59.

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J. (1986b) An introduction to the European Hydrological System – Systeme Hydrologique European, "SHE", 2: Structure of a physically-based, distributed modelling system. *Journal of Hydrology* 87, 61–77.

Abdelnour, A., Stieglitz, M., Pan, F. and McKane, R. (2011) Catchment hydrological responses to forest harvest amount and spatial pattern. *Water Resources Research* 47, e2024WR039854.

Abdelnour, A., McKane, R., Stieglitz, M., Pan, F. and Cheng, Y. (2013) Effects of harvest on carbon and nitrogen dynamics in a pacific-northwest forest catchment. *Water Resources Research* 49, 1292–1313.

Aber, J.D. and Federer, C.A. (1992) A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems. *Oecologia* 92, 463–474.

Amatya, D.M. and Jha, M.K. (2011) Evaluating SWAT model for a low gradient forested watershed in coastal South Carolina. *Transactions of the ASABE* 54, 2151–2163.

Amatya, D.M., Douglas-Mankin, K.R., Williams, T.M., Skaggs, R.W. and Nettles, J.E. (2011) Advances in forest hydrology: Challenges and opportunities. *Transactions of the ASABE* 54, 2049–2056.

Amatya, D.M., Rossi, C.G., Dai, Z., Williams, R., Saleh, A. *et al*. (2013) Review of nitrogen fate models applicable to forest landscapes in the Southern US. *Transactions of the ASABE* 56, 1731–1757.

Arnold, J.G., Srinivasan, R., Muttiah, R.S. and Williams, J.R. (1998) Large-area hydrological modeling and assessment: Model development. *Journal of the American Water Resources Association* 34, 73–89.

Arnold, J.G., Youssef, M.A., Yen, H., White, M.J., Sheshukov, A. *et al*. (2016) Hydrological processes and model representation: Impact of soft data on calibration. *Transactions of the ASABE* 58, 1637–1660.

Arp, P.A. and Yin, X. (1992) Predicting water fluxes through forests from monthly precipitation and mean monthly air temperature records. *Canadian Journal of Forest Research* 22, 864–877.

Arsenault, R., Brissette, F. and Martel, J.-L. (2018) The hazards of split-sample validation in hydrological model calibration. *Journal of Hydrology* 566, 346–362.

Band, L.E., Patterson, P., Nemani, R. and Running, S.W. (1993) Forest ecosystem processes at the watershed scale: Incorporating hillslope hydrology. *Agricultural and Forest Meteorology* 63, 93–126.

Barlow, P.M., Cunningham, W.L., Zhai, T. and Gray, M. (2015) *Groundwater Toolbox, A Graphical and Mapping Interface for Analysis of Hydrologic Data (Version 1.0) – User Guide for Estimation of Base Flow, Runoff, and Groundwater Recharge from Streamflow Data. Techniques and Methods, Book 3, Chapter B10*. US Geological Survey, US Department of Interior, Reston, Virginia.

Bates, C.G. and Henry, A.J. (1928) *Forest and Stream-flow Experiment at Wagon Wheel Gap, Colorado*. US Weather Bureau Monthly Weather Review, Supplement No. 30.

Bathurst, J.C., Birkinshaw, S.J., Cisneros, F., Fallas, J., Iroumé, A. *et al*. (2011) Forest impact on floods due to extreme rainfall and snowmelt in four Latin American Environments 2: Model analysis. *Journal of Hydrology* 400, 292–304.

Beasley, D.B., Huggins, L.F. and Monke, A. (1980) ANSWERS: A model for watershed planning. *Transactions of the ASAE* 23, 938–944.

Beckers, J., Smerdon, B. and Wilson, M. (2009) *Review of Hydrologic Forest Models for Forest Management and Climate Change Applications in British Columbia and Alberta*. FORREX Series Report No. 25. FORREX Forum for Research and Extension in Natural Resources Society, Kamloops, British Columbia, Canada.

Bernier, P.Y. (1985) Variable source areas and storm-flow generation: An update of the concept and a simulation effort. *Journal of Hydrology* 79, 195–213.

Beven, K. (1993) Prophecy, reality and uncertainty in distributed hydrological modeling. *Advances in Water Resources* 16, 41–51.

Beven, K. and Kirkby, M. (1979) A physically-based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin* 24, 43–69.

