Chapter 85

Forest Hydrology

BY

GE SUN, DEVENDRA M. AMATYA, AND STEVEN G. MCNULTY

ABSTRACT

Forest hydrology studies the distribution, storage, movement, and quality of water and the hydrological processes in forest-dominated ecosystems. Forest hydrological science is regarded as the foundation of modern integrated watershed management. This chapter provides an overview of the history of forest hydrology and basic principles of this unique branch of hydrological sciences and forest ecology. Then, the chapter presents the general methodology and techniques that are widely used in forest hydrological investigations. A summary of key world-wide discoveries on the forest-water relations over the past century is presented as well as the progress made on the understanding of the forest-climate-water-people interactions. The perspectives of forest hydrology to solve environmental challenges in the twenty-first century are discussed.

85.1 INTRODUCTION

About one-third of the earth's land surface is covered by forests. As the single largest ecosystem type, forests significantly affect the global hydrological cycle and provide a myriad of ecosystem services to humans (Sedell, 2000; Chang, 2013) . The study of water in forests is termed *forest hydrology* and includes *the distribution, storage, movement, and quality of water; hydrologic processes within forested areas; and the delivery of water from forested areas* (NRC, 2008). Traditionally, forest hydrology focuses on the effects of forests and associated wildland vegetation on the water cycle, including the effects on streamflow, soil erosion, water quality, and micro-climate (Hewlett, 1982; NRC, 2008). Forest hydrology studies the interactions between forest ecosystems and water quantity and quality at multiple scales from a tree leaf to the landscape. The forest hydrologic processes and pathways and their interactions with climate, moisture, soils, and geology are much complex and less studied comparing to agricultural counterpart. As such, forest hydrology is an interdisciplinary science that evolved from the specialization of traditional hydrological science and forest ecosystem science during the past century (NRC, 2008). Forest hydrology is viewed as one of the foundational sciences in integrated watershed management (IWM) (Black, 1996; Brooks et al., 2012). The goal of IWM is to provide natural and human resources in a watershed to sustain the goods and services demanded by the society. IWM is critical to solving contemporary environmental and ecological problems such as the loss of aquatic resources, water shortages, and climate change. The scope of forest hydrological science has expanded from understanding the meteorological and hydrological influences of forests in small watersheds during in the early twentieth century (Hewlett, 1982), to quantifying the eco-hydrological impacts of global changes today (Amatya et al., 2011; Vose et al., 2011b).

This chapter first introduces the history of forest hydrology and basic principles of the unique branch of hydrological science, and then presents the general methodology and techniques widely used in forest hydrological studies. A summary of key discoveries on the forest-water relations around the world and progress made on the understanding of the forest-climate-water-people interactions in modern forest hydrology are then explored before the chapter ends with a discussion on the potential future development of forest hydrology in the twenty-first century.

85.2 HISTORICAL DEVELOPMENT

There are many long-standing beliefs about the relations between forests and water around the world (McCulloch and Robinson, 1993; Andreassian, 2004; De la Crétaz and Barten, 2007) that involve impacts of forest management on water quantity and quality, forest influences on local climate, and forests' ability to generate precipitation and prevent floods and landslides, or to augment dry season river flows (Simonit and Perrings, 2013). These have been the central questions that forest hydrologists are addressing. The early debate on the role of forests in affecting streamflow and debris flow in Europe can be traced back to the sixteenth century in Austria, France, and Italy, with the first small watershed-scale (60 ha) hydrologic study performed in the Bernese Emmental region of Switzerland in 1900. This study demonstrated that streamflow, sediment loads, and landslides in the Sperbelgraben (99% forested) are much lower than the Rappengraben (69% pasture and 31% forest) (McCulloch and Robinson, 1993).

In the United States, forest hydrology is deeply rooted in understanding the disastrous impacts of deforestation on climate, floods, and soil erosion during the late 1800s and the early 1900s (Hewlett, 1982). From 1891 through 1935, following the "propaganda period" of forest influences, several legendary forest conservationists emerged including B. E. Fernow, R. B. Hough, C. Pinchot, F. Roth, and T. Roosevelt. A series of historical laws including the famous. "Weeks law" (1911) were passed to "protect the headwaters of navigable streams." The Weeks law and the likes would define the missions of U.S. Forest Service for the next 100 years. Since the middle 1930s, 77 experimental forests and ranges have been established across a large geographic and climatic gradient in the United States and Puerto Rico, with a focus to address forest management and water issues (Adams, 2003). The earliest watershed study can be attributed to an observation of peak flow in the winter of 1911–1912 in the White Mountains of New Hampshire (McCulloch and Robinson, 1993). This study reported that the peak flow rate in a forested catchment is lower than that from a felled area. However, the first true "paired watershed" study (i.e., using individual control and treatment watersheds) occurred with the Wagon Wheel Gap Experiment conducted during 1911–1928 in southern Colorado. This study compared cleared and noncleared forest watersheds (Bates and Henry, 1928) and marked the beginning of modern forest hydrological research using a watershed approach. Findings from this study inspired and promoted similar long-term watershed experimental studies using the same approach throughout the United States in places such as the Coweeta Hydrological Laboratory (1934) in North Carolina, Fraser Experimental Forest (1937) in Colorado, H. J. Andrews Experimental Forest (1948) in Oregon, Hubbard Brook Experimental Forest (1955) in New Hampshire, and Santee Experimental Forest in coastal South Carolina (1968).

The earliest publications that specifically address forest-climate-water relationships can be traced back to "Forests and Moisture" or "Effect of Forests on Humidity of Climate" by John Brown (1877), "The Earth as Modified by Human Action" by G. Marsh (1874), "Forests and Water in the Light of Scientific Investigation" by Zon (1927), and "Forest Influences" by Kittredge (1948). The 1965 International Symposium on Forest Hydrology held at Penn State University highlighted findings on forest-soil-water relations up to the

1960s and marked a new era of modern forest hydrological studies around the world (Sopper et al., 1967). This symposium was attended by leading forest hydrologists such as J. Hewlett and H. Penman, and it provided a solid foundation for advancing the forest hydrological research in the decades ahead. The 1970s also saw a rapid expansion of forest hydrological research into water quality and ecosystem process studies that directly addressed environmental issues such as acid rain. During the 1970s–1980s, several textbooks were published including *Forest Hydrology (Lee, 1980) and Principles of Forest Hydrology* (Hewlett, 1982), each of which greatly fostered forest hydrology education in universities. In the 1980s, many of the forest hydrological research stations including Coweeta (Swank et al., 1988), H. J. Andrew, and Hubbard Brook (Bormann and Likens, 1994) were selected as the core long-term ecological research sites that provided process-based understanding of the full biogeochemical cycles of forested watersheds (Ice et al., 2004a). During the 1980s, long-term data in forest hydrological research in other countries such as Canada (Buttle et al., 2000; Buttle et al., 2005; Buttle et al., 2009), Australia (O'Loughlin et al., 1982), Europe (McCulloch and Robinson, 1993; Puhlmann, 2007), Africa (Edwards and Roberts, 2006), and Asia (Ffolliott et al., 1989; Onda et al., 2010; Wei et al., 2013) emerged. The 1990s onward saw rapid maturity of forest hydrology as one distinct discipline within the forestry and hydrology communities as indicated by tremendous growth of university curriculums and journal publications (Sun et al., 2008a). Notable forest hydrology books include *Watershed Hydrology* (Black, 1996), 3rd edition of *Forest Hydrology: An Introduction to Water and Forests* (Chang, 2013), and *Hydrology and the Management of Watersheds* (Brooks et al., 2012). Two most recent books include a textbook *Forest Hydrology and Catchment Management—An Australian Perspective* (Bren, 2014) and *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions* (Levia et al., 2011). Managing forests is becoming an increasing challenge in the twenty-first century as the demands on multiple forest ecosystems services also increase (Amatya et al., 2011; Levia et al., 2011; Sun et al., 2011b). Advanced understanding and predictions are needed on ecohydrological responses to changes in climate, human population, development, land use, wildfire regimes, insects, and diseases, as well as changes in forest management (e.g., reforestation, bioenergy, intercropping, and agro-forestry) and carbon sequestration-water supply tradeoffs (Vose et al., 2011b).

