17 Future Directions in Forest Hydrology

J. Nettles[1]*, L. J. Bren[2], D. M. Amatya[3], G. Sun[4], T. M. Williams[5] and C. De Jong[6]
[1]Weyerhaeuser Company, Columbus, Mississippi, USA; [2]The University of Melbourne, Creswick, Victoria, Australia; [3]Santee Experimental Forest, Southern Research Station, USDA Forest Service, Cordesville, South Carolina, USA; [4]Eastern Forest Environmental Threat Assessment Center, USDA Forest Service, Research Triangle Park, North Carolina, USA; [5]Clemson University, Clemson, South Carolina, USA; [6]University of Strasbourg, Strasbourg, France

Abstract
The chapter highlights the similarities and differences in hydrological characteristics and research needs among boreal, temperate, subtropical and tropical forests. Forest hydrology began as an attempt to understand the variations in stream behavior induced both naturally and by humankind's management of forests. This interest is now being pushed along by the realities of "climate change," with new demands. The major volumetric component of the hydrological cycle is evapotranspiration, and its quantification (and management) presents key challenges. Difficulties in measurement at both tree and forest scales are still present, but there are whole new sources of information from flux towers to satellite measurements now publicly available. These will allow insights into ecohydrology, viewed as the basis of modern watershed ecosystem management.

17.1 Forest Hydrology: What Have We Learned?

17.1.1 The hydrological cycle in forests

Forest hydrology is a distinct branch of hydrology that addresses the unique conditions created by trees and the understory within forests. Understanding forests, with trees that can grow over 100m tall, have crowns up to 20–30m in diameter, roots extending 5–10m deep and lifespans ranging from 50 to 5000 years, presents significant scientific challenges. Forests cover approximately one-third of the world, with over half of that in just five countries – Russia, Brazil, Canada, the USA and China. Tropical forests make up 45% of area by climatic region, followed by boreal (27%), temperate (16%) and subtropical (11%) forests (FAO, 2020). The wide distribution of forests makes it difficult to generalize about the role of trees and forest ecosystems in the global hydrological cycle, and although *in situ* data collection has been decreasing for several decades (Tourian *et al.*, 2022), satellite data, models and public data sets are increasingly available to study the global hydrological cycle (e.g. Koutsoyiannis, 2020).

The chapters in this book have dealt with major hydrological processes such as runoff, drainage and evapotranspiration (ET) in forests across scales, climatic regimes and dominant processes – from snow-dominated temperate mountain forest watersheds to low-gradient humid coastal plain forests, and most other forest

*Corresponding author: jami.nettles@weyerhaeuser.com

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types including flooded and wetland forests. In most forests, the largest component of water loss is evaporation of precipitation (see Chapter 3, Fig 3.1, this volume), with losses greatest for conifers in regions of frequent low-intensity rainfall separated by dry periods (see Chapter 11). Yet in some tropical montane forests, water condenses from the atmosphere on to tree leaves and the resulting drip may increase precipitation by up to 20% (see Chapter 9). In very cold continental climates, open areas are more likely to lose water (snow) by sublimation and wind than forests, but in warmer regions, openings have greater melt and produce more water than forests. Transpiration is a dominant process in the forest hydrological cycle but is generally difficult to measure directly (see Chapter 3), except on a single tree basis. The word 'evapotranspiration' was coined less than 100 years ago to reflect the difficulty in separating water loss processes, but recent authors suggest that use of ET undermines our recognition of these as separate processes (Savenije, 2004; Miralles *et al*., 2020). Although the abovementioned issues are only a few of the challenges in understanding the many hydrological processes that depend upon temperature, rainfall, species, tree age, slope, drainage and soil type, the summary provided in the 16 chapters of this book strives to outline some of the major findings on the most recent forest hydrological science and applications across the forests of the world.