Beven, K. and Young, P. (2013) A guide to good practice in modeling semantics for authors and referees. *Water Resources Research* 49, 5092–5098.
Beyene, M.T., Leibowitz, S.G. and Pennino, M.J. (2021) Parsing weather variability and wildfire effects on the post-fire changes in daily stream flows: A quantile-based statistical approach and its application. *Water Resources Research* 57, e2020WR028029.
Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jobes, T.H. and Donigian, A.S. (2005) *Hydrological Simulation Program-Fortran: HSPF Version 12.2 User's Manual*. Environmental Research Laboratory Office of Research and Development, US Environmental Protection Agency, Athens, Georgia.
Birkinshaw, S.J., Bathurst, J.C., Iroumé, A. and Palacios, H. (2011) The effect of forest cover on peak flow and sediment discharge – An integrated field and modelling study in central–Southern Chile. *Hydrological Processes* 25, 1284–1297.
Bowling, L.C. and Lettenmaier, D.P. (2001) The effects of forest roads and harvest on catchment hydrology in a mountainous maritime environment. In: Wigmosta, M.S. and Burges, S.J. (eds) *Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas*. American Geophysical Union, Washington, D.C, pp. 145–164. DOI: 10.1029/WS002p0145.
Boyle, D.P., Gupta, H.V. and Sorooshian, S. (2003) Multicriteria calibration of hydrologic models. In: Duan, Q., H.V., Gupta., Sorooshian, S., Rousseau, A.N. and Turcotte, R. (eds) *Calibration of Watershed Models*. American Geophysical Union Publications, Washington, DC, pp. 185–196.
Brooks, E.S., Dobre, M., Elliot, W.J., Wu, J.Q. and Boll, J. (2016) Watershed-scale evaluation of the Water Erosion Prediction Project (WEPP) model in the Lake Tahoe Basin. *Journal of Hydrology* 533, 389–402.
Brunner, P. and Simmons, C.T. (2012) HydroGeoSphere: A fully integrated, physically based hydrological model. *Ground Water* 50, 170–176.
Burnash, R.J.C. (1995) The NWS river forecast system – catchment modeling. In: Singh, V.P. (ed.) *Computer Models of Watershed Hydrology*. Water Resources Publication, Littleton, Colorado, pp. 311–366.
Buttle, J.M. (2011) The effects of forest harvesting on forest hydrology and biogeochemistry. In: Levia, D.F., Tanaka, T. and Carlyle-Moses, D. (eds) *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions*. Springer, Dordrecht, Netherlands, pp. 659–677.
Calder, I.R. (2003) Assessing the water use of short vegetation and forests: Development of the Hydrological Land Use Change (HYLUC) model. *Water Resources Research* 39, 1318.
Caldwell, P.V., Sun, G., McNulty, S.G., Cohen, E.C. and Myers, M.J.A. (2012) Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US. *Hydrology and Earth System Sciences* 16, 2839–2857.
Cao, W., Zhang, Z., Liu, Y., Band, L.E., Wang, S. *et al*. (2021) Seasonal differences in future climate and streamflow variation in a watershed of Northern China. *Journal of Hydrology: Regional Studies* 38, 100959.
Clark, M.P., Fan, Y., Lawrence, D.M., Adam, J.C., Bolster, D. *et al*. (2015) Improving the representation of hydrologic processes in Earth System Models. *Water Resources Research* 51, 5929–5956.
Clark, M.P., Bierkens, M.F.P., Samaniego, L., Woods, R.A., Uijlenhoet, R. *et al*. (2017) The evolution of process-based hydrologic models: Historical challenges and the collective quest for physical realism. *Hydrology and Earth System Sciences* 21, 3427–3440.
Cornelissen, T., Diekkrüger, B., Bogena, H.R. (2014) Significance of scale and lower boundary condition in the 3D simulation of hydrological processes and soil moisture variability in a forested headwater catchment. *Journal of Hydrology* 516, 140–153.
Coville, R., Endreny, T. and Nowak, D.J. (2020) Modeling the impact of urban trees on hydrology. In: Levia, D.F., Carlyle-Moses, D.E., Iida, S., Michalzik, B., Nanko, K. *et al*. (eds) *Forest–Water Interactions*, Vol. 240. Ecological Studies, Springer, Cham, Switzerland, pp. 459–487.
Crawford, N.H. and Linsley, R.K. (1966) *Digital Simulation in Hydrology: Stanford Watershed Model IV*. Technical Report no.39. Department of Civil and Environmental Engineering, Stanford University, Stanford, California.
Cristea, N.C., Lundquist, J.D., Loheide, S.P., Lowry, C.S. and Moore, C.E. (2014) Modelling how vegetation cover affects climate change impacts on streamflow timing and magnitude in the snowmelt-dominated upper Tuolumne Basin, Sierra Nevada. *Hydrological Processes* 28, 3896–3918.

de Oliveira, V.A., Rodrigues, A.F., Vieira Morais, M.A., de Castro Nunes Santos Terra, M., Guo, L. *et al*. (2021) Spatiotemporal modelling of soil moisture in an Atlantic forest through machine learning algorithms. *European Journal of Soil Science* 72, 1969–1987.

de Schepper, G., Therrien, R., Refsgaard, J.C. and Hansen, A.L. (2015) Simulating coupled surface and subsurface water flow in a tile-drained agricultural catchment. *Journal of Hydrology* 521, 374–388.

Dehotin, J. and Braud, I. (2008) Which spatial discretization for distributed hydrological models? Proposition of a methodology and illustration for medium to large-scale catchments. *Hydrology and Earth System Sciences* 12, 769–796.

Department of Environmental Resources (1999) *Low-Impact Development Design Strategies; an Integrated Design Approach*. US Environmental Protection Agency Washington, DC. Available at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20004JX4.TXT (accessed 2 May 2025).

DeWalle, D.R. (2003) Forest hydrology revisited. *Hydrological Processes* 17, 1255–1256.

Doherty, J. and Johnston, J.M. (2003) Methodologies for calibration and predictive analysis of a watershed model. *Journal of the American Water Resources Association* 39, 251–265.

Douglass, J.E. (1983) The potential for water yield augmentation from forest management in the Eastern United States 1. *Journal of the American Water Resources Association* 19, 351–358.

Dunne, T. and Black, R.D. (1970) Partial-area contributions to storm runoff in a small New England watershed. *Water Resources Research* 6, 1296–1311.

Elliot, W.J. (2013) Erosion processes and prediction with WEPP technology in forests in the northwestern US. *Transactions of the ASABE* 56, 563–579.

EPA (US Environmental Protection Agency) (2017) *Storm Water Management Model Reference Manual Volume II – Hydraulics*. EPA/600/R-17/111. US Environmental Protection Agency, Washington, DC.

Ercolani, G., Chiaradia, E.A., Gandolfi, C., Castelli, F. and Masseroni, D. (2018) Evaluating performances of green roofs for stormwater runoff mitigation in a high flood risk urban catchment. *Journal of Hydrology* 566, 830–845.