85.3 PRINCIPLES OF FOREST HYDROLOGY

Water balance of a forested watershed or a region within a geographic area can be expressed in the following general equation and illustrated in Fig. 85.1.

$$\Delta S = P - \mathrm{ET} - Q \tag{85.1}$$

where ΔS, P, ET, and Q represent the change in soil water storage, precipitation, evapotranspiration (the combination of evaporation and transpiration), streamflow (surface and subsurface flow) or groundwater recharge generated within the watershed boundary, respectively. Over the shortterm, all four variables can change dramatically. However, over the longterm, the change in storage (ΔS) can be minor and are often assumed to be negligible. Climate change can alter the water balance and thus ΔS may not be zero before the ecosystem reaches a new steady state.

Compared to other land uses such as cropland and urban landscape, forest hydrological processes have a few unique features. These processes are discussed here using the water balance equation as a guide.

First, compared to croplands or urban systems, mature forests have relatively large above-ground (i.e., overstory and understory layers) and below-ground (i.e., roots) biomass (Waring and Running, 2007; Chapin et al., 2011). Trees are perennial woody plants with long life spans from decades to millennia, which can grow to heights of over 100 m, crown spreads can be over 30 m, and root systems can extend over 10 m deep into the earth and also expand laterally in shallow soils. Forests can only be found in certain geographic regions or elevations where water (annual P > 400 mm) and energy (mean annual net radiation > 27 W/m^2) are sufficient to support large water demands by the forest (Chang, 2013). Matured forests generally have lower albedo, higher canopy surface roughness, higher leaf area index, and deeper roots compared to the crops and or grass (Bonan, 2008). These biophysical properties have a strong influence on the energy and water balances in forests (Bonan, 2008), resulting in relatively higher ET (both canopy interception and transpiration), lower water yield and groundwater tables, and lower surface temperature than other land covers. Depending on forest stand age, species, structure and composition, and precipitation characteristics, multilayered forest canopies can intercept and evaporate 10–30% of the precipitation, part or most of which is directly evaporated and, therefore, represents as an important part of the total water loss (ET) in the forest water budget (Chang, 2013). Large forest canopies can intercept fog in some humid montane regions such as the Pacific Northwest in the United States resulting in an increase in total precipitation (Dawson, 1998). This process explains why deforestation can decrease streamflow in some watersheds in this particular region (Beschta, 1998). Precipitation, not intercepted by the canopy, falls on the forest floor as throughfall available for infiltration, soil/litter evaporation, and possibly runoff.

Second, well-structured forest soils develop high organic matter content and networks of soil macro-pores from decomposed dead plants and animal burrows (Chapin et al., 2011). In most cases, the top soils are even covered by thick leaf litter layers. Consequently, undisturbed forest soils have an extremely high infiltration capacity that often exceeds rainfall intensity, resulting in very little overland flow on forest floors and surface erosion. The saturated hydraulic conductivity of forest soils can be 10–100 times higher than that of cultivated agricultural soils (Skaggs et al., 2011). Crop cultivation, silvicultural activities, and urbanization alter watershed hydrology by influencing both soil properties and vegetation transpiration processes (Sun and Lockaby, 2012).

Third, forests have deeper root systems that can access water during meteorological drought conditions. Rooting depths of forests are much higher than grass or crops (Jackson et al., 1996). As a result, trees are rarely under water stress and forest ET rates are generally stable except under continuous droughts when soil water storage is exhausted (Xie et al., 2014). Under droughts, the tree roots bring soil water from deep layers to the shallow layers a process called "hydraulic lift," which is helpful for increasing the surface soil moisture for tree growth during droughts (Domec et al., 2010).

Because of these unique features discussed previously, compared to agricultural or urban watersheds, forests have relatively high ET (Sun et al., 2011a) and soil infiltration capacity. These conditions can greatly reduce the

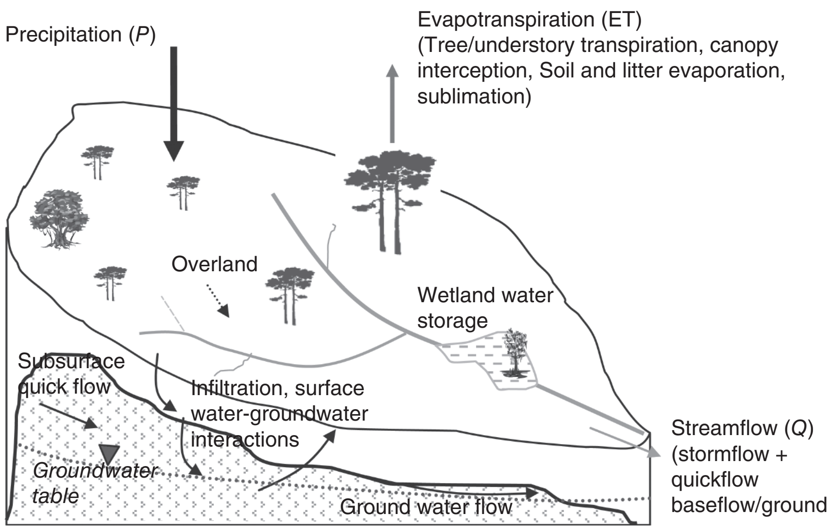

Figure 85.1 A schematic of major hydrologic processes in an undisturbed forest watershed.

potential for overland flow, lower total streamflow, lower peak flow, and mitigate pollutant loading in forested watersheds (Amatya et al., 2015). Forest streams are less flashy than watersheds dominated by other land uses (Sun and Lockaby, 2012). Forest streamflow generally originates from subsurface flow or groundwater discharge at the headwater streams.

Early observations of hydrologic processes in forested watersheds in humid regions contradict traditional Hortonian Theory (Horton, 1933) that explains storm-flow generation by infiltration excess overland flow (Bonell, 1993). Studies on forested watersheds lead to alternative explanations of stormflow generation using a variable source area concept (VSAC) (Hewlett and Hibbert, 1967). VSAC states that stormflow in forested watersheds is generated from surface flow in stream channels and subsurface quick flows. Additionally, the contributing area can expand and shrink over time, and streamflow is sustained by soil moisture (Hewlett, 1982). The concept of flow originating from a variable-sized portion of forested watersheds led to many hillslope and small watershed projects to describe the processes by which this zone operates including lateral recharge from upslope unsaturated areas, surface runoff from saturated sections of the watershed, flow in soil macropores or preferential flow paths such as "pipe flow" (McDonnell et al., 1991), or release of groundwater to the stream by rapid increase in hydrostatic head "piston flow" (Gilliam, 1984). These early literature is fundamental to our understanding of watershed subsurface flow processes (Weiler and McDonnell, 2007; Band et al., 2014).