Figure 16.1 shows the distribution of forests spread over much of the earth. Tropical forests are concentrated in Africa, South America and South-East Asia, and subtropical forests in south-eastern North America and south-eastern Asia. Temperate forests are concentrated in Europe, coastal Australia, eastern North America and far eastern Asia, while the vast northern boreal forests circle the Earth in a band across Europe, Asia and North America. Temperature limits alpine forests with treeline elevations varying from 700 m in Sweden (68°N) to 4000 m in Mexico (19°N) and Ecuador (0°), but all with mean annual surface temperatures of 6–7°C (Körner and Paulsen, 2004). Likewise, forests are absent in regions of permafrost that occur with mean annual air temperatures below about –6°C (Smith and Riseborough, 2002). The other major limit to forest distribution is the balance of annual precipitation and potential evaporation. In the tropics, forests are absent when precipitation is below 1000 mm (Staver *et al*., 2011), but in the arctic (61°N), forests are present with 260 mm of annual precipitation (Carey and Woo, 2001). In both subtropical and temperate zones, forests are also constrained by precipitation and evaporation, but patterns of forest are highly fragmented due to human land uses. Analysis of tropical forests shows forest-rainfall feedback at a region scale, with loss of precipitation following deforestation (Smith *et al*., 2023), increasing the vulnerability of areas already facing drought due to climate change.

Below are highlights of learnings, applied to the major forest climatic regions, or various aspects of forest hydrological science, including its applications, limitations, challenges and opportunities for a future of changing land use and climate.

Boreal forests

Boreal forests, found in high latitudes of the northern hemisphere, are the second most widespread forest in the world (FAO, 2020). Chapters 7 and 11, on mountains and taiga, discuss how forests cause snow hydrology to vary with temperature and winds during and shortly after snow falls. In colder regions, snow does not adhere to tree crowns as well and is easily dislodged by wind, and on the ground, snow is subject to further wind distribution and sublimation (Chapter 11). In warmer and more maritime regions, interception of snow is greater due to the tendency of snow near 0°C to adhere to foliage, with greater likelihood of partial melting and refreezing. These effects reverse the normal impact of forest removal in far northern regions of Siberia, causing a postharvest reduction of water available for streamflow (Chapter 11). While snowmelt is the most important factor in streamflow, in more southern areas, rain-on-snow events are often associated with the largest flows. Streamflow may cease in small watersheds due to freezing in winter and/or increased ET rates in the summer, while flow beneath the ice in larger rivers is difficult to measure.

Temperate forests

The vast majority of temperate forests lie in the northern hemisphere, with other areas found in the South Island of New Zealand, south-eastern Australia and Chile. These forest types have been studied the most extensively, and forest hydrology as a science originated in the temperate forests of central Europe in the 18th century. Most of the long-term US forest hydrology data originated in temperate forest types (see Chapter 5). Nearly all the runoff process studies cited in Chapter 2 occurred in the temperate forests of North America, Europe, New Zealand and Australia.

Distinctive characteristics of this forest region are a long dormant season due to low temperatures, and extensive deciduous forests in the northern hemisphere. High ET rates during late spring and summer generally result in considerably more ET demand than precipitation in late summer and early autumn. Precipitation during the winter may be stored as snow or soil moisture, when deciduous forest vegetation is dormant and evergreen vegetation is semi-dormant. Streamflow is generally seasonal, with highest flows during the spring (Wasko *et al*., 2020), due to snowmelt, rain on snow or high soil moisture.

Subtropical forests

Forests in the subtropical climatic zones have two distinct climatic patterns: (i) rainfall well distributed throughout the year; and (ii) winter rainfall with hot dry summers. Forests in the well-distributed rainfall zone occur in the south-eastern USA, south-eastern China, southern Japan, north-eastern Australia and the North Island of New Zealand. Winter rainfall and hot dry summers are typical around the Mediterranean Sea, which gives this climatic type its common name. Mediterranean climates are also common in parts of south-western North America and southern Australia.

The higher latitudes of the subtropical zone, as in the temperate zone, have a winter season of plant dormancy and lower evaporative demands. In the Mediterranean climate, lower winter evaporative demand combines with higher rainfall for a highly seasonal runoff pattern. Although forest fires are common in all climate types, the dry summers of the Mediterranean type make the hydrological impacts of forest fire (see Chapter 10) an important aspect in this region.