Federer, C.A. (2002) BROOK 90: A simulation model for evaporation, soil water, and streamflow. Available at: www.ecoshift.net/brook/brook90.htm (accessed 13 May 2025).

Federer, C.A., Vorosmarty, C. and Fekete, B. (2003) Sensitivity of annual evaporation to soil and root properties in two models of contrasting complexity. *Journal of Hydrometeorology* 4, 1276–1290.

Feng, D., Liu, J., Lawson, K. and Shen, C. (2022) Differentiable, learnable, regionalized process-based models with multi-physical outputs can approach state-of-the-art hydrologic prediction accuracy. *Water Resources Research* 58, e2022WR032404.

Flerchinger, G.N., Caldwell, T.G., Cho, J. and Hardegree, S.P. (2012) Simultaneous heat and water (SHAW) model: Model use, calibration, and validation. *Transactions of the ASABE* 55, 1395–1411.

Foster, G.R. and Lane, L.J. (1987) *User Requirements: USDA-Water Erosion Prediction Project (WEPP)*. NSERL Report No.1. National Soil Erosion Research Laboratory, USDA ARS, West Lafayette, Indiana.

Garcia-Prats, A., Campo, A.D. and Pulido-Velazquez, M. (2016) A hydroeconomic modeling framework for optimal integrated management of forest and water. *Water Resources Research* 52, 8277–8294.

Gassman, P.W., Reyes, M.R., Green, C.H. and Arnold, J.G. (2007) The soil and water assessment tool: Historical development, applications, and future directions. *Transactions of the ASABE* 50, 1211–1250.

Gauch, M., Kratzert, F., Klotz, D., Nearing, G., Lin, J. *et al*. (2021) Rainfall–runoff prediction at multiple timescales with a single long short-term memory network. *Hydrology and Earth System Sciences* 25, 2045–2062.

Gbondo-Tugbawa, S.S., Driscoll, C.T., Aber, J.D. and Likens, G.E. (2001) Evaluation of an integrated biogeochemical model (PnET-BGC) at a Northern Hardwood Forest Ecosystem. *Water Resources Research* 37, 1057–1070.

Gochis, D.J., Barlage, M., Cabell, R., Casali, M., Dugger, A. *et al*. (2020) The WRF-Hydro® modeling system technical description (version 5.1.1). National Center for Atmospheric Research, Boulder, Colorado. Available at: https://ral.ucar.edu/projects/wrf_hydro/documentation/wrf-hydro-v511-documentation (accessed 13 May 2025).

Golden, H.E., Lane, C.R., Amatya, D.M., Bandilla, K.W., Raanan Kiperwas, H. *et al*. (2014) Hydrologic connectivity between geographically isolated wetlands and surface water systems: A review of select modeling methods. *Environmental Modelling and Software* 53, 190–206.

Golden, H.E., Creed, I.F., Ali, G., Basu, N.B., Neff, B.P. *et al*. (2017) Integrating geographically isolated wetlands into land management decisions. *Frontiers in Ecology and the Environment* 15, 319–327.

Goldstein, R.A., Mankin, J.B. and Luxmoore, R.J. (1974) *Documentation of PROSPER. A Model of Atmosphere–Soil–Plant Water Flow*. No. EDFB-IBP-73-9Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Graham, D.N. and Butts, M. (2005) Flexible, integrated watershed modeling with MIKE SHE. In: Singh, V.P. and Frevert, D.K. (eds) *Watershed Models*. CRC Press, Boca Raton, pp. 242–272.

Haas, H., Kalin, L. and Srivastava, P. (2022b) Improved forest dynamics leads to better hydrological predictions in watershed modeling. *Science of the Total Environment* 821, 153180.

Haas, H., Reaver, N.G.F., Karki, R., Kalin, L., Srivastava, P. *et al*. (2022a) Improving the representation of forests in hydrological models. *Science of the Total Environment* 812, 151425.

Hallema, D.W., Sun, G., Caldwell, P.V., Norman, S.P., Cohen, E.C. *et al*. (2018) Burned forests impact water supplies. *Nature Communications* 9, 1307.

Hamon, W.R. (1963) Computation of direct runoff amounts from storm rainfall. *International Association of Science Hydrology Publishing* 63, 52–62.

Harbaugh, A.W. (2005) *MODFLOW-2005, the US Geological Survey Modular Ground-water Model: The Ground-water Flow Process*. US Department of the Interior, US Geological Survey, Reston, Virginia.

Harbaugh, A.W., Banta, E.R., Hill, M.C. and McDonald, M.G. (2000) *MODFLOW-2000, The US Geological Survey Modular Ground-water Model: User Guide to Modularization Concepts and the Ground-water Flow Process*. US Geological Survey, Reston, Virginia.

He, K., Li, W., Zhang, Y., Sun, G., McNulty, S.G. *et al*. (2023) Identifying driving hydrogeomorphic factors of coastal wetland downgrading using random forest classification models. *Science of the Total Environment* 894: 164995.

Herrera, P.A., Marazuela, M.A. and Hofmann, R. (2022) Parameter estimation and uncertainty analysis in hydrological modeling. *WIREs Water* 9: e1569.

Höge, M., Scheidegger, A., Baity-Jesi, M., Albert, C. and Fenicia, F. (2022) Improving hydrologic models for predictions and process understanding using neural ODEs. *Hydrology and Earth System Sciences* 26, 5085–5102.

Horton, R.E. (1933) The role of infiltration in the hydrologic cycle. *Transactions of the American Geophysical Union* 14, 446–460.