85.4 RESEARCH METHODS

85.4.1 Paired Watershed

Our knowledge about forest hydrological processes and the interactions between forests and water is mostly derived from empirical field experimentation using the "paired watershed" approach that has been widely adopted worldwide (Brown et al., 2005; NRC, 2008; Vose et al., 2011a). In a "paired watershed" study design, two watersheds that have similar climate, sizes, elevations, soils, geomorphology, aspects, and initial land use or land cover are selected to monitor their water quantity and/or water quality simultaneously. One watershed serves as the "control" that will remain undisturbed during the entire course of the study. The other watershed serves as "treatment" that is subject to manipulations such as forest cutting, thinning, tree species conversion, or permanent land use conversions (e.g., grass to forest). The "calibration" period, the first phase of the study, establishes the empirical relationship between water quantity or quality, including the peak flow rate from the "control" and the "treatment" watersheds at daily, monthly, or even annual scale. A statistically significant relationship between the control and treatment watersheds is established during the calibration period such that any significant shift detected in the relationship during "treatment" is attributed to the treatment effects. The second phase of the study quantifies the treatment effects by comparing the measured hydrological parameters, including water quantity and/or quality, to those "expected" as determined from the empirical models developed during the "calibration" period. The time of the calibration period necessary to develop a reliable model can vary from 2 to 10 years depending on the climatic variability (Bren and Lane, 2014). The treatment effects on watershed hydrology can be detected immediately in the case of clear-cutting a mature forest, or they may take a long time for reforestation depending on how quickly the ET of the new vegetation and soils recover or stabilize after disturbances. Background climate is a major factor influencing the time required for calibration and detection of treatment effects. The size of the watershed is often limited to 1 km^2 (100 ha) due to the cost and logistics associated with manipulations of "paired watershed" experiments, although larger watersheds (>150 ha) have also been used recently for assessing hurricane impacts in coastal South Carolina (Jayakaran et al., 2014). These small watershed studies allow for the direct attribution hydrologic change associated with land cover or land use change. Thus the paired watershed approach offers the ability to identify roles of forest cover and internal watershed behavior to establish a "baseline" for reference(Zégre et al., 2010). Advantages of using the paired watershed approach include statistical control of climatic and hydrological differences between the pair, eliminating the necessity to monitor all variables causing the changes, and developing social indicators to assess the effectiveness of watershed management programs compared to single-watershed studies (discussed as follows) (Clausen et al., 1993; Loftis et al., 2001; Prokopy et al., 2011) .

85.4.2 Single Watershed

"paired watershed' studies are, however, not always practical due to resource limitations such as research site or financial conditions (Wei et al., 2013). In such cases, the "single watershed" approach can be used to evaluate the hydrologic effects of certain forest management options. "Single watershed" method develops rainfall-runoff relationships during the "control" period and then applies the relationships to the second period to the same watershed that is subject to treatment. The major assumption is that the rain-runoff relationships from the first period hold over time and climate is stationary. This method has been widely used for studies on the effects of land use change for large watersheds when long-term hydrometeorological data are available and land use history is available (Wei and Zhang, 2010). An overview of pros and cons on using the paired versus the single-watershed approach is available elsewhere (Ssegane et al., 2013).

Various statistical methods have been developed to detect hydrologic change over time to separate the individual effects of land cover and climate change by analyzing hydrometrological data (Zhao et al., 2010). For example, the climate elasticity model (Schaake and Waggoner, 1990) has been widely used to evaluate the sensitivity of streamflow to climate changes impact (Fu et al., 2007) and thus can tease out the effects of climate change or land use change only from the observed total hydrologic changes during postdisturbance period in a watershed (Ma et al., 2008).

The double-mass curve (DMC) method plots accumulated precipitation against streamflow, and has been widely used to detect the "break point" that would indicate land cover change (e.g., harvesting or wildfires) on watershed hydrology (Maidment, 1993). The slope of the DMC is expected to remain constant unless there have been changes in the drainage basin that alter hydrologic regimes. The significance of changes in the slope of the relation at the breakpoint is evaluated by visual inspection and intervention analysis, an extension of autoregressive integrated moving average (ARIMA) modeling (Wei and Zhang, 2010). The DMC method and a modified version (MDMC) have been widely used to determine the timing and magnitude of flow regime change due to gradual forest cover changes (Wei and Zhang, 2010). Climatic variability and its effects on the annual streamflow can be teased out by using accumulative effective precipitation, defined as the difference between measured precipitation and actual evapotranspiration calculated by an annual ET model (Wei and Zhang, 2010). The flow duration curves (FDCs) for "before" and "after" watershed disturbances have also been used to examine flow regime changes (i.e., stormflow, baseflow, annual total) (Amatya et al., 2015). An FDC can be constructed from daily streamflow data by ranking the flows from the maximum to minimum with each flow plotted against the percentage of time it is exceeded. (Zhang et al., 2011).

85.4.3 Mathematical Modeling

In addition to field-based forest hydrological research methods used in "Paired Watershed" or "single-watershed" studies, computer simulation models have also been widely used to understand or predict the complex interactions within the forest hydrological cycle from a leaf to the regional scale (Golden et al., 2015). Computer models have become powerful and effective tools in assessing forest watershed management impacts (Amatya et al., 2015). Models can be categorized by the ways they are constructed with mathematical formulas as either empirical or theoretical. Empirical models are developed through statistical relationships between ecosystem parameters such as streamflow and forest cover. Conversely, process-based models attempt to simulate the biophysical functioning of a watershed that controls hydrologic processes such as predicting processes of streamflow generation and tree water uptake, and then extrapolating that process over the entire forest canopy and watershed. Forest hydrology models can also be categorized as "lumped" such as BROOK90 (Federer et al., 2003) or "distributed" models such as DSHVM (Wigmosta et al., 2002) and MIKE SHE (Abbott et al., 1986a, b), depending on how the spatial heterogeneity of a simulation domain, such as a field or watershed, is handled. Regardless of the complexity of models, the goal of the computer modeling is to accurately describe water and/or chemical transport through the soil-plant-atmospheric continuum at different temporal (e.g., hours to annual) and spatial scales (e.g., a field to a large basin) (Golden et al., 2015). Models are simplifications of the real hydrological systems, and thus they always have uncertainty in the mathematical formulations. Most models require calibrations to achieve the best set of "effective" parameters to represent the real world (Arnold et al., 2015; Malone, 2015), for "real world" applications such as designing forest management options to adapt to climate change (Vose et al., 2011a) and quantifying the hydrologic sensitivity to climate and forest changes (Sun et al., 2015). Model algorithms must be validated at least with point-level measurements such as streamflow recorded at a watershed's outlet or other in-stream subcatchment outlets, or spatial distribution of water table depths (Dai et al., 2010), soil moisture or ET measured by the sapflow, eddyflux, or remote sensing methods (Sun et al., 2011b). Arnold et al. (2015) recently recommended an approach using "hard" (field measured) and "soft" (qualitative only) data for model output validation. For example, annual water balances simulated by the BASINS/HSPF should be consistent with expected values such as general regional ET values, as "soft"

