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9 Hydrological Modelling in Forested Systems

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9.1 Introduction

Characterizing and quantifying interactions among components of the forest hydrological cycle is complex and usually requires a combination of field monitoring and modelling approaches (Weiler and McDonnell, 2004; National Research Council, 2008). Models are important tools for testing hypotheses, understanding hydrological processes and synthesizing experimental data (Sun *et al.*, 1998, 2011). A well-calibrated 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) and, in turn, these measurements can provide data to improve a model and its performance. Forest hydrology models can also project water quantity and quality in catchments with limited recorded measurements, such as stream discharge (Sivapalan, 2003) and water balances at broad spatial scales (Sun *et al.*, 2011). Many forest hydrology models can also quantify forest biogeochemical cycling as well as surface water quality in catchments (DeWalle, 2003; Nelitz *et al.*, 2013).

There are increasing demands for improved hydrological models that project the hydrological responses to forest management practices (National Research Council, 2008; Amatya *et al.*, 2011; Vose *et al.*, 2011). This requires a suite of approaches that incorporate decades of research on the processes regulating transfers of water in forests and hydrological responses to forest management (Jones *et al.*, 2009; Buttle, 2011). Forest hydrology models are a necessity to project beyond current hydrological conditions from young stands to forests with full canopied catchments (e.g. quantifying the effects of forest site preparation, forest growth and silvicultural techniques on the hydrological cycle). Many forest hydrology models can also be applied to query how management, climate change and/or other land cover changes together affect the forest hydrological cycle and link physical and hydrological processes at the stand scale to that of the whole catchment. This involves projecting changes in components of the forest or forest catchment's water balances, including runoff, evapotranspiration, 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). Projecting such shifts in the forest hydrological cycle requires numerical modelling methods

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because of their ability to conduct time-stepped simulations of specific hydrological processes and scale data to broader spatial extents using physically or process-based approaches (National Research Council, 2007).

This chapter provides a brief overview of forest hydrology modelling approaches 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; Nelitz *et al.*, 2013; Amatya *et al.*, 2014). The focus of this chapter is on process-based models and approaches, specifically 'forest hydrology models'; that is, 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 modelling methods, these approaches can be embedded within physically based models. For example, runoff from a parcel of land may be calculated using the USDA Natural Resources Conservation Service curve number method, an empirical approach for estimating rainfall–runoff responses based on combinations of soil, land cover and slope characteristics of a land parcel. While some modelling approaches we discuss are appropriate at the plot or stand scale, many are considered within the context of catchments. We consider the catchment scale to include multiple drainage areas ranging across various orders of magnitude (e.g. 0.1 km^2 to 1000 km^2), based on Golden *et al.* (2014), which is also consistent with Wei and Zhang (2011). Temporal scales of each model are associated with the time step the modeller selects to solve the governing equations within the model, typically hourly for streamflow hydrograph predictions, daily or monthly for large-scale ecosystem models and annually for the transient groundwater flow models.

9.2 Model Functionality and Complexity

Forest hydrology models can range in functionality and complexity. Each model's functionality results, in part, from the hydrological processes represented in the model, the mathematical equations expressed in these processes and how the spatial extent of the model domain is discretized (Beckers *et al.*, 2009). Most models simulate, at minimum, a basic water balance that includes moisture inputs (e.g. rainfall, snow and/or snowmelt) and outputs via evapotranspiration including canopy evaporation and runoff as a combination of surface and subsurface flows (Fig. 9.1). How the water balance is calculated varies widely based upon the complexity and spatial/temporal scale of the model. Simulated outputs are diverse across models as well, but generally include peak flow, low flow, total streamflow/water yield, evapotranspiration and/or changes in soil moisture over time.

9.2.1 Forest stand and soil moisture functions

Representation of forest hydrological processes is also diverse across different models. Typically, many models consider the forest ecosystem as mature (e.g. static) while other selected models (e.g. DRAINMOD-FOREST; Tian *et al.*, 2012) 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).

The majority of forest hydrology models require a numerical approach for estimating soil moisture dynamics, which are a key component of regulating evapotranspiration rates (often estimated by empirical methods such as the Priestly–Taylor, Hamon or Penman–Monteith approach for potential evapotranspiration (as the upper limit of evapotranspiration)) and rainfall–runoff processes at the catchment scale. Soil moisture conditions in forests reflect the water balances that are controlled by precipitation inputs (e.g. direct rainfall, throughfall, snow/snowmelt), evapotranspiration, the forest's soil water-storage capacity, other physical soil properties such as effective porosity, bulk density and