In eastern North America and Asia, the subtropical climatic zone is also influenced by the maritime climate from the Northern Tropical Convergence Zone during summer and fall. Tropical cyclones (hurricanes and typhoons) are the most spectacular aspect of this influence, but higher summer rainfall is common. Summer runoff is generally small or non-existent. However, rainfalls of 100–600 mm associated with tropical cyclones produce large areas (approaching 100% of the catchment) of saturation-excess overland flow throughout coastal low-gradient watersheds. For example, the bar graph with 95% confidence intervals of the 1 and 24 hour 100 year intensity rainfall of close to 9.3 cm/h and 1.45 cm/h at the Santee site in Fig. 5.5 in Chapter 5 includes approximately 500 mm of rainfall recorded in 48 hour as an indirect result of Hurricane Joaquin at the Santee Experimental Forest in coastal South Carolina when almost the whole forest was flooded (see Fig. 8.4, Chapter 8). This extreme precipitation-induced flood may have had severe impacts on both forest stands and road infrastructure, disrupting both traffic and aquatic organism passage and causing economic losses.

Tropical forests

One important aspect of tropical forest hydrology is the lack of cold-temperature-induced dormancy. Trees are evergreen and transpire the entire year, as long there is adequate rainfall. Tropical forests are divided into rainforests, with high year-round rainfall, and seasonal monsoonal forests, with a pronounced dry season. High energy associated with direct solar angles causes high rates of evaporation and intense thunderstorms where high atmospheric moisture is available. High energy results in extreme rates of hydrological processes, which may not follow the principles tested primarily in the temperate zone.

Tropical rainforests are located primarily in the Amazon and Congo Basins and south-east Asia, as well as insular and montane forests where prevailing winds cause advection of coastal moisture. These forests are generally close to the equator and have relatively constant daily temperature fluctuations throughout the year. Despite multi-layered evergreen forests, interception losses can be 9–11.6% of rainfall in the Amazonian rainforest (Lloyd *et al*., 1988; Shuttleworth and Pereira, 1997; Czikowsky and Fitzjarrald, 2009).

Seasonal monsoons are most typically associated with India and South-East Asia, but seasonality is fairly high between 15° and 20° latitudes, associated with seasonal movement of the Intertropical Convergence Zone. During the rainy season, these regions may have high-intensity rainfall over sustained periods. Bonell and Gilmour (1978) found that surface runoff and rainfall intensity were factors in the forest hydrology of northern Australia, in contradiction to contention that rainfall intensity did not explain streamflow volume or peak discharge in humid temperate forests of the Appalachian Mountains in the USA (Hewlett *et al*., 1977, 1984). Chapter 9 discussed the importance of understanding stream generation pathways in tropical forests, along with noting that, while field data collection lags behind that of temperate regions, the large fluxes significantly impact regional and global climate and are increasingly important.

17.2 Where Do We Go from Here?

17.2.1 What will forest hydrology become?

Forest hydrology, the study of water dynamics within forest catchments, emerged in an effort to understand how human interference to forests alters the amount of water in our rivers during floods and droughts. Now humans are changing both landscape and climate, while depending on forests for resources and sustainability of both ecosystems and societies. Farooqi *et al*. (2024) also stated that the intensified changes in global climate, land use and cover, and pollution that occurred over last the century have brought about adverse impacts on forests and their services in terms of water regulation, signifying the importance of forest hydrological research as a re-emerging topic of scientific interest. Accordingly, there is an urgent need for a better understanding of the linkages between trees, forests and water to raise awareness and increase capacity building in forest hydrology, and for embedding this knowledge and research findings in policies and management practices. In addition, Farooqi *et al*. (2024) emphasized that there is also an urgent need to include more under-represented nations and regions in future investigations to comprehensively grasp how interactions between forest ecosystems and water can impact the entire planet.