Hursh, C.R. and Brater, E. (1941) Separating storm hydrographs from small drainage areas into surface and subsurface flow. *Transactions of the American Geophysical Union* 22, 863–871.

Jiang, S., Zheng, Y., Wang, C. and Babovic, V. (2022) Uncovering flooding mechanisms across the contiguous united states through interpretive deep learning on representative catchments. *Water Resources Research* 58, e2021WR030185.

Jones, J.A., Achterman, G.L., Augustine, L.A., Creed, I.F., Folliott, P.F. *et al*. (2009) Hydrologic effects of a changing forested landscape-challenges for the hydrological sciences. *Hydrological Processes* 23, 2699–2704.

Jovanovic, N. and Israel, S. (2012) Critical review of methods for the estimation of actual evapotranspiration in hydrological models. In: Irmak, A. (ed.) *Evapotranspiration: Remote Sensing and Modeling*. IntechOpen, London. Available at: www.intechopen.com/books/200 (accessed 2 May 2025).

Kampf, S.K. and Burges, S.J. (2007) A framework for classifying and comparing distributed hillslope and catchment hydrologic models. *Water Resources Research* 43, W05423.

Kim, J.B., Kerns, B.K., Drapek, R.J., Pitts, G.S. and Halofsky, J.E. (2018) Simulating vegetation response to climate change in the blue mountains with MC2 dynamic global vegetation model. *Climate Services* 10, 20–32.

Klemes, V. (1986) Operational testing of hydrological simulation models. *Hydrological Sciences Journal* 31, 13–24.

Komatsu, H. (2020) Modeling evapotranspiration changes with managing Japanese cedar and cypress plantations. *Forest Ecology and Management* 475, 118395.

Komatsu, H. and Kume, T. (2020) Modeling of evapotranspiration changes with forest management practices: A genealogical review. *Journal of Hydrology* 585, 124835.

Kratzert, F., Klotz, D., Shalev, G., Klambauer, G., Hockreiter, S. *et al*. (2019) Towards learning universal, regional, and local hydrological behaviors via machine learning applied to large-sample datasets. *Hydrology and Earth System Sciences* 23, 5089–5110.

Krogh, S.A., Broxton, P.D., Manley, P.N. and Harpold, A.A. (2020) Using process based snow modeling and lidar to predict the effects of forest thinning on the northern sierra nevada snowpack. *Frontiers in Forest and Global Change* 3, 21.

Landsberg, J.J. and Waring, R.H. (1997) A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management* 95, 209–228.

Lange, H. and Sippel, S. (2020) Machine learning applications in hydrology. In: Levia, D.F., Carlyle-Moses, D.E., Iida, S., Michalzik, B., Nanko, K. *et al*. (eds) *Forest-–Water Interactions*, Vol. 240. Ecological Studies, Springer, Cham, Switzerland, pp. 223–257.

Leavesley, G.H., Lichty, R.W., Troutman, B.M. and Saindon, L.G. (1983) *Precipitation-Runoff Modeling System; User's Manual*. Water-Resources Investigations Report 83-4238. US Geological Survey, Denver, Colorado. Available at: http://pubs.usgs.gov/wri/1983/4238/report.pdf (accessed 2 May 2025).

Leavesley, G.H. and Stannard, L.G. (1995) The precipitation-runoff modeling system PRMS. In: Singh, V.P. (ed.) *Computer Models of Watershed Hydrology*. Water Resources Publications, Highlands Ranch, Colorado, pp. 281–310.

Leavesley, G.H., Markstrom, S.L., Viger, R.J. and Hay, L.E. (2005) USGS modular modeling system (MMS) – precipitation-runoff modeling system (PRMS). In: Singh, V. and Frevert, D. (eds) *Watershed Models*. CRC Press, Boca Raton, Florida, pp. 159–177.

LeCun, Y., Bengio, Y. and Hinton, G. (2015) Deep learning. *Nature* 521, 436–444.

Li, C., Frolking, S. and Frolking, T.A. (1992) A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. *Journal of Geophysical Research: Atmospheres* 97, 9759–9776.

Li, C., Aber, J., Stange, F., Butterbach-Bahl, K. and Papen, H. (2000) A process-oriented model of N_2O and NO emissions from forest soils: 1. Model development. *Journal of Geophysical Research: Atmospheres* 105, 4369–4384.

Li, C., Trettin, C., Sun, G., McNulty, S. and Butterbach-Bahl, K. (2005) Modeling carbon and nitrogen biogeochemistry in forest ecosystems. In: Zhu, Z., Minami, K. and Xing, G. (eds) *3rd International Nitrogen Conference, 12–16 October 2004, Nanjing, China*, Science Press, Monmouth Junction, New Jersey, pp. 893–898.

Li, M., Zhang, Y., Wallace, J. and Campbell, E. (2020) Estimating annual runoff in response to forest change: A statistical method based on random forest. *Journal of Hydrology* 589, 125168.

Li, Y., Piao, S., Li, L.Z.X., Chen, A., Wang, X. *et al*. (2018) Divergent hydrological response to large-scale afforestation and vegetation greening in China. *Sciences Advances* 4, aar4182.

Lew, R., Dobre, M., Srivastava, A., Brooks, E.S. and Elliot, W.J. (2022) WEPPcloud: An online watershed-scale hydrologic modeling tool. Part I. Model description. *Journal of Hydrology* 608, 127603.

Liang, X., Lettenmaier, D.P., Wood, E.F. and Burges, S.J. (1994) A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research* 99, 415–528.