Table 85.1 A Survey of Forest Hydrology Simulation Models in the United States

Models	Scale	Key Functions	References
iTree Hydro	Tree, a parcel, or neighbor-hoods	Canopy interception, runoff from impervious surface, soil evaporation and tree transpiration, flow routing, and pollution, hydrograph	http://www.itreetools.org/resources/manuals/Hydro_Manual_v5.pdf
Brook90 (from Hubbard Brook watersheds)	Lumped, daily	ET process, soil water content, overland flow, bypass flow from soil layers, subsurface flow	(Federer et al., 2003) (Yu et al., 2013)
Forest-DNDC (Forest Denitrification and Decomposition)	Field, daily combining PnET and DNDC	Forest productivity, ET, soil moisture, CO_2, N_2O gas exchange with the atmosphere	(Li et al., 2000) (Dai et al., 2012)
DRAINMOD-Forest	Field, daily, process-based	hydrology, soil *C* and *N* cycles, and vegetation growth in lowland forests	(Amatya and Skaggs, 2001) (Tian et al., 2012)
SWAT (Soil Water Assessment Tool)	Process based, distributed, daily	Simulating hydrology and water quality for agri-culture watersheds including flow, sediment, *N*, *P* loading, also generating weather variables, crop growth	(Arnold et al., 1998) (Amatya and Jha, 2011)
PRMS (Precipitation-Runoff Modeling System)	Semidistributed, daily	Evaporation, transpiration, runoff, and infiltra-tion, and quantifies interactions with forest/plant canopy, snowpack dynamics, and soil hydrologi-cal processes	(Leavesley et al., 1995) (Qi et al., 2009)
TOPMODEL (Topographic model)	Distributed, hourly	Variable source area dynamics; saturated excess and infiltration excess overland flows; assuming groundwater table follows topography	(Beven and Kirkby, 1979)
MIKE SHE (System Hydrology System)	Model the full hydrological cycle of the land phase of a watershed	Canopy interception, soil evaporation, transpira-tion, infiltration, overland flow, unsaturated flow in soils, groundwater flow in aquifers, and chan-nel flows in rivers	(Abbott et al., 1986a) (Abbott et al., 1986b) (Lu et al., 2009)
DHSVM (Distributed Hydrology Soil Vegetation Model)	Watershed-scale operated at subdaily to annual time steps.	ET, snowpack accumulation and melting, canopy snow interception and release, unsaturated sub-surface flow, saturated subsurface flow, surface overland flow, and channel flow	(Wigmosta et al., 1994) (Wigmosta et al., 2002)
RHYSSys (Regional Hydroecological Simulation System)	Semidistributed (patch)	TOPMODEL, CENTURY, DHSVM, and BIOME BGC models; coupling of water with *C* and *N* cycles	(Band et al., 1993) (Tague and Band, 2004)
VIC (Variable Infiltration Capacity)	Macroscale, distributed, daily-monthly	Interfaced with general circulation models (GCMs) for climate simulations and weather pre-diction	(Liang et al., 1994) (Liang et al., 1996)
WaSSI (Water Stress Supply Index)	Distributed at 12-digit hydrologic unit code, watersheds, monthly scale	Water yield, ecosystem productivity, and net eco-system production, water supply and demand, and water stress	(Sun et al., 2011b) (Caldwell et al., 2012) http://www.wassiweb.sgcp.ncsu.edu/

data, for a region even when observed ET values are not available (Duda et al., 2012). If models are used properly, they can help test hypothesis, understand the processes, and synthesize field measurements across scales. Most importantly, models may serve as cost-effective tools for answering "what if" questions that are not practical to address using a field-based approach (Caldwell et al., 2012). A sample of forest hydrological models is provided to demonstrate the diversity of model objectives and uses (Table 85.1).

85.5 KEY FINDINGS IN FOREST-STREAM WATER QUANTITY AND QUALITY RELATIONSHIPS

During the past century, forest hydrology has made great strides in answering the basic questions regarding forest and water relationships. Now, based on global studies from both empirical small watershed experiments and theoretical modeling, we have gained profound understanding of forest-water relations (Andreassian, 2004; Ice et al., 2004b; Brown et al., 2005). Deforestation generally results in an increase in annual total water yield (Bosch and Hewlett, 1982), peak flow rates (Alila et al., 2009), groundwater recharge (Sun et al., 2002), and baseflow and dry seasonal flows (Stednick, 1996). Afforestation or reforestation by planting trees or restoring vegetation covers on degraded lands or grasslands with native forests generally reduce streamflow, peak flow, groundwater recharge by lowing water tables (Sun et al., 2000), and baseflow, especially during the growing season (Zhang et al., 2012). Reforestation, especially fast growing trees, is not likely to augment baseflow in most cases because the increased ET generally overwhelms the increased groundwater recharge due to enhanced soil infiltration capacity from soil improvement (Brown et al., 2013). Understanding ET processes is the key to correctly interpreting the observed hydrological responses to vegetation change (Zhang et al., 2001) and stand structure and management strategy (McLaughlin et al., 2013) given that ET links the biological and hydrological processes primarily through the leaf area index (Sun et al., 2011a) and canopy conductance and their interactions with climate and soils (Irmak and Mutiibwa, 2010; Mohamed et al., 2012). Additionally, ET controls the ecosystem energy balance that ultimately controls the hydrologic recovery processes from disturbances including extreme events such as hurricanes (Jayakaran et al., 2014) and catastrophic wildfires (Ice et al., 2004a; Bladon et al., 2014).

Although debates on the forest-water relationship remain (Andreassian, 2004; Calder, 2007; Ellison et al., 2012), consensus on the role of forests in impacting water resources are converging within the forest hydrologic community (Zhou et al., 2015). The large observed and modeled variability of hydrological responses to vegetation changes encourages process-based studies at larger scales (Sun et al., 2006; Wei and Zhang, 2010). Compared to small watershed scale studies, most empirical studies show that climate is the major control on ecosystem water balance and effects of vegetation cover on streamflow are often significant at the watershed, but minor at a large basin scale (Oudin et al., 2008). Extrapolating forest hydrologic findings from a small field or watershed scale to the large basin scale is inherently difficult due to the increasing variability with space and the compounded influence of geology, geomorphology, soil (Bruijnzeel, 2004), and vegetation on watershed water balances (Wei and Zhang, 2010). The effects of forests on regional climate, and precipitation patterns in particular, are difficult to detect with measurements. Therefore, our understanding of forest influence on regional climate is mostly based on models with unrealistic assumptions (Jackson et al., 2005; Liu, 2011).

A stable and clean water supply is one of the major forest ecosystem services that watershed managers value (Brown et al., 2008). Forests, managed or unmanaged, provide the best water quality along all land uses in the United States (Brown, 1980; Binkley and Brown, 1993), especially when forestry best management practices are used (Edwards and Williard, 2010). Under minimal disturbances, biogeochemical exports of sediment and nitrogen, phosphorus, and potassium from forests are very low (Sun and Lockaby, 2012) and were found lower than adjacent agricultural watersheds even during the extreme disturbances (Shelby et al., 2005). Many forested ecosystems are "nutrient conservative"—highly deficient in those nutrients often found in overabundance in agricultural lands that can be major sources of nonpoint pollution from watersheds (Bormann and Likens, 1994). Consequently, water quality under most forested conditions is quite good in terms of sediment, nitrogen, phosphorus, and potassium concentrations (Binkley et al., 1999). Patterns of atmospheric deposition of N and soil N saturation have major influences on forest stream water chemistry (Aber et al., 1997). Urbanization that often involves removing forests permanently and increasing impervious surface areas can result in significant production of pollutants due to disruptions in the retention capacity of forested watersheds (Sun and Lockaby, 2012) and also due to reduction in groundwater recharge (Callahan et al., 2012), including short circuiting of pollutant flow paths. In this case, forests in a watershed with mixed land uses have "dilution" effects to reduce the cumulative impact of urbanization on water quantity and quality (Bolstad and Swank, 1997).