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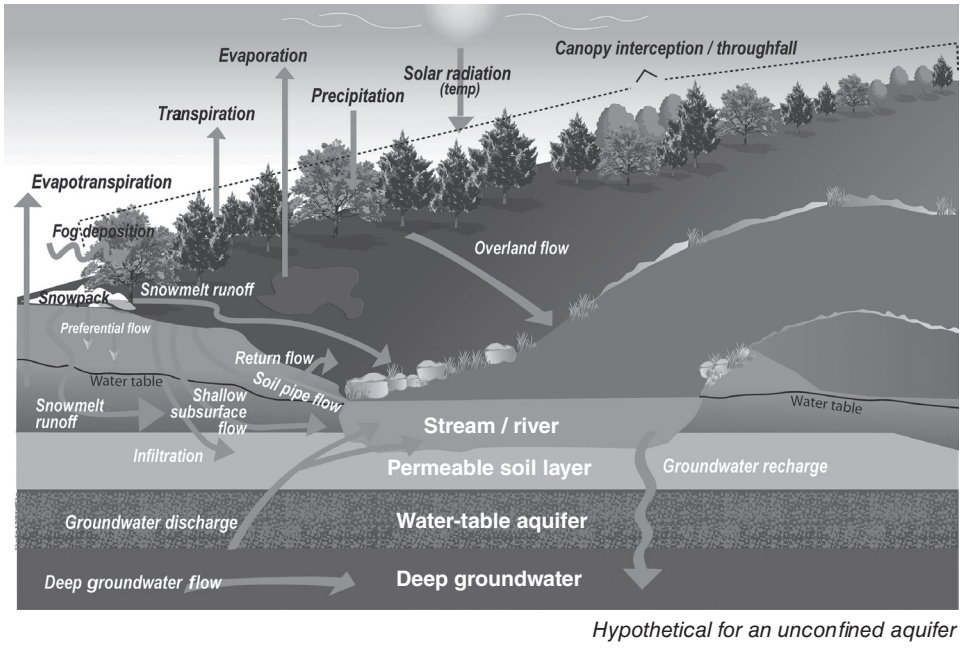

Fig. 9.1. Processes that can be modelled with forest hydrology simulation tools.

saturated hydraulic conductivity, and water table dynamics. Evaporation from the canopy interception and evapotranspiration rates are also controlled by leaf area index (LAI), canopy storage capacity and stomatal conductance, in addition to the soil moisture and climatic parameters. These time-varying soil moisture conditions and evapotranspiration rates are typically represented by a series of partial differential equations for different soil layers with variables (e.g. precipitation, canopy and soil/litter evaporation, evapotranspiration, flow inputs and outputs) that are calculated at the same time step.

9.2.2 Rainfall–runoff functions

The initiation of overland flow or subsurface flow in models that include rainfall–runoff dynamics (i.e. 'catchment 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 that 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. HSPF), Hooghoudt's equation for shallow water table and drainage rates (e.g. DRAINMOD-FOREST; Tian *et al.*, 2012), soil moisture response function (e.g. VELMA; Abdelnour *et al.*, 2011) or soil moisture balance (WaSSI; Sun *et al.*, 2011) approaches, depending upon the temporal scale of simulation. Additional details on these processes are covered in Chapters 4, 6 and 8 (this volume).

For forest hydrology models that explicitly simulate rainfall–runoff processes, once runoff is initiated, several primary catchment-scale flowpath types could be represented in the model of interest. Surface runoff will likely include 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 stormflow (Hursh and Brater, 1941), including preferential flows, may also be implemented in the model's water balance routine, as well as return flows

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(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 route the excess rainfall after soil saturation to the nearest stream. Depending on the model's structure, deep groundwater flow, which produces baseflow in the study catchment's stream network, is calculated as part of the water balance (i.e. the surplus from water percolated to the deep bedrock and groundwater storage) or, in the cases where groundwater models or coupled surface–subsurface models are applied, the groundwater flow equation (i.e. the mathematical representation of groundwater flow through an aquifer) is solved explicitly using various soil hydraulic properties, particularly hydraulic conductivity. Several forest hydrology models calculate channel flow routing times to the catchment outlet once surface and subsurface runoff reaches the stream (e.g. SWAT). This is estimated using variables such as channel water levels, velocities, channel geometry and Manning's roughness coefficient.