Liang, X., Wood, E.F. and Lettenmaier, D.P. (1996) Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification. *Global and Planetary Change* 13, 195–206.

Liu, N., Caldwell, P.V., Miniat, C.F., Sun, G., Duan, K. *et al*. (2022) *Quantifying the Role of National Forest System and Other Forested Lands in Providing Surface Drinking Water Supply for the Conterminous United States*. General Technical Report WO-100. US Department of Agriculture, Forest Service, Washington DC.

Lundquist, J.D., Dickerson-Lange, S.E., Lutz, J.A. and Cristea, N.C. (2013) Lower forest density enhances snow retention in regions with warmer winters: A global framework developed from plot-scale observations and modeling. *Water Resources Research* 49, 6356–6370.

Malone, R.W., Yagow, G., Baffaut, C., Gitau, M., Qi, Z. *et al*. (2015) Parameterization guidelines and considerations for hydrologic models. *Transactions of the ASABE* 58, 1681–1703.

Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E. and Barlow, P.M. (2008) *GSFLOW, coupled ground-water and surface-water flow model based on the integration of the precipitation-runoff modeling system (PRMS) and the modular ground-water flow model (MODFLOW-2005*), Chapter 1 of Section D, Ground-Water/Surface-Water, Book 6, Modeling Techniques. US Deptartment of the Interior, US Geological Survey, Reston, Virigina. Available at: http://pubs.usgs.gov/tm/tm6d1/pdf/tm6d1.pdf (accessed 2 May 2025).

Matott, L.S. (2005) *OSTRICH: An Optimization Software Tool, Documentation and User's Guide, Version 1.6*. University at Buffalo, Buffalo, New York. Available at: www.eng.buffalo.edu/~lsmatott/Ostrich/OstrichMain.html (accessed 2 May 2025).

Matott, L.S., Babendreier, J.E. and Purucker, S.T. (2009) Evaluating uncertainty in integrated environmental models: A review of concepts and tools. *Water Resources Research* 45, W06421.
McDonald, M.G. and Harbaugh, A.W. (1988) *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*. US Geological Survey, Reston, Virginia.
McMillan, H., Westerberg, I. and Branger, F. (2017) Five guidelines for selecting hydrological signatures. *Hydrological Processes* 31, 4757–4761.
McMillan, H., Westerberg, I.K. and Krueger, T. (2018) Hydrological data uncertainty and its implications. *WIREs Water* 5, e1319.
McMillan, H., Araki, R., Gnann, S., Woods, R. and Wagener, T. (2023) How do hydrologists perceive watersheds? A survey and analysis of perceptual model figures for experimental watersheds. *Hydrological Processes* 37, e14845.
McNaughton, K.G. and Black, T.A. (1973) A study of evapotranspiration from a Douglas fir forest using the energy balance approach. *Water Resources Research* 9, 1579–1590.
Melillo, J.M., McGuire, A.D., Kicklighter, D.W., Moore, B., Vorosmarty, C.J. *et al*. (1993) Global climate change and terrestrial net primary production. *Nature* 363, 234–240.
Meng, F.R., Bourque, C.P.A., Jewett, K., Daugharty, D. and Arp, P.A. (1995) The Nashwaak Experimental Watershed Project – analyzing effects of clearcutting on soil-temperature, soil-moisture, snowpack, snowmelt and stream-flow. *Water, Air, and Soil Pollution* 82, 363–374.
Mu, Q., Zhao, M. and Running, S. (2011) Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote Sensing of Environment* 115, 1781–1800.
Mulligan, M. (2013) WaterWorld: A self-parameterising, physically based model for application in data-poor but problem-rich environments globally. *Hydrology Research* 44, 748–769.
National Research Council (2007) *Models in Environmental Decision Making*. National Academies Press, Washington, DC.
National Research Council (2008) *Hydrologic Effects of a Changing Forest Landscape*. National Academies Press, Washington, DC. Available at: www.nap.edu/catalog/12223.html (accessed 2 May 2025).
Neitsch, S.L., Arnold, J.G., Kiniry, J.R. and Williams, J.R. (2011) *Soil and Water Assessment Tool: Theoretical Documentation Version 2009, TR-2011*. Texas Water Resources Institute, College Station, Texas.
Nelitz, M., Boardley, S. and Smith, R. (2013) *Tools for Climate Change Vulnerability Assessments for Watersheds*. PN 1494. ESSA Technologies Ltd, prepared for Canadian Council of Ministers of the Environment.
Panday, S. and Huyakorn, P.S. (2004) A fully coupled physically-based spatially-distributed model for evaluating surface/subsurface flow. *Advances in Water Resources* 27, 361–382.
Parajuli, P.B. (2010) Assessing sensitivity of hydrologic responses to climate change from forested watershed in mississippi. *Hydrologic Processes* 24, 3785–3797.
Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Gilmanov, T.G., Scholes, R.J. *et al*. (1993) Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. *Global Biogeochemical Cycles* 7, 785–809.
Parton, W.J. (1996) The CENTURY model. In: Powlson, D., Smith, P. and Smith, J. (eds) *Evaluation of Soil Organic Matter Models*. Springer, Berlin/Heidelberg, pp. 283–291.
Paul, M.J., LeDuc, S.D., Lassiter, M.G., Moorhead, L.C., Noyes, P.D. *et al*. (2022) Wildfire induces change in receiving waters: A review with considerations for water quality management. *Water Resources Research* 58, e2021WR030699.
Perkins, W.A., Duan, Z., Sun, N., Wigmosta, M.S., Richmond, M.C. *et al*. (2019) Parallel distributed hydrology soil vegetation model (DHSVM) using global arrays. *Environmental Modelling & Software* 122, 104533.
Peña-Arancibia, J.L., Bruijnzeel, L.A., Mulligan, M. and Dijk, A.I. (2019) Forests as 'pumps' and 'sponges': Assessing the impact of deforestation on dry-season flows across the tropics. *Journal of Hydrology* 574, 946–963.
Pianosi, F. and Wagener, T. (2016) Understanding the time-varying importance of different uncertainty sources in hydrological modelling using global sensitivity analysis. *Hydrological Processes* 30, 3991–4003.
Povak, N.A., Furniss, T.J., Hessburg, P.F., Salter, R.B., Wigmosta, M. *et al*. (2022) Evaluating basin-scale forest adaptation scenarios: Wildfire, streamflow, biomass, and economic recovery synergies and trade-offs. *Frontiers in Forests and Global Change* 5, 805179.