85.6 FUTURE DIRECTIONS

The Earth has entered into the Anthropocene, a new geological epoch dominated by people who pose great threat to sustainability (Vorosmarty et al., 2013). Forests and their ecosystem functions of providing stable and clean water are increasingly threatened by human-caused climate change (Sun et al., 2008b; Vose et al., 2012), urbanization and land use change (Foley et al., 2005), and increased human water demands for meeting energy needs (Averyt et al., 2013; King et al., 2013). Extreme weather (i.e., droughts, hurricanes) (Vose et al., 2012) and rise in sea level are becoming grave concerns in forest conservation and management in the twenty-first century across many areas of the United States (Day et al., 2007).

Therefore, the science of forest hydrology is facing new challenges and opportunities in answering questions under an ever-changing world characterized by rapid change in global climate, urbanization, and human dominance (Jackson et al., 2009). Recent advances in forest hydrology emphasized a need to address forest hydrology at the landscape scale that embraces the interactive effects of various land-based activities on water supplies (Vose et al., 2011b). Climate change is hydrologic change, and hydrologic stationarity is dead (Milly et al., 2008). A changing climate, including the form and intensity of precipitation and atmospheric CO_2 concentrations, brings in a series of cascading effects (Vose et al., 2012) on forest phenology, species composition, leaf area and biomass (McNulty et al., 1996), plant ecophysiological properties, outbreaks of insects (Mikkelson et al., 2013), fire regimes (Ice et al., 2004a; Luce et al., 2012), and thus basic hydrological processes (Jones et al., 2009), including rainfall infiltration and ET. The established forest-water relationships and related forest hydrological research methods developed in the past century are useful to predict the future (Vose et al., 2011b), but they must be revisited to fully understand and predict forest ecohydrological response to future natural and human disturbances in a new environmental regime (Creed et al., 2014). Competition for clean water between ecosystem needs and human demands is likely to intensify in the twenty-first century (Sun et al., 2008b; Caldwell et al., 2012). Successful watershed restoration and management efforts require better understanding of how policy and socioeconomics interact with ecohydrological processes. Policy makers, natural resource managers, forest hydrologists, and expertise from other disciplines need to develop collaborative, science-based strategies to sustain water resources in the face of multiple threats (Vose et al., 2011b).

Intelligent, field-based, real-time monitoring of forest hydrological processes will improve data collection at a much finer spatial and temporal scale than traditional research methods. Applications of remote sensing and other spatial information technology including the LiDAR data continue to improve our understanding of hydrological responses to large-scale disturbances. Existing forest hydrological models should be improved by tightly coupling hydrological processes with ecological processes (i.e., carbon, nutrient cycling, and vegetation dynamics). Unprecedented processes need to be considered to fully account for the effects of climate change and land cover change (Amatya et al., 2011). Ultimately, forest hydrological models must be incorporated into land surface models so the role of forests and human activities (e.g., reforestation or deforestation) at the landscape to global scale can be quantified (Bonan, 2008). In addition, land surface models must have the ability to model the influences of external disturbances such as climate variability (e.g., drought and flood) and physical and chemical climate effects (e.g., greenhouse gases), species invasion, wildfire, insect outbreak (i.e., water and carbon cycles), and human interventions (i.e., policy).

REFERENCES

Abbott, M. B., J. C. Bathurst, J. A. Cunge, P. E. Oconnell, and J. Rasmussen, "An introduction to the European hydrological system—Systeme Hydrologique Europeen, She. 1. History and philosophy of a physically-based, distributed modeling system," *Journal of Hydrology*, 87: 45–59, 1986a.

Abbott, M. B., J. C. Bathurst, J. A. Cunge, P. E. Oconnell, and J. Rasmussen, "An introduction to the European hydrological system—Systeme Hydrologique Europeen, She. 2. Structure of a physically-based, distributed modeling system, *Journal of Hydrology*, 87: 61–77, 1986b.

Aber, J. D., S. V. Ollinger, and C. T. Driscoll, "Modeling nitrogen saturation in forest ecosystems in response to land use and atmospheric deposition," *Ecological Modelling*, 101: 61–78, 1997.

Adams, M. B., Experimental forests and ranges of the USDA forest service, *General Technical Report NE-321*, United States Department of Agriculture Forest Service Northeastern Research Station, 2003, p. 191. Newtown Square, PA.

Alila, Y., P. K. Kuras, M. Schnorbus, and R. Hudson, "Forests and floods: a new paradigm sheds light on age-old controversies, *Water Resources Research*, 45: 2009. W08416, 1-24.

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

Amatya, D. M. and M. K. Jha, "Evaluating the Swat model for a low-gradient forested watershed in coastal South Carolina," Transactions of the ASAE, 54: 2151–2163, 2011.

Amatya, D. M. and R. W. Skaggs, "Hydrologic modeling of a drained pine plantation on poorly drained soils," *Journal of Forest Science*, 47: 103–114, 2001.

Amatya, D. M., G. Sun, C. G. Rossi, H. S. Segane, J. E. Nettles, and S. Panda, Forests, land use change, and water, *Impact of Climate Change on Water Resources in Agriculture*, edited by R. Rodrigues, CRC Press/Taylor & Francis, 2015. Boca Raton, FL.

Andreassian, V., "Waters and forests: from historical controversy to scientific debate," *Journal of Hydrology*, 291: 1–27, 2004.

Arnold, J. G., M. A. Youssef, H. Yen, M. J. White, A. Sheshukov, A. M. Sadeghi, D. N. Moriasi, et al., "Hydrological processes and model representation, Transactions of the ASABE. 58:1637-1660, 2015.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams, "Large area hydrologic modeling and assessment—Part 1: Model development, *Journal of the American Water Resources Association* 34: 73–89, 1998.

Averyt, K., J. Meldrum, P. V. Caldwell, G. Sun, S. G. McNulty, A. Huber-Lee, and N. Madden, Sectoral vulnerabilities to changing water resources in the conterminous U.S. *Environmental Research Letters*, 8 (035046): 2013, doi:10.1088/1748-9326/8/3/035046. P 1-9.

Band, L. E., J. J. McDonnell, J. M. Duncan, A. Barros, A. Bejan, T. Burt, W. E. Dietrich, et al., "Ecohydrological flow networks in the subsurface," *Ecohydrology*, 7: 1073–1078, 2014.

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

Beschta, R. L., "Forest hydrology in the Pacific Northwest: additional research needs," *Journal of the American Water Resources Association*, 34: 729–741, 1998.

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

Binkley, D. and T. C. Brown, "Forest practices as nonpoint sources of pollution in North-America," *Water Resources Bulletin*, 29: 729–740, 1993.

Binkley, D., H. Burnham, and H. L. Allen, "Water quality impacts of forest fertilization with nitrogen and phosphorus," *Forest Ecology and Management*, 121: 191–213, 1999.

Black, P. E., *Watershed Hydrology*, Ann Arbor Press, Chelsea, MI, 1996.

Bladon, K. D., M. B. Emelko, U. Silins, and M. Stone, "Wildfire and the future of water supply," *Environmental Science & Technology*, 48: 8936–8943, 2014.