Many of the challenges of the coming decades discussed in the context of Europe and the south-eastern USA (see Chapters 5 and 15) are equally applicable to many other parts of the world. Forest hydrology over the last century has been concerned primarily with the effects of various forms of forest management on water quantity and quality, but the coming years will see a greater understanding of the important role of forests, both managed and unmanaged, as a natural infrastructure for water supporting ecosystem health – a ‘nature-based solution’ – across the globe (Springgay, 2019).

Over the next century, the role of forests in mitigating climate change may become the greatest challenge. Forests currently sequester a substantial amount of anthropogenic carbon, but there is potential for much more, either through improved management of existing forests or through afforestation (Mo *et al*., 2023). Rapidly growing forests can provide sustainable resources and carbon-neutral energy, but as we saw in Chapter 3, forest carbon assimilation and transpiration are controlled by the same physiological mechanism, stomatal opening. While we do understand the correlation between carbon intake and transpiration, we have a limited understanding of the integration of tree genetics and larger-scale factors that influence the variation in that relationship (i.e. water-use efficiency) or rates. Zhang *et al*. (2023) outlined many of the factors involved in this relationship, including forest composition, climate and forest management, along with the future research needed to understand and manage forests to balance growth for wood products, energy production and carbon sequestration. The stakes are high: the Global Commission on the Economics of Water stated: ‘We will fail on climate change if we fail on water’ (Mazzucato *et al*., 2023).

Streamflow from forested watersheds produces high-quality water requiring minimal treatment for drinking water (Neary *et al*., 2009), an increasingly valuable and scarce resource. In the USA, 46% of the total surface water supply comes from forests (Liu *et al.*, 2022). Forests play a role in aquifer recharge by affecting the processes by which rain is partitioned into subsurface flow and surface runoff. Although these processes have been well defined (see Chapter 2), understanding how climate, forest characteristics, soils and geology determine the pathways and quantities of water movement, from crowns to streams or aquifers, is still far from our grasp. Because forests make up a relatively large portion of many of our watersheds, it is important to understand the hydrology, processes and pathways of the water cycle on both natural and managed forests, while considering the contribution of other land uses.

Much of our present understanding of forest hydrology is limited mainly to research on temperate forests, so even the most well-established tenets do not apply universally. We have given examples of contrasting situations; for example, cutting forests in parts of Siberia may decrease streamflow rather than increase it. In another example, forest floor infiltration may not exceed rainfall intensity during intense tropical thunderstorms. To extend forest hydrology, we must understand the large variations of hydrological responses and their drivers, and extend research into all forested regions. Farooqi *et al.* (2024) conducted a thorough review of global research, trends and future directions in advancing forest hydrological research.

17.2.2 ET and transpiration

The studies of ET reveal how little we really know about the principles that drive movement of water from forests into the atmosphere. ET accounts for the greatest loss of precipitation in most forested ecosystems (see Chapter 3), but in traditional paired-watershed studies, it is estimated as the residual water balance, assuming no loss of water from the watershed other than that measured as stream outflow. While these relationships have taught us much about individual watersheds and led to general principles (Zhang *et al.*, 2001), more direct measurement of ET will help us close gaps in the water balance.

Although many studies have been done on forest interception, our understanding of how interception varies as a function of forest structure is limited due to a lack of sufficient observational data and thus remains poorly constrained, with estimates ranging from 10% to 50% of precipitation, depending on canopy characteristics (Grunicke *et al.*, 2020). Recently, Lian *et al.* (2022) reported a recent decline in global interception due to altered rainfall regimes (e.g. rainfall events are becoming less frequent and more intense since 2000), suggesting that ongoing rainfall changes favor a partitioning toward more soil moisture and runoff, benefiting ecosystem functions but simultaneously increasing flood risks.

Sapflow measurements have been a part of forest hydrology research for almost 100 years (Swanson, 1994), although of course the technology has advanced in accuracy and deployability. Wide differences in sapflow are evident among different tree species and sizes as can be seen in Fig. 3.3 in Chapter 3. Upscaling to the stand level has long been recognized as a challenge (Čermák *et al.*, 2004), with upscaled sap flux measurements not capturing the variability in forest characteristics across the landscape (Ford *et al.*, 2007).