9.2.3 Parameterization of functions

Depending upon the study or management objectives, 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 parameters related to soil and runoff, parameters related to simulation of forest evapotranspiration may include rooting depth and distribution, LAI, canopy density, canopy structure and interception capacity, stomatal or canopy conductance, and other biophysical characteristics including those that represent the understorey type/species (additional details are included in Chapter 3, this volume). 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 modelling approaches to project the effects of forest harvesting and management on peak flows in British Columbia (Whitaker *et al.*, 2003; Schnorbus and Alila, 2004; Thyer *et al.*, 2004), portions of South America (Bathurst *et al.*, 2011; Birkinshaw *et al.*, 2011), China (Sun *et al.*, 2006), the north-western USA (Stednick, 1996, 2008; Schnorbus and Alila, 2004; Abdelnour *et al.*, 2011), among others. In a recent synthesis study, Amatya *et al.* (2014) outlined eight criteria for an ideal forest hydrology model that can describe impacts of forest fertilization on southern US forest landscapes. Model functionality may focus more strongly on glacial, tundra and permafrost processes, such as glacier melt (e.g. PREVAH; Viviroli *et al.*, 2009) and permafrost (e.g. Variable Infiltration Capacity (VIC) model; Liang *et al.*, 1994), and responses of these processes to anthropogenic changes. Further, some models have been developed and tested in mountainous systems where snowfall and snowmelt dynamics dominate (e.g. TOPMODEL; Hornberger *et al.*, 1994; Buytaert and Beven, 2011). Additional models better represent hydrological processes of low-gradient forest systems and/or where humid subtropical environments dominate (e.g. FLATWOODS, Sun *et al.*, 1998; DRAINMOD, Amatya and Skaggs, 2001; DRAINMOD-FOREST, Tian *et al.*, 2012).

9.2.4 Balancing model functionality and complexity

Model functionality and complexity go hand in hand: typically, the greater the number of functions the model simulates, the more complex the model. 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 (ForHYM; Arp and Yin, 1992) to medium (VELMA; Abdelnour *et al.*, 2011) to highly complex (e.g. HydroGeoSphere; Brunner and Simmons, 2012) hydrological representations; that is, from simple bucket-type models to models that implement multiple water 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, resolution of the modelled system necessarily

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needs to coarsen to decrease computational demands. Forest hydrology process-based studies coupled with modelling approaches have most commonly been approached from a small catchment scale (National Research Council, 2008) using paired catchment approaches (von Stackelberg *et al.*, 2007) starting as early as 1909 to 1928 in North America (Bates and Henry, 1928). However, more recent studies have expanded their spatial scales towards the scale of management (e.g. large catchments, regions, nations, globally) and used generalizing principles derived from finer-scale studies. As such, based on the model structure, the spatial scale of interest and the management or research question, models can be discretized in different ways (e.g. by hydrological response units, sub-basins, finite difference grids) and parameters and processes can be spatially characterized as lumped (parameters and processes are generalized across space), semi-distributed (areas of the catchment are 'lumped' based on different physical characteristics such as land cover and soils) or distributed (parameters and processes vary spatially across the modelled system) (Kampf and Burges, 2007; Arnold *et al.*, 2015). Forest hydrology models can vary temporally, with some operating on a continuous time step (e.g. daily, monthly and/or annually).

9.3 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. The current state-of-the-science remains limited on insights to choosing the most appropriate spatial resolution to represent hydrological processes of a specific system. Of utmost importance is developing a conceptual hydrological model of the study area based on spatial data (e.g. remote sensing (LiDAR), GIS), monitoring (e.g. streamflow, snowpack depths, temperature and humidity data, evapotranspiration, well- and piezometer-level measurements), and past modelling efforts and professional knowledge 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 and resolution) are valid for the system. For example, if a catchment's soils exhibit low infiltration capacity or precipitation rates exceed infiltration rates, a Hortonian rainfall–runoff model might be appropriate (Downer *et al.*, 2002). However, Hortonian flows rarely occur in fully forested conditions. Moreover, a lumped parameter model might be appropriate (compared with a spatially explicit model) where spatial heterogeneity is low, the spatial scale of the study area is broad (e.g. region, national), or 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 input data needs and parameter availability, computational time and cost–benefits of model complexity. For example, most catchment-based forest hydrology models require an accurate digital elevation model (DEM) and stream network layers as base data, in addition to measurements of hydrological processes (e.g. precipitation, temperature and relative humidity from meteorological station or modelled data); evapotranspiration (e.g. using water budget measurements, water vapour transfer methods, remote sensing, etc.); snowpack depths; water table variations); and downstream streamflow measurements (e.g. a stream gauge). Depending on the study question, water level data from groundwater wells, piezometers and other surface water features in the catchment (e.g. wetlands, lakes, dams) to better parameterize the model and quantify the full water balance are important. Further, model set-up, implementation and spin-up (the period taken for the model to equilibrate under the forcing, typically precipitation and temperature conditions) times – as well as the skill level required to execute the model – all increase with model complexity. Therefore, a consideration between the balance of benefits associated with minimizing model uncertainty versus the increased computational intensity costs associated with added model complexity is imperative (Freeze *et al.*, 1990).