Bolstad, P. V. and W. T. Swank, "Cumulative impacts of landuse on water quality in a southern Appalachian watershed1, *Journal of the American Water Resources Association*, 33: 519–533, 1997.

Bonan, G. B., "Forests and climate change: forcings, feedbacks, and the climate benefits of forests," *Science*, 320: 1444–1449, 2008.

Bonell, M., "Progress in the understanding of runoff generation dynamics in forests," *Journal of Hydrology*, 150: 217–275, 1993.

Bormann, F. H. and G. E. Likens, Pattern and Process in a Forested Ecosystem: Disturbance, Development, and the Steady State Based on the Hubbard Brook Ecosystem Study, Springer-Verlag, New York, 1994.

Bosch, J. M. and J. D. Hewlett, "A review of catchment experiments to determine the effect of vegetation changes on water yield and evapo-transpiration," *Journal of Hydrology*, 55: 3–23, 1982.

Bren, L., *Forest Hydrology and Catchment Management: An Australian Perspective*, Springer, ISBN 978-94-017-9336-0 ISBN 978-94-017-9337-7 (eBook) DOI 10.1007/978-94-017-9337-7, 2014, pp. XIV, 268 p. 129 illus., 264 illus. in color.

Bren, L. J. and P. N. J. Lane, "Optimal development of calibration equations for paired catchment Projects," *Journal of Hydrology*, 519: 720–731, 2014.

Brooks, K. N., P. F. Folliott, and J. A. Magner, *Hydrology and the Management of Watersheds*, Wiley-Blackwell, Ames, IA, 2012, p. 1 online resource.

Brown, A. E., L. Zhang, T. A. McMahon, A. W. Western, and R. A. Vertessy, "A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation," *Journal of Hydrology*, 310: 28–61, 2005.

Brown, G. W., *Forestry and Water Quality*, O.S.U. Book Stores, Corvallis, OR, 1980.

Brown, T. C., M. T. Hobbins, and J. A. Ramirez, "Spatial distribution of water supply in the coterminous United States," *Journal of the American Water Resources Association*, 44: 1474–1487, 2008.

Bruijnzeel, L. A., "Hydrological functions of tropical forests: not seeing the soil for the trees?" *Agriculture Ecosystems & Environment* 104: 185–228, 2004.

Buttle, I. M., I. F. Creed, and R. D. Moore, "Advances in Canadian forest hydrology, 2003–2007," *Canadian Water Resources Journal*, 34: 113–125, 2009.

Buttle, J. M., I. F. Creed, and R. D. Moore, "Advances in Canadian forest hydrology, 1999–2003," *Hydrological Processes*, 19: 169–200, 2005.

Buttle, J. M., I. F. Creed, and J. W. Pomeroy, "Advances in Canadian forest hydrology, 1995–1998," *Hydrological Processes*, 14: 1551–1578, 2000.

Calder, I. R., "Forests and water-Ensuring forest benefits outweigh water costs," *Forest Ecology and Management*, 251: 110–120, 2007.

Caldwell, P. V., G. Sun, S. G. McNulty, E. C. Cohen, and J. A. M. Myers, "Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US," *Hydrology and Earth System Sciences*, 16, 2839–2857, 2012.

Callahan, T. J., V. M. Vulava, M. C. Passarello, and C. G. Garrett, "Estimating groundwater recharge in lowland watersheds," *Hydrological Processes*, 26: 2845–2855, 2012.

Chang, M., *Forest Hydrology: An Introduction to Water and Forests*, CRC Press, Boca Raton, FL, 2013.

Chapin, F. S., P. A. Matson, and P. M. Vitousek, *Principles of Terrestrial Ecosystem Ecology*, Springer, New York, 2011.

Clausen, J. C. and J. Spooner, United States. Environmental Protection Agency. Office of Water, 1993, *Paired Watershed Study Design*, U.S. Environmental Protection Agency, Office of Water, Washington, D. C., 1993.

Creed, I. F., A. T. Spargo, J. A. Jones, J. M. Buttle, M. B. Adams, F. D. Beall, E. G. Booth, et al., "Changing forest water yields in response to climate warming: results from long-term experimental watershed sites across North America," *Global Change Biology*, 20: 3191–3208, 2014.

Dai, Z., C. Li, C. Trettin, G. Sun, D. Amatya, and H. Li, "Bi-criteria evaluation of the MIKE SHE model for a forested watershed on the South Carolina coastal plain," *Hydrology and Earth System Sciences*, 14: 1033–1046, 2010.

Dai, Z. H., C. C. Trettin, C. S. Li, H. Li, G. Sun, and D. M. Amatya, "Effect of assessment scale on spatial and temporal variations in CH_4, CO_2, and N_2O fluxes in a forested wetland," *Water, Air, & Soil Pollution*, 223: 253–265, 2012.

Dawson, T. E., "Fog in the California redwood forest: ecosystem inputs and use by plants," *Oecologia*, 117: 476–485, 1998.

Day, J. W., D. F. Boesch, E. J. Clairain, G. P. Kemp, S. B. Laska, W. J. Mitsch, K. Orth, et al., "Restoration of the Mississippi Delta: lessons from hurricanes Katrina and Rita," *Science*, 315: 1679–1684, 2007.

De la Crétaz, A. L. and P. K. Barten, *Land Use Effects on Streamflow and Water Quality in the Northeastern United States*, CRC; Taylor & Francis, Boca Raton, FL, London, 2007.

Domec, J. C., J. S. King, A. Noormets, E. Treasure, M. J. Gavazzi, G. Sun, and S. G. McNulty, "Hydraulic redistribution of soil water by roots affects whole-stand evapotranspiration and net ecosystem carbon exchange," *New Phyto*logist, 187: 171–183, 2010.

Duda, P. B., P. R. Hummel, A. S. Donigian, and J. C. Imhoff, "Basins/HSPF: model use, calibration, and validation," *Transactions of the ASAE*, 55: 1523–1547, 2012.

Edwards, M. B. P. and P. J. T. Roberts, "Managing forests for water: the South African experience," *The International Forestry Review*, 8: 65–71, 2006.

Edwards, P. J. and K. W. J. Williard, "Efficiencies of forestry best management practices for reducing sediment and nutrient losses in the Eastern United States," *Journal of Forestry*, 108: 245–249, 2010.

Ellison, D., M. N. Futter, and K. Bishop, "On the forest cover-water yield debate: from demand- to supply-side thinking," *Global Change Biology*, 18: 806–820, 2012.

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

Folliott, P. F., G. J. Gottfried, and M. B. Baker, "Water yield from forest snowpack management: research findings in Arizona and New Mexico," *Water Resources Research*, 25: 1999–2007, 1989.

Foley, J. A., R. DeFries, G. P. Asner, C. Barford, G. Bonan, S. R. Carpenter, F. S. Chapin, et al., "Global consequences of land use," *Science*, 309: 570–574, 2005.

Fu, G., S. P. Charles, and F. H. S. Chiew, "A two-parameter climate elasticity of streamflow index to assess climate change effects on annual streamflow," *Water Resources Research*, 43:1-12, 2007.

Gilliam, R. W., "The capillary fringe and its effects on water table response," *Journal of Hydrology*, 67: 307–324, 1984.

Golden, H. E., G. R. Evenson, S. Tian, D. Amatya, and G. Sun, "IForest hydrology modeling," n: Amatya, D.M., Williams, T.M., Bren, L. and de Jong, C. (Eds) (2016) Forest Hydrology: Processes, Management and Assessment. CAB International, Wallingford, UK.