Fortunately, ET measurement and modeling may be the most rapidly expanding part of forest hydrology, with programs developed to aggregate ground-based data, such as Ameriflux, Fluxnet and Sapfluxnet with satellite measurements, and models, such as in OpenET in a 30m spatial scale. Integration of site-specific data with satellite data is giving scientists and land managers the ability to estimate site ET at a tract scale, although currently OpenET shows higher model error and variability for forested landscapes than for agricultural land (Volk *et al.*, 2024), consistent with Rashid and Tian (2024). OpenET provides data in timesteps as small as daily, and ultimately plans to provide retrospective ET data, giving scientists the ability to compare satellite data with historical watershed study data. This is currently being developed in the USA by a non-profit consortium, expanding across the Amazon Basin (OpenET-Brazil), and has the goal of being available in other regions across the globe. Similar other efforts by NASA's ECOSTRESS (Ecosystem Spaceborn Thermal Radiometric instrumentation on Space

Satellite) program are under way to quantify surface temperature and its derived products such as ET and its components on a 70m scale in 3–4 days interval (Fisher *et al.*, 2020). However, strong divergences exist among remote-sensing products when partitioning ET, and thus the individual components remain largely unvalidated (Talsma *et al.*, 2018). Therefore, future studies should also focus on obtaining field data for the ET components, particularly the canopy evaporation and the understory ET on varying forest types of ecoregions for ground-truthing of remote sensing products applied to large-scale assessments.

While ET measurements will be invaluable, research is still needed to improve models to predict the effect of forest management on water resources (Komatsu and Kume, 2020; Sun *et al.*, 2023). New remote-sensing techniques of spaceborne, airborne or ground-based LiDAR (light detection and ranging) will produce the better estimates of forest structure needed for hydrological and ecosystem models (Massey *et al.*, 2023). LiDAR data from GEDI (Global Ecosystem Dynamics Investigation), a project to map vertical structures in the world's forests (Dubayah *et al.*, 2020), will be combined with other remote-sensing products for more accurate and extensive data (e.g. Silva *et al.*, 2021) and Landsat data including Landsat Operational Land Imager and ICESAT-2 (ice, cloud and elevation Satellite) for change estimates. New approaches can be explored for forest systems, such as the one studied by Good *et al.* (2015), who combined two distinct stable-isotope flux partitioning techniques to quantify ET subcomponents (interception, transpiration, soil evaporation and surface water evaporation) and the hydrological connectivity of bound, plant-available soil waters with more mobile surface waters. Stoy *et al.* (2019) conducted a detailed review and synthesis of studies for partitioning ecosystem ET, including the challenges and opportunities. Others are using machine learning techniques to improve ET model accuracy (e.g. Jiang *et al.*, 2021; Elbeltagi *et al.*, 2024). While there is established work on partitioning ET into evaporation and transpiration (Kool *et al.*, 2014), there is much less on partitioning transpiration by vegetation, despite evidence that in temperate and boreal forests, understory vegetation averages one-third of growing-season ET (Balandier *et al.*, 2022). Below-canopy eddy flux towers, while still relatively rare, are producing valuable insights into vegetative water use (e.g. Constantin *et al.*, 1999; Kassuelke *et al.*, 2022; Wolf *et al.*, 2024). Short time-scale data may also improve our understanding of processes such as hydraulic redistribution of soil water (Domec *et al.*, 2010) and upscaling instantaneous ET to daily time scales (Jiang *et al.*, 2021).