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9.4 Model Diagnostics and Evaluation

In order to determine whether a forest hydrology model is characterizing the system appropriately, model evaluation needs to be conducted. In the most general sense, model calibration is a process by which model parameters are adjusted within a predefined acceptable range so that the simulated model output matches an observed set of data. Traditionally with catchment models, the observed data are stream gauge records but can also include spatially distributed data on water table depths, soil moisture, evapotranspiration and other water balance components. In forest hydrology models that incorporate plant growth components, it may also be appropriate to use measured LAI, total biomass and other variables estimated by remote sensing for validation of productivity factors in addition to the hydrological variables. For parameter estimation programs (e.g. PEST, Doherty and Johnston, 2003; OSTRICH, Matott, 2005) an objective function (optimization) or, more accurately, multiple objective functions 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. It also 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). Most recently, Arnold *et al.* (2015) recommended a diagnostic approach that looks at signature patterns of behaviour 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. 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.

Validation of the model traditionally suggests the successful testing of simulated outputs against observed data using an input data set different from the calibration data set. A split-sample approach (Klemes, 1986) 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. Such an approach to validation can be termed 'conditional validation', suggesting that the model has been validated using the calibrated model and separate data but can be updated with data that measure future conditions (e.g. changes in catchment factors or new state-of-the-science information) (Young, 2001).

9.4.1 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. Uncertainty analysis is conducted to quantify simulation output uncertainty by propagating uncertainties throughout the model and generating a probabilistic distribution of simulated outputs. How to handle uncertainties in hydrological modelling is a debate that has continued for decades (Matott *et al.*, 2009). Beven and Young (2013) suggest 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. Whichever form of uncertainties exists 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 of 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 disproportionate change in simulated outputs based on a relatively small change in a parameter's value. For example,

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Tian *et al.* (2014) and Dai *et al.* (2010) provide recent insights on global sensitivity analyses using the forest hydrological model DRAINMOD-FOREST and MIKE SHE, respectively.

9.5 Example Forest Hydrology Models

9.5.1 Watershed and plot 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-stepped and stand-level model that quantifies carbon and water dynamics in mature forests. Hydrological processes simulated by the 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 sub-models representing forest production, grassland and crop production, soil organic matter and a water budget. The simplified water budget sub-model simulates monthly evaporation, transpiration, soil water content, snow water content and saturated flow between soil layers.

Catchment rainfall–runoff models refer to physically based models that simulate the forest hydrology water balance and predominant rainfall–runoff processes, including routing to a surface water system. These models use topographically defined catchments as boundaries and simulate surface and shallow subsurface processes. Unlike groundwater models, rainfall–runoff models quantify groundwater as part of the catchment water balance; the groundwater flow equation is not solved explicitly. Therefore, the deep groundwater system is considered a hydrological 'sink'. Several examples of catchment rainfall–runoff models that can be applied for forest hydrology include ForHyM (Arp and Yin, 1992; Meng *et al.*, 1995), TOPMODEL (Beven and Kirkby 1979), i-Tree Hydro (Wang *et al.*, 2008), VELMA (Abdelnour *et al.*, 2011, 2013), APEX (Williams and Izaurralde, 2005; Gassman *et al.*, 2007), PRMS (Leavesly *et al.*, 1983, 2005), DHSVM (Wigmosta *et al.*, 1994, 2002), BROOK90 (Federer *et al.*, 2003), VIC (Liang *et al.*, 1994, 1996) and INCA (Wade *et al.*, 2002) (Table 9.1).

ForHyM (Arp and Yin, 1992; Meng *et al.*, 1995) is a one-dimensional, empirical, lumped watershed hydrology model that operates at a daily time step and has been applied across multiple physiographical settings. The model includes a single vegetation layer and two soil layers. Hydrological processes simulated by the model include interception, throughfall, evapotranspiration, infiltration, vertical unsaturated water movement, streamflow, surface runoff, interflow, groundwater flow and snowmelt. TOPMODEL is a semi-physically based flexible mass balance modelling tool that simulates catchment-scale rainfall–runoff (Beven and Kirkby, 1979) and is particularly robust in forested catchments with shallow soils. Flow routing in TOPMODEL is driven by VSA dynamics and includes both saturated- and infiltration-excess overland flow. i-Tree Hydro (previously called UFORE-Hydro; Wang *et al.*, 2008) is a physically based, semi-distributed urban forestry hydrological model that simulates runoff volume and 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, evapotranspiration, infiltration and runoff. The Visualizing Ecosystems for Land Management Assessment (VELMA) model is a spatially distributed ecohydrological model initially developed for forested catchments, particularly in the Pacific Northwest of the USA (Abdelnour *et al.*, 2011, 2013). VELMA can simulate multiple parts of the forest hydrological cycle (e.g. daily infiltration and redistribution, evapotranspiration, surface and subsurface runoff) using a four-layer soil column structure. The 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 pipeflow equations (Saleh *et al.*, 2004; Williams and Izaurralde, 2005).

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Table 9.1. Example catchment models for forest hydrology applications.