Hewlett, J. D., *Principles of Forest Hydrology*, University of Georgia Press, Athens, GA, 1982.

Hewlett, J. D. and A. R. Hibbert, "Factors affecting the response of small watersheds to precipitation in humid areas," *Forest Hydrology*, 275–290, 1967.

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

Ice, G. G., D. G. Neary, and P. W. Adams, "Effects of wildfire on soils and watershed processes," *Journal of Forestry*, 102: 16–20, 2004a.

Ice, G. G. and J. D. Stednick, Society of American Foresters, *A Century of Forest and Wildland Watershed Lessons*, Society of American Foresters, Bethesda, MD, 2004b.

Irmak, S. and D. Mutiibwa, "On the dynamics of canopy resistance: Generalized linear estimation and relationships with primary micrometeorological variables," *Water Resources Research*, 46:1-20. W08526, 2010.

Jackson, R. B., J. Canadell, J. R. Ehleringer, H. A. Mooney, O. E. Sala, and E. D. Schulze, "A global analysis of root distributions for terrestrial biomes," *Oecologia*, 108: 389–411, 1996.

Jackson, R. B., E. G. Jobbagy, R. Avissar, S. B. Roy, D. J. Barrett, C. W. Cook, K. A. Farley, et al., "Trading water for carbon with biological sequestration," *Science*, 310: 1944–1947, 2005.

Jackson, R. B., E. G. Jobbagy, and M. D. Nosetto, "Ecohydrology in a human-dominated landscape," *Ecohydrology*, 2: 383–389, 2009.

Jayakaran, A. D., T. M. Williams, H. Segane, D. M. Amatya, B. Song, and C. C. Trettin, "Hurricane impacts on a pair of coastal forested watersheds: implications of selective hurricane damage to forest structure and streamflow dynamics," *Hydrology and Earth System Sciences*, 18: 1151–1164, 2014.

King, J. S., R. Ceulemans, J. M. Albaugh, S. Y. Dillen, J-C. Domec, R. Fichot, M. Fischer, et al., "The challenge of lignocellulosic bioenergy in a water-limited world," *Bioscience*, 63: 102–117, 2013.

Leavesley, G., L. Stannard, and V. Singh, "The precipitation-runoff modeling system-PRMS," *Computer Models of Watershed Hydrology*, 281–310, 1995.

Lee, R., *Forest Hydrology*, Columbia University Press, New York, 1980.

Levia, D. F., D. Carlyle-Moses, and T. Tanaka, "Forest hydrology and biogeochemistry: synthesis of past research and future directions," Springer, Dordrecht, New York, 2011.

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

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges, "A simple hydrologically based model of land surface water and energy fluxes for general circulation models," *Journal of Geophysical Research: Atmospheres (1984–2012)*, 99: 14415–14428, 1994.

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

Liu, Y. Q., "A numerical study on hydrological impacts of forest restoration in the southern United States," *Ecohydrology*, 4: 299–314, 2011.

Loftis, J. C., L. H. MacDonald, S. Streett, H. K. Iyer, and K. Bunte, "Detecting cumulative watershed effects: the statistical power of pairing," *Journal of Hydrology*, 251: 49–64, 2001.

Lu, J. B., G. Sun, S. G. McNulty, and N. B. Comerford, "Sensitivity of pine flatwoods hydrology to climate change and forest management in Florida, USA," *Wetlands*, 29: 826–836, 2009.

Luce, C., P. Morgan, K. Dwire, D. Isaak, Z. Holden, and B. Rieman, Climate change, forests, fire, water, and fish: building resilient landscapes, streams, and managers, *General Technical Report RMRS-GTR-290*, USDA Forest Service, Fort Collins, CO. 2012.

Ma, Z., S. Kang, L. Zhang, L. Tong, and X. Su, "Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest China," *Journal of Hydrology*, 352: 239–249, 2008.

Maidment, D. R., *Handbook of Hydrology*, McGraw-Hill, New York, 1993.

Malone, R. W., G. Yagow, C. Baffaut, M. Gitau, Z. Qi, D. M. Amatya, P. B. Parajuli, et al., " " Parameterization guidelines and considerations for hydrologic models," *Transactions of the ASABE*, 58:1681-1703.

McCulloch, J. S. G. and M. Robinson, "History of forest hydrology," *Journal of Hydrology*, 150: 189–216, 1993.

McDonnell, J. J., I. F. Owens, and M. K. Stewart, "A case-study of shallow flow paths in a steep zero-order basin," *Water Resources Bulletin*, 27: 679–685, 1991.

McLaughlin, D. L., D. A. Kaplan, and M. J. Cohen, "Managing forests for increased regional water yield in the southeastern US coastal plain, *Journal of the American Water Resources Association*, 49: 953–965, 2013.

McNulty, S. G., J. M. Vose, and W. T. Swank, "Potential climate change effects on loblolly pine forest productivity and drainage across the southern United States," *Ambio*, 25: 449–453, 1996.

Mikkelson, K. M., L. A. Bearup, R. M. Maxwell, J. D. Stednick, J. E. McCray, and J. O. Sharp, "Bark beetle infestation impacts on nutrient cycling, water quality and interdependent hydrological effects," *Biogeochemistry*, 115: 1–21, 2013.

Milly, P. C. D., J. Betancourt, M. Falkenmark, . M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer, "Climate change—stationarity is dead: Whither water management?" *Science*, 319: 573–574, 2008.

Mohamed, V. A., W. G. M. Bastiaanssen, H. H. G. Savenije, B. J. J. M. van den Hurk, and C. M. Finlayson, "Wetland versus open water evaporation: an analysis and literature review," *Physics and Chemistry of the Earth*, 47–48: 114–121, 2012.

NRC, *Hydrologic Effects of a Changing Forest Landscape*, The National Academies Press, Washington, D. C., 2008.

O'Loughlin, E. M. and L. J. Bren, Institution of Engineers Australia. National Committee on Hydrology and Water Resources, Australian Forestry Council. Forest Hydrology Working Group, *The First National Symposium on Forest Hydrology, Melbourne, May 11–13, 1982: Preprints of Papers*, Institution of Engineers, Australia, Barton, A.C.T., 1982.

Onda, Y., T. Gomi, S. Mizugaki, T. Nonoda, and R. C. Sidle, "An overview of the field and modelling studies on the effects of forest devastation on flooding and environmental issues," *Hydrological Processes*, 24: 527–534, 2010.

Oudin, L., V. Andreassian, J. Lerat, and C. Michel, "Has land cover a significant impact on mean annual streamflow? An international assessment using 1508 catchments," *Journal of Hydrology*, 357: 303–316, 2008.

Prokopy, L. S., Z. A. Gocmen, J. Gao, S. B. Allred, J. E. Bonnell, K. Genskow, A. Molloy, et al., "Incorporating social context variables into paired watershed designs to test nonpoint source program effectiveness," *Journal of the American Water Resources Association*, 47: 196–202, 2011.

Puhlmann, H., *Forest Hydrology: Results of Research in Germany and Russia*, IHP/HWRP-Sekretariat, Koblenz, 2007.

Qi, S., G. Sun, Y. Wang, S. G. McNulty, and J. A. M. Myers, "Streamflow response to climate and landuse changes in a coastal watershed in North Carolina," *Transactions of the ASAE*, 52: 739–749, 2009.