Price, K., Purucker, S.T., Kraemer, S.R. and Babendreier, J.E. (2012) Tradeoffs among watershed model calibration targets for parameter estimation. *Water Resources Research* 48, W10542.

Priestley, C.H.B. and Taylor, R.J. (1972) On assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review* 100, 81–92.

Rajib, A., Evenson, G.R., Golden, H.E. and Lane, C.R. (2018) Hydrologic model predictability improves with spatially explicit calibration using remotely sensed evapotranspiration and biophysical parameters. *Journal of Hydrology* 567, 668–683.

Regan, R.S., Markstrom, S.L., Hay, L.E., Viger, R.J., Norton, P.A. *et al*. (2018) Description of the national hydrologic model for use with the precipitation-runoff modeling system (PRMS). In: *Techniques and Methods*. Book 6, Chapter B9, US Geological Survey, Reston, Virginia. DOI: 10.3133/tm6B9. (accessed 2 May 2025).

Renschler, C.S. (2003) Designing geo-spatial interfaces to scale process models: The GeoWEPP approach. *Hydrological Processes* 17, 1005–1017.

Riley, J.W. and Stillwell, C.C. (2023) Predicting inundation dynamics and hydroperiods of small, isolated wetlands using a machine learning approach. *Wetlands* 43, 63.

Running, S.W. and Gower, S.T. (1991) Forest-BGC, a general-model of forest ecosystem processes for regional applications. 2. Dynamic carbon allocation and nitrogen budgets. *Tree Physiology* 9, 147–160.

Running, S.W. and Hunt, E.R., Jr (1993) Generalization of a forest ecosystem model for other biomes, BIOME-BGC, and an application for global-scale models. In: Ehleringer, J.R. and Field, C.B. (eds) *Scaling Physiological Processes: Leaf to Globe*. Academic Press, London, pp. 141–158.

Saleh, A., Williams, J.R., Wood, J.C., Hauck, L.M. and Blackburn, W. (2004) Application of Apex for forestry. *Transactions of the ASAE* 47, 751–765.

Sass, G.Z. and Creed, I.F. (2011) Bird's-eye view of forest hydrology: Novel approaches using remote sensing techniques. In: Levia, D.F., Carlyle-Moses, D. and Tanaka, T. (eds) *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions*. Springer, Dordrecht, Netherlands, pp. 45–68.

Schmidt, A., Mainwaring, D.B. and Maguire, D.A. (2020) Development of a tailored combination of machine learning approaches to model volumetric soil water content within a mesic forest in the Pacific Northwest. *Journal of Hydrology* 588, 125044.

Sellers, P., Mintz, Y., Sud, Y.E.A. and Dalcher, A. (1986) A simple biosphere model (SiB) for use within general circulation models. *Journal of the Atmospheric Sciences* 43, 505–531.

Sharp, R., Douglass, J., Wolny, S., Arkema, K., Bernhardt, J. *et al*. (2020) *InVEST 3.8.5 User's Guide*. The Natural Capital Project. Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Shen, C. (2018) A transdisciplinary review of deep learning research and its relevance for water resources scientists. *Water Resources Research* 54, 8558–8593.

Shen, C., Laloy, E., Elshorbagy, A., Albert, A., Bales, J. *et al*. (2018) Opinions: Incubating deep-learning-powered hydrologic science advances as a community. *Hydrology and Earth System Sciences* 22, 5639–5656.

Shen, C. and Lawson, K. (2021) Applications of deep learning in hydrology. In: Camps-Valls, G., Tuia, D., Zhu, X.X. and Reichstein, M. (eds) *Deep Learning for the Earth Sciences: A Comprehensive Approach to Remote Sensing, Climate Science, and Geosciences*. Wiley, Chichester, UK, pp. 283–297.

Shen, C., Appling, A.P., Gentine, P., Bandai, T., Gupta, H. *et al*. (2023) Differentiable modelling to unify machine learning and physical models for geoscience. *Nature Reviews Earth & Environment* 4, 552–567.

Sidle, R.C., Kim, K., Tsuboyama, Y. and Hosoda, I. (2011) Development and application of a simple hydrogeomorphic model for headwater catchments. *Water Resources Research* 47, W00H13.

Sivapalan, M. (2003) Prediction in ungauged basins: A grand challenge for theoretical hydrology. *Hydrological Processes* 17, 3163–3170.

Skaggs, R.W. (1978) *A Water Management Model for Shallow Water Table Soils*. Raleigh, North Carolina: Technical Report no.134. North Carolina State University, Water Resources Research Institute.

Sloto, R.A. and Crouse, M.Y. (1996) *HYSEP: A Computer Program for Streamflow Hydrograph Separation and Analysis. Water-Resources Investigations Report 96-4040*. US Geological Survey, Reston, Virginia. Available at: http://water.usgs.gov/software/HYSEP/ (accessed 2 May 2025).