Model	Hydrological approach	Time step(s)	Spatial scale(s)	Level of complexity	Appropriate regions of application	Model files publically accessible	Availability of online user manual and website
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	Daily	Multi-scale catchments 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; http://www.itreetools.org/hydro/
PnET (all)	Lumped-parameterized one-dimensional water balance model from canopy to soil	Daily to monthly	Plot to regional	Low	All forest ecosystems, both upland and lowland	Yes	Yes; http://www.pnet.sr.unh.edu/
CENTURY	Simplified water balance incorporating evapotranspiration, soil water content, saturated flow	Monthly	Plot	Low	Temperate and tropical forests	Yes	Yes; https://www.nrel.colostate.edu/projects/century/
ForHyM	One-dimensional process-based water balance model that also embodies some general empirical relationships for multiple model layers (forest canopy, snowpack, forest floor, soil and subsoil)	Daily, weekly	Catchment	Medium	Typically applied for northern forested watersheds with one or multiple biomes	Yes	Yes; http://watershed.for.unb.ca/research/forhym/
TOPMODEL	Semi-distributed rainfall–runoff model; variable source area dynamics but simulates both saturated- and infiltration-excess overland flows; assumes water table follows topography	Daily	Multi-scale catchments	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: http://cran.r-project.org/web/packages/dynatopmodel/index.html

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VELMA	Spatially distributed ecohydrological model; simulates daily infiltration, evapotranspiration and surface/subsurface runoff through four soil layers	Daily	Multi-scale catchments	Medium	Multiple – developed in small forested catchments of Pacific Northwest of USA but applied/tested elsewhere	No	Coming soon
APEX	Curve number method (five options) and Green–Ampt infiltration (four options), subsurface drainage, and five options for potential evapotranspiration for evapotranspiration estimates	Hourly, daily, monthly or annual	Field; catchment; grid-based	Medium	Upland agricultural and forested fields or watersheds	Yes	Yes; http://epicapex.tamu.edu/apex/
PRMS	Semi-distributed processed-based rainfall–runoff model for multiple spatial and temporal scales	Daily to centuries	Multi-scale catchments	Medium	Multiple	Yes	Yes; http://wwwbrr.cr.usgs.gov/prms/
DHSVM	Saturation excess infiltration; Darcy's law for unsaturated and kinematic for saturated subsurface	Sub-daily to annual	Catchment	Medium	Mountainous watersheds in Pacific Northwest of USA	Yes	Yes; http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/
BROOK90	One-dimensional water balance with canopy and multi-layer soil profile	Daily	Plot	Low	Applied worldwide although designed for forests within north-eastern USA	Yes	Yes; http://www.ecoshift.net/brook/brook90.htm
VIC	Grid-cell based water balance with canopy and three-layer soil profile	Daily to monthly	Regional, global	Medium	Any as intended to accompany large-scale general circulation models	Yes	Yes; http://www.hydro.washington.edu/Lettenmaier/Models/VIC/
INCA	Semi-distributed water balance with canopy, soil and riparian components	Daily	Catchment	Medium	No limitations; applied extensively in Europe	By request	Yes; http://www.reading.ac.uk/geographyandenvironmentalscience/research/INCA/

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The Precipitation–Runoff Modeling System (PRMS) is a semi-distributed processed-based rainfall–runoff model that simulates components of the water balance, including evaporation, transpiration, runoff and infiltration, and quantifies interactions with forest/plant canopy, snowpack dynamics and soil hydrological processes (Leavesly *et al.*, 1983, 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 hydrological model that operates on a daily time step and was originally developed for forested catchments in the 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. The Distributed Hydrology Soil Vegetation Model (DHSVM) is a watershed-scale hydrological model that operates at sub-daily to annual time steps (Wigmosta *et al.*, 1994, 2002). The model is composed of seven modules representing evapotranspiration, 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).

The Variable Infiltration Capacity (VIC) model is a macro-scale hydrological model that operates at daily to monthly time steps; it complements global-scale general circulation models (GCMs) used for climate simulations and weather prediction (Liang *et al.*, 1994, 1996). The model includes simulated forest evapotranspiration, canopy storage, surface and surface runoff, aerodynamic flux, and snow accumulation and melt. The Integrated Nitrogen Catchment Model (INCA) is a semi-distributed process-based watershed model that operates at a daily time step and is popularly used in Western European forested catchment 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 catchment-scale hydrology and biogeochemical cycling. Finally, a widely used watershed-scale distributed model, SWAT (Soil and Water Assessment Tool; Arnold *et al.*, 1998), originally developed for upland agricultural landscapes, has been tested, modified and updated for its application on large landscapes containing large portions of forest lands (von Stackelberg *et al.*, 2007; Watson *et al.*, 2009; Parajuli, 2010; Amatya and Jha, 2011).