Schaake, J. C. and P. E. Waggoner, "From climate to flow," *Climate Change and US Water Resources*, 177–206, 1990.

Sedell, J. R., *Water & the Forest Service*, The USDA Forest Service, Washington, D. C. 2000.

Simonit, S. and C. Perrings, "Reply to Ogden and Stallard: phenomenological runoff models in the Panama Canal watershed," *Proceedings of the National Academy of Sciences U S A*, 110: E5038–E5038, 2013.

Skaggs, R. W., G. M. Chescheir, G. P. Fernandez, D. M. Amatya, and J. Diggs, "Effects of land use on soil properties and hydrology of drained coastal plain watersheds," *Transactions of the ASAE*, 54: 1357–1365, 2011.

Sopper, W. E. and H. W. Lull, National Science Foundation (U.S.), Pennsylvania State University, School of Forest Resources, *Forest Hydrology; Proceedings of a National Science Foundation Advanced Science Seminar Held at the Pennsylvania State University, University Park, Pennsylvania, August 29–September 10, 1965*, Symposium Publications Division, Oxford, 1967.

Ssegane, H., D. M. Amatya, G. M. Chescheir, W. R. Skaggs, and J. E. Nettles, "Consistency of hydrologic relationships of a paired watershed approach," *American Journal of Climate Change*, 2: 147–164, 2013.

Stednick, J. D., "Monitoring the effects of timber harvest on annual water yield," *Journal of Hydrology*, 176: 79–95, 1996.

Sun, G., K. Alstad, J. Q. Chen, S. P. Chen, C. R. Ford, G. H. Lin, C. F. Liu, et al., "A general predictive model for estimating monthly ecosystem evapotranspiration," *Ecohydrology*, 4: 245–255, 2011a.

Sun, G., K. Alstad, J. Q. Chen, S. P. Chen, C. R. Ford, G. H. Lin, C. F. Liu, et al., "Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model," *Journal of Geophysical Research: Biogeosciences*, 116: 2011b.

Sun, G., P. V. Caldwell, and S. G. McNulty, "Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States," *Hydrological Processes*, dOI:10.1002/hyp.10469, 29:5016-5030, 2015.

Sun, G., S. R. Liu, Z. Q. Zhang, and X. H. Wei, X. H., "Forest hydrology in China: Introduction to the featured collection," *Journal of the American Water Resources Association*, 44: 1073–1075, 2008a.

Sun, G. and B. G. Lockaby, "Water quantity and quality at the urban–rural interface," *Urban–Rural Interfaces: Linking People and Nature*, 29–48, 2012.

Sun, G., S. G. McNulty, D. M. Amatya, R. W. Skaggs, L. W. Swift, J. P. Shepard, and H. Riekerk, "A comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the Southern US," *Journal of Hydrology*, 263: 92–104, 2002.

Sun, G., S. G. McNulty, J. A. M. Myers, and E. C. Cohen, "Impacts of multiple stresses on water demand and supply across the southeastern United States, *Journal of the American Water Resources Association*, 44: 1441–1457, 2008b.

Sun, G., H. Riekerk, and L. V. Kornhak, "Ground-water-table rise after forest harvesting on cypress-pine flatwoods in Florida," *Wetlands*, 20: 101–112, 2000.

Sun, G., G. Zhou, Z. Zhang, X. Wei, S. G. McNulty, and J. M. Vose, "Potential water yield reduction due to forestation across China,"*Journal of Hydrology*, 328: 548–558, 2006.

Swank, W. T. and D. A. Crossley, Coweeta Hydrologic Laboratory (U.S.), *Forest Hydrology and Ecology at Coweeta*, Springer-Verlag, New York, 1988.

Tague, C. L. and L. E. Band, 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, 2004.

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

Vorosmarty, C. J., C. Pahl-Wostl, and A. Bhaduri, "Water in the anthropocene: new perspectives for global sustainability," *Current Opinion Environmental Sustainability*, 5: 535–538, 2013.

Vose, J. M., C. R. Ford, S. Laseter, S. Dymond, G. Sun, B., M., Adams, S. Sebestyen, et al., *Can Forest Watershed Management Mitigate Climate Change Impacts on Water Resources?*, IAHS, 2011a. Wallingford UK.

Vose, J. M., D. Peterson, and T. Patel-Weynand (Eds.), *Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector*, U.S. Forest Service, Pacific Northwest Research Station, Portland, OR, 2012.

Vose, J. M., G. Sun, C. R. Ford, M. Bredemeier, K. Otsuki, X. H. Wei, Z. Q. Zhang, and L. Zhang, "Forest ecohydrological research in the 21st century: what are the critical needs?" *Ecohydrology*, 4: 146–158, 2011b.

Waring, R. H. and S. W. Running, *Forest Ecosystems: Analysis at Multiple Scales*, Elsevier/Academic Press, Amsterdam, Boston, 2007.

Wei, X. H., W. F. Liu, and P. C. Zhou, "Quantifying the relative contributions of forest change and climatic variability to hydrology in large watersheds: a critical review of research methods," *Water*, 5: 728–746, 2013.

Wei, X. H. and M. F. Zhang, "Quantifying streamflow change caused by forest disturbance at a large spatial scale: a single watershed study," *Water Resources Research*, W12525, 46: 1-15 2010.

Weiler, M. and J. J. McDonnell, "Conceptualizing lateral preferential flow and flow networks and simulating the effects on gauged and ungauged hillslopes," *Water Resources Research*, 43: 2007. 0.1029/2006WR004867.

Wigmosta, M. S., B. Nijssen, P. Storck, and D. Lettenmaier, "The distributed hydrology soil vegetation model," *Mathematical Models of Small Watershed Hydrology and Applications*, 7–42, 2002.

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

Xie, J., G. Sun, H. S. Chu, J. G. Liu, S. G. McNulty, A. Noormets, R. John, et al., "Long-term variability in the water budget and its controls in an oak-dominated temperate forest," *Hydrological Processes*, 28: 6054–6066, 2014.

Yu, P. T., Y. H. Wang, A. P. Du, W. Guan, K. H. Feger, K. Schwarzel, M. Bonell, W. Xiong, and S. Pan, "The effect of site conditions on flow after forestation in a dryland region of China," *Agricultural and Forest Meteorology*, 178: 66–74, 2013.

Zégre, N., A. E. Skaugset, N. A. Som, J. J. McDonnell, and L. M. Ganio, "In lieu of the paired catchment approach: Hydrologic model change detection at the catchment scale," *Water Resources Research*, 46: 2010.

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

Zhang, L., F. F. Zhao, and A. E. Brown, "Predicting effects of plantation expansion on streamflow regime for catchments in Australia," *Hydrology and Earth System Sciences*, 16: 2109–2121, 2012.

Zhang, L., F. F. Zhao, Y. Chen, and R. N. M. Dixon, "Estimating effects of plantation expansion and climate variability on streamflow for catchments in Australia," *Water Resources Research*, 47: 20111.

Zhao, F. F., L. Zhang, Z. X. Xu, and D. F. Scott, "Evaluation of methods for estimating the effects of vegetation change and climate variability on streamflow," *Water Resources Research*, 46: 2010.

Zhou, G., X. Wei, X. Chen, P. Zhou, X. Liu, Y. Xiao, G. Sun, et al., "Global pattern for the effect of climate and land cover on water yield," *Nature Communications*, 6: 1-9, 2015.