Smith, R.A., Schwarz, G.E. and Alexander, R.B. (1997) Regional interpretation of water-quality monitoring data. *Water Resources Research* 33, 2781–2798.

Speich, M.J., Zappa, M., Scherstjanoi, M. and Lischke, H. (2020) FORests and hydrology under climate change in Switzerland v1. 0: A spatially distributed model combining hydrology and forest dynamics. *Geoscientific Model Development* 13, 537–564.

Stange, F., Butterbach-Bahl, K., Papen, H., Zechmeister-Boltenstern, S., Li, C. *et al*. (2000) A process-oriented model of N_2O and NO emissions from forest soils: 2. Sensitivity analysis and validation. *Journal of Geophysical Research: Atmospheres* 105, 4385–4398.

Stednick, J. (ed.) (2008) *Hydrological and Biological Responses to Forest Practices*, Ecological Studies, No. 190. Springer, New York.

Storck, P., Bowling, L., Wetherbee, P. and Lettenmaier, D. (1998) Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak stream flow in the Pacific Northwest. *Hydrological Processes* 12, 889–904.

Sun, G., Riekerk, H. and Comerford, N.B. (1998a) Modeling the hydrologic impacts of forest harvesting on Florida Flatwoods. *Journal of the American Water Resources Association* 34, 843–854.

Sun, G., Riekerk, H. and Comerford, N.B. (1998b) Modeling the forest hydrology of wetland-upland ecosystems in Florida. *Journal of the American Water Resources Association* 34, 827–841.

Sun, G., Zhou, G., Zhang, Z., Wei, X., McNulty, S.G. *et al*. (2006) Potential water yield reduction due to forestation across China. *Journal of Hydrology* 328, 548–558.

Sun, G., Caldwell, P., Noormets, A., Cohen, E., McNulty, S. *et al*. (2011) Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model. *Journal of Geophysical Research* 116, G00J05.

Sun, G., Caldwell, P.V. and McNulty, S.G. (2015) Modeling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States. *Hydrological Processes* 29, 5016–5030.

Sun, G., Domec, J.-C. and Amatya, D. (2016) Forest evapotranspiration: Measurements and modeling at multiple scales. In: Amatya, D.M., Williams, T.M., Bren, L. and Jong, C. (eds) *Forest Hydrology: Processes, Management and Assessment*. CAB International, Wallingford, UK, pp. 32–50.

Sun, G., Wei, X., Hao, L., Gonzalez Sanchis, M., Hou, L. *et al*. (2023) Forest hydrology modeling tools for watershed management: A review. *Forest Ecology and Management* 530, 120755.

Sun, N., Yan, H., Wigmosta, M.S., Lundquist, J., Dickerson-Lange, S. *et al*. (2022) Forest canopy density effects on snowpack across the climate gradients of the western United States mountain ranges. *Water Resources Research* 58, e2020WR029194.

Tague, C.L. and Band, L.E. (2004) RHESSys: Regional hydro-ecologic simulation system – An object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling. *Earth Interactions* 8, 1–42.

Tasdighi, A., Arabi, M., Harmel, D. and Line, D. (2018) A bayesian total uncertainty analysis framework for assessment of management practices using watershed models. *Environmental Modelling and Software* 108, 240–252.

Tedela, N.H., McCutcheon, S.C., Rasmussen, T.C., Hawkins, R.H., Swank, W.T. *et al*. (2012) Runoff curve numbers for 10 small forested watersheds in the mountains of the eastern United States. *Journal of Hydrologic Engineering* 17, 1188–1198.

Therrien, R., McLaren, R.G., Sudicky, E.A. and Panday, S.M. (2010) *HydroGeoSphere: A Three-dimensional Numerical Model Describing Fully-integrated Subsurface and Surface Flow and Solute Transport*. Groundwater Simulations Group, University of Waterloo, Waterloo, Ontario.

Thyer, M., Beckers, J., Spittlehouse, D., Alila, Y. and Winkler, R. (2004) Diagnosing a distributed hydrologic model for two high-elevation forested catchments based on detailed stand- and basin-scale data. *Water Resources Research* 40, W01103.

Tian, H.Q., Liu, M.L.S., Xu, X.F. and Lu, C.Q. (2005) *DLEM – The Dynamic Land Ecosystem Model, User Manual*. Ecosystem Science and Regional Analysis Laboratory, Auburn University, Auburn, Alabama.

Tian, M.A., Youssef, M.A., Skaggs, R.W., Amatya, D.M. and Chescheir, G.M. (2012a) DRAINMOD-FOREST: Integrated modeling of hydrology, soil carbon, and nitrogen dynamics, and plant growth for drained FOREST. *Journal of Environmental Quality* 41, 764–782.

Tian, M.A., Youssef, M.A., Skaggs, R.W., Amatya, D.M. and Chescheir, G.M. (2012b) Modeling water, carbon and nitrogen dynamics for two drained pine plantations under intensive management practices. *Forest Ecology and Management* 264, 20–36.

Vélez, J., Francés, F. and Vélez, I. (2005) TETIS: A catchment hydrological distributed conceptual model. *Geophysical Research Abstracts* 7, 03503.

Von Stackelberg, N.O., Chescheir, G.M., Skaggs, R.W. and Amatya, D.M. (2007) Simulation of the hydrologic effect of afforestation in the Tacuarembo River Basin, Uruguay. *Transactions of the ASABE* 50, 455–468.