9.5.2 Ecosystem models

Broad-scale ecosystem models are those that simulate combined terrestrial ecosystem processes with catchment rainfall–runoff and hydrological routing. These models can range in complexity from fully coupled physically based ecosystem dynamics and hydrological modelling systems to less mechanistic decision-making tools. Examples across this range of complexity include FOREST-BGC (Running and Gower, 1991), BIOME BGC (White *et al.*, 2000), RHESSys (Band *et al.*, 1993; Tague and Band, 2004) and WaSSI (Sun *et al.*, 2011, 2015; Caldwell *et al.*, 2012) (Table 9.2; Fig. 9.2 presents WaSSI as an example low-complexity ecosystem model). The FOREST-BGC model (Running and Gower, 1991) and its successors, such as BIOME-BGC model (White *et al.*, 2000) and other BGC family models, are process-based, stand-level ecosystem 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. The Regional Hydro-Ecological Simulation System (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, soil hydrological and transport processes including vertical seepage, soil evaporation and lateral flow, and canopy radiative and moisture processes. The WaSSI model is a relatively low-complexity, integrated, process-based model that

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Table 9.2. Example ecosystem-scale models for forest hydrology applications.

Model	Hydrological approach	Simulation outputs: hydrology	Time step(s)	Spatial scale(s)	Level of complexity	Appropriate regions of application	Model files publically accessible	Availability of online user manual and website
FOREST-BGC	One-dimensional water balance with forest canopy and soil surface	Outflow, evapotranspiration	Daily	Catchment to regional	Medium	Any forest catchments	Yes	Yes; http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=36
BIOME BGC	Ecosystem model simulating hydrology across multiple scales based on one-dimensional water balance concepts	Evapotranspiration, soil water, snow depth, outflow	Daily	Multiple scale	Medium	Terrestrial ecosystem consisting of one or multiple biomes	Yes	Yes; http://www.ntsg.umt.edu/project/biome-bgc
RHESSys	Semi-distributed water balance incorporating TOPMODEL, CENTURY, DHSVM, BIOME BGC	Streamflow, carbon and nutrient dynamics at watershed outlet and within model components	Daily	Catchment	Medium	Mountainous catchments	Yes	Yes; http://fiesta.bren.ucsb.edu/~rhessys/
WaSSI	Distributed by HUC-12 (12-digit Hydrologic Unit Code) watersheds at the continental scale	Water yield, evapotranspiration, ecosystem productivity, water supply stress index	Monthly	Catchment	Low	Continental	Yes	Yes; http://www.fs.usda.gov/ccrc/tools/wassi

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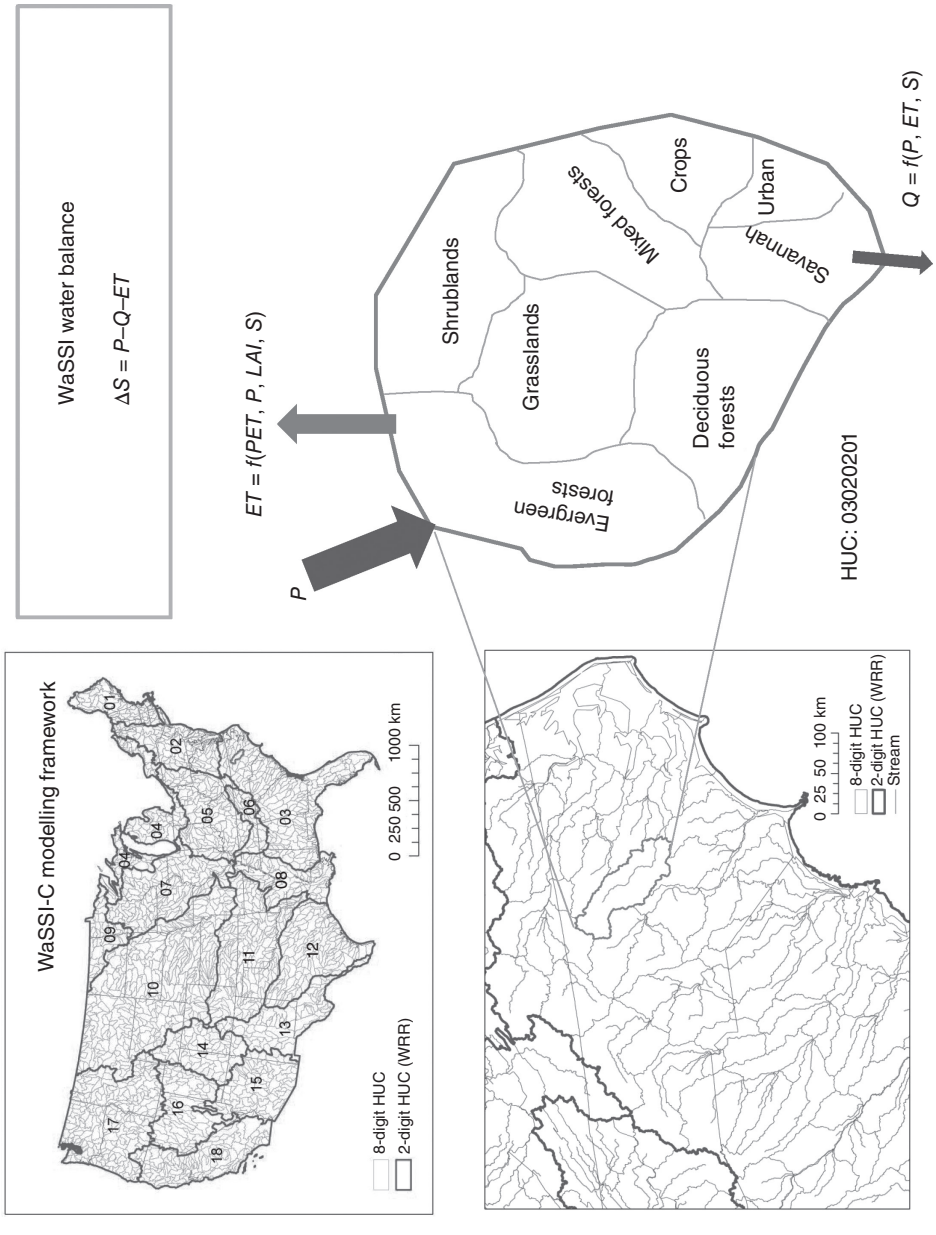