Vose, J.M., Sun, G., Ford, C.R., Bredemeier, M., Otsuki, K. *et al*. (2011) Forest ecohydrological research in the 21st century: What are the critical needs? *Ecohydrology* 4, 146–158.

Wade, A., Durand, P., Beaujouan, V., Wessel, W., Raat, K. *et al*. (2002) A nitrogen model for European catchments: INCA, new model structure and equations. *Hydrology and Earth System Sciences* 6, 559–582.

Wang, J., Endreny, T.A. and Nowak, T.J. (2008) Mechanistic simulation of tree effects in an urban water balance model. *Journal of the American Water Resources Association* 44, 75–85.

Watson, B.M., McKeown, R.A., Putz, G. and MacDonald, J.D. (2009) Modification of SWAT for modelling streamflow from forested watersheds on Canadian boreal plain. *Journal of Environmental Engineering and Science* 7, 145–159.

Wei, A. and Zhang, M. (2011) A review on research methods for assessing the impacts of forest disturbance on hydrology at large-scale watersheds. In: Li, C., Lafortezza, R. and Chen, J. (eds) *Landscape Ecology and Forest Management: Challenges and Solutions in a Changing Globe*. Springer, New York, pp. 119–147.

Weiler, M. and McDonnell, J. (2004) Virtual experiments: A new approach for improving process conceptualization in hillslope hydrology. *Journal of Hydrology* 285, 3–18.

Whitaker, A., Alila, Y., Beckers, J. and Toews, D. (2003) Application of the distributed hydrology soil vegetation model to redfish Creek, British Columbia: Model evaluation using internal catchment data. *Hydrological Processes* 17, 199–224.

White, M.A., Thornton, P.E., Running, S.W. and Nemani, R.R. (2000) Parameterization and sensitivity analysis of the BIOME-BGC terrestrial ecosystem model: Net primary production controls. *Earth Interactions* 4, 1–85.

Whitehead, P., Wilson, E. and Butterfield, D. (1998a) A semi-distributed integrated nitrogen model for multiple source assessment in catchments (INCA): Part I – model structure and process equations. *Science of the Total Environment* 210, 547–558.

Whitehead, P., Wilson, E., Butterfield, D. and Seed, K. (1998b) A semi-distributed integrated flow and nitrogen model for multiple source assessment in catchments (INCA): Part II – Application to large river basins in South Wales and Eastern England. *Science of the Total Environment* 210, 559–583.

Wigmosta, M.S., Vail, L.W. and Lettenmaier, D.P. (1994) A distributed hydrology–vegetation model for complex terrain. *Water Resources Research* 30, 1665–1679.

Wigmosta, M.S., Nijssen, B., Storck, P. and Lettenmaier, D. (2002) The distributed hydrology soil vegetation model. In: Singh, V.P. and Frevert, D.K. (eds) *Mathematical Models of Small Watershed Hydrology and Applications*. Water Resources Publications, Littleton, Colorado, pp. 7–42.

Willard, J., Jia, X., Xu, S., Steinback, M. and Kumar, V. (2022) Integrating scientific knowledge with machine learning for engineering and environmental systems. *ACM Computing Surveys* 55, 1–37.

Williams, J.R. and Izaurralde, R.C. (2005) The APEX model. In: Singh, V.P. and Frevert, D.K. (eds) *Watershed Models*. CRC Press, Boca Raton, Florida, pp. 437–482.

Yan, H., Sun, N., Fullerton, A. and Baerwalde, M. (2021) Greater vulnerability of snowmelt-fed river thermal regimes to a warming climate. *Environmental Research Letters* 16, 054006.

Yan, H., Sun, N., Eldardiry, H., Thurber, T.B., Reed, P.M. *et al*. (2023) Large ensemble diagnostic evaluation of hydrologic parameter uncertainty in the community land model version 5 (CLM5). *Journal of Advances in Modeling Earth Systems* 15, e2022MS003312.

Wischmeier, W.H. and Smith, D.D. (1960) A universal soil-loss equation to guide conservation farm planning. In: *Transactions of the 7th International Congress of Soil Science, 14–24 August 1960, Madison, Wisconsin*. International Society of Soil Science, Madison, Wisconsin, pp. 418–425.

Yang, Y., Endreny, T.A. and Nowak, D.J. (2011) ITree-hydro: Snow hydrology update for the urban forest hydrology model. *Journal of the American Water Resources Association* 47, 1211–1218.

Zema, D.A. and Lucas-Borja, M.E. (2022) The impact of climate change on forest hydrology. In: *The Handbook of Environmental Chemistry*. Springer, Berlin/Heidelberg.

Zhang, L. and Dawes, W. (1998) WAVES – an integrated energy and water balance model. *CSIRO Land Water Technical Report* 31, 98.

Zhang, L., Dawes, W. and Walker, G. (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* 37, 701–708.

Zhang, M., Liu, S., Jones, J., Sun, G., Wei, X. *et al*. (2022) Managing the forest–water nexus for climate change adaptation. *Forest Ecology and Management* 525, 120545.

Zhang, Y., Song, C., Sun, G., Band, L.E., McNulty, S. *et al*. (2016) Development of a coupled carbon and water model for estimating global gross primary productivity and evapotranspiration based on eddy flux and remote sensing data. *Agricultural and Forest Meteorology* 223, 116–131.

Zhao, R. (1980) The Xinanjiang model. In: *Proceedings of the Oxford Symposium on Hydrological Forecasting*, IAHS Publication 129, pp. 351–356.

Zhi, W., Appling, A.P., Golden, H.E., Podgorski, J. and Li, L. (2024) Deep learning for water quality. *Nature Water* 2, 228–241.