Fig. 9.2. WaSSI: an example relatively low-complexity, large-scale ecosystem model that can be applied for forest hydrology management and research questions. HUC is the Hydrologic Unit Code (a catchment identifier), WRR is water resource region, ΔS is the change in water storage at the catchment scale, P is precipitation, Q is catchment runoff, ET is evapotranspiration, PET is potential evapotranspiration and LAI is leaf area index.

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describes key ecohydrological processes at broad spatial scales (Sun *et al.*, 2011, 2015; Caldwell *et al.*, 2012) (Fig. 9.2). It operates on a monthly time step and simulates the full monthly water balance (evapotranspiration, streamflow and soil moisture storage) for each land cover class at a user-defined watershed scale.

9.5.3 Groundwater models

Groundwater models can be applied to research and management questions related to forest hydrology to focus on the movement and transport of subsurface flows through saturated porous media. Groundwater models typically are bounded by deep subsurface flow networks that reach across multiple catchment boundaries and use Darcy's flow equation (i.e. the groundwater flow equation) to estimate deep groundwater transport, which is based on relationships among hydraulic conductivity, hydraulic gradient, fluid flow rates and the model domain contributing area. Surface water flows and features (e.g. lakes, ponds, wetlands, streams, rivers) are not modelled explicitly 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 include MIKE SHE (Abbott, 1986a,b) and DRAINMOD-FOREST (Tian *et al.*, 2012) (Table 9.3). The MIKE SHE model (Abbott, 1986a,b) is a physically based, fully distributed hydrological modelling system 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.*, 2012) is a field-scale, 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 evapotranspiration, rainfall interception, infiltration, subsurface drainage, surface runoff, deep seepage, and soil water dynamics in the unsaturated zone.

9.5.4 Coupled surface–subsurface models

Coupled surface–subsurface models are highly complex modelling systems that link surface and groundwater models by dividing surface and subsurface flow into regions and solve the governing equations in each region using iterative solutions 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 evapotranspiration), 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 (Brunner and Simmons, 2012; Therrien *et al.*, 2010) and GSFLOW (Markstrom *et al.*, 2008) (Table 9.4). HydroGeoSphere is a 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 modelled (i.e. overland flow, streamflow, evaporation, transpiration, groundwater recharge, subsurface discharge into surface waterbodies) (Brunner and Simmons, 2012; Therrien *et al.*, 2010). GSFLOW is a high-complexity coupled surface–subsurface hydrological model that operates at a daily time step (Markstrom *et al.*, 2008; Fig. 9.3). The model integrates the surface-water Precipitation-Runoff Modeling System (PRMS) (Leavesley *et al.*, 1983, 1995) and the Modular Groundwater Flow Model (MODFLOW) (Harbaugh *et al.*, 2000; Harbaugh, 2005). PRMS simulates land-surface hydrological processes in evapotranspiration, runoff, infiltration and interflow, plant canopy interception and storage, and snowpack. MODFLOW simulates three-dimensional saturated groundwater flow and storage, one-dimensional unsaturated flow, and groundwater interaction with streams.

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Table 9.3. Example groundwater models for forest hydrology applications.

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

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Table 9.4. Example coupled surface–subsurface models for forest hydrology applications.

Model	Hydrological approach	Simulation outputs: hydrology	Time step(s)	Spatial scale(s)	Level of complexity	Appropriate regions of application	Model files publically accessible	Availability of 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 modelled (i.e. overland flow, streamflow, evaporation, transpiration, groundwater recharge, subsurface discharge to surface waterbodies)	Daily to centuries	Multi-scale domains (e.g. plots, catchments)	Very high	Multiple	No, this is a commercial product	No; but information can be found at http://www.aquanty.com/hydrogeosphere/
GSFLOW	Coupled surface and groundwater model; PRMS for surface; finite difference equation for subsurface	HRU (hydrological response unit) water balance, streamflow, groundwater dynamics	Daily	Watershed, regional	High	Any	Yes	Yes; http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/GSFLOW.html

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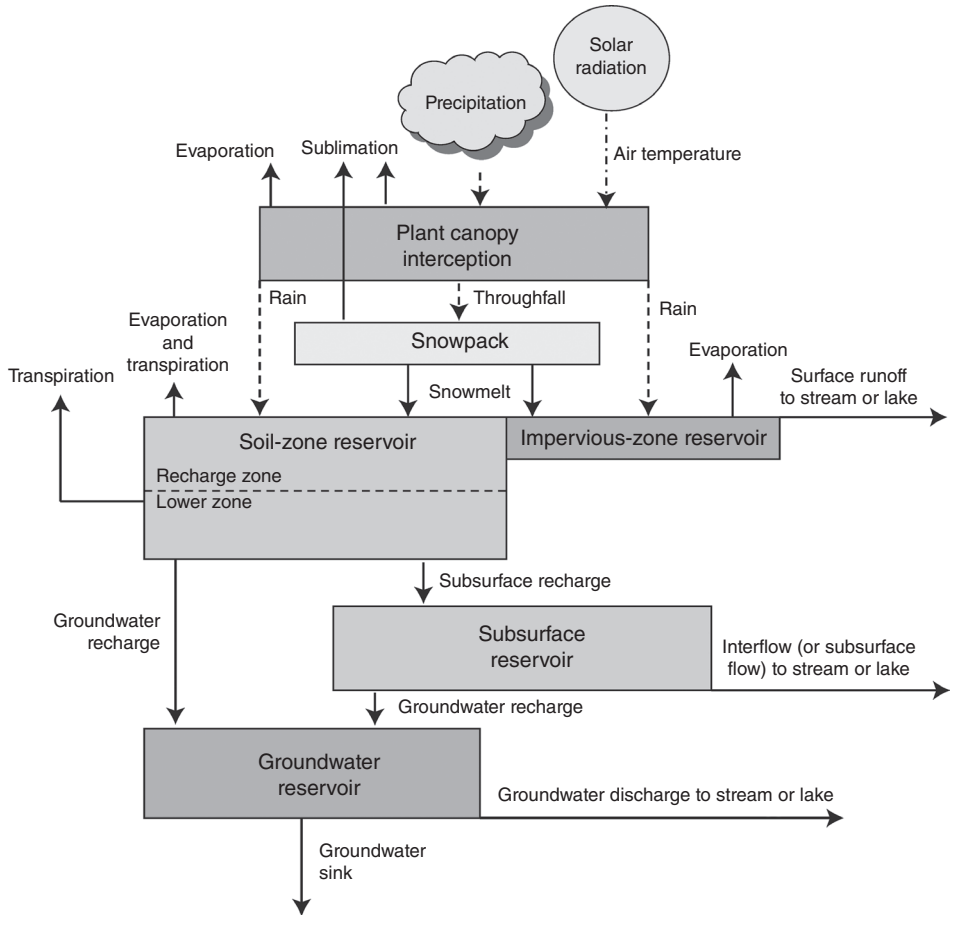

Fig. 9.3. GSFLOW model structure: an example complex, coupled surface–subsurface modelling system. (From Markstrom *et al*., 2008, with permission; S. Markstrom, US Geological Survey, personal communication, 2015.)

9.6 Summary and Conclusions

Forest hydrology models are important tools for developing a clearer understanding of a forest stand or catchment's dominant hydrological processes 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 with regard to the research or management question in addition to the conceptual hydrological model of the forest stand or catchment 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 modelled system are well-characterized. With technological and high-speed computing developments in recent years, future forest hydrology modelling work will move further towards incorporating innovative remote sensing, geophysical and biogeochemical methods for improved parameterization and process understanding. Further, empirical methods (e.g. tracer and isotopic studies for hydrograph separation) and statistical

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approaches should continue to be integrated into mechanistic modelling structures. Finally, the development of new, simplified, yet physically based models might be most appropriate in some forested systems (Sidle *et al.*, 2011).

9.7 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.

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