17.2.3 Atmospheric redistribution of ET

One of the most important factors in the water cycle, the atmospheric redistribution of water, has possibly been the least pursued in forest hydrology, even though it may be the most critical for the future. This process of ET, condensation and precipitation drives downwind water availability (Ellison *et al.*, 2017), and the cooling effect also extends beyond the watershed scale, allowing reforesting regions to better weather temperature increases due to climate change (Barnes *et al.*, 2024). Historically, people associated forests and rainfall, assuming that forests increased rainfall instead of understanding that forests thrived in areas of higher rainfall (van Meerveld and Seibert, 2024). However, the relationship of forest to airshed is not as well understood as forest to watershed, and predictions of the atmospheric response to forest management are limited. A study by Hoek van Dijke *et al.* (2022) based on models and moisture recycling data showed that potential reforestation efforts could increase water availability by 6% in some regions while decreasing other regions by up to 38%, with streamflow also responding regionally. Another model of moisture recycling also showed large variability between regions in the amount of precipitation from vegetative ET, but also noted how sensitive some areas were to even small losses of precipitation (Keys *et al.*, 2016).

As regions improve sustainable forest-management practices, increase forest area and density to sequester carbon, and respond to the demand for wood and wood products, atmospheric effects will transcend borders. There is a critical need to understand and predict these effects of forest policy and practice, as they have the potential to affect water availability at local to global scales (Creed *et al.*, 2019).

17.2.4 Runoff processes

Chapter 2 discussed runoff concepts, with interesting observations of how early research assumed site-specific conditions to be more generalized than they are, biasing results. More recently, we have come to understand how multiple thresholds of runoff generation influence response, and that interactions of weather, climate, surface and subsurface connections vary with location and time. This includes the 'fill and spill' concept introduced by Spence and Woo (2003), and recently generalized by McDonnell *et al.* (2021), that allow representation of processes common to forested systems. However, quantitative estimates of flow generation mechanisms are dependent on the climate and physiographic characteristics of the site (Wu *et al.*, 2021). Most of our quantitative understanding has come from isotope or geochemical tracer analysis of streamflow. An outstanding discussion of the use and limitations of isotopes can be found in Klaus and McDonnell (2013), and a call for standardization of isotope methods includes a thorough discussion of challenges in their use in ecohydrological research (Millar *et al.*, 2022). While end-member mixing has been a common technique using geochemical tracers, the recent ability to differentiate dissolved organic carbon fractions of stream natural organic matter may provide alternatives to examine flow through the forest floor (Yang *et al.*, 2015).

17.2.5 Merging forest hydrology and ecosystems

Ecohydrology includes forest hydrology as the study of climate, soil and vegetation dynamics through space and time, and the intersection with ecological dynamics (Rodriguez-Iturbe, 2000), with recent scientists including the microbiome, atmosphere, climate and humans (Porporato and Yin, 2022) and emphasizing the importance of the catchment as the fundamental scale (Rinaldo and Rodriguez-Iturbe, 2022).

A recent concept that integrates sustainability and ecology is nature-based solutions, a concept especially applicable to forests and water (Springgay, 2019). While forests have been recognized as providing a wide range of ecosystem services that include water quality and quantity, nature-based solutions are actions that use, improve or protect ecosystems to provide multiple benefits for humans and biodiversity (Cohen-Shacham *et al.*, 2016). Springgay (2019) called forests a 'natural infrastructure for water,' and recognition of the central role of forests in natural and optimized solutions will only increase the need for accurate analysis and prediction of the effects of forest management on water resources.

17.2.6 Broader dimensions of forest hydrology

The scope of forest hydrological science must be expanded from understanding the meteorological and hydrological influences of forests based on small watershed research of the 20th century (Hewlett, 1982) to quantifying the ecohydrological impacts of global changes today (Amatya *et al.*, 2011; Vose *et al.*, 2011). It must also advance to address current complex issues, including urbanization, climate change, wildfires, invasive species, instream flow, floods, droughts, beneficial water uses, changing patterns of development and ownership, and changing societal values. In this context, there is a critical need for continued monitoring of existing long-term forest watersheds worldwide, as they are well suited for documenting and detailing baseline hydrological conditions and serving as valuable benchmarks for advancing forest hydrological science and addressing emerging forest and water issues. In addition, such research should be undertaken as an integrated approach in collaboration with a multidisciplinary team in future forest hydrological research that emphasizes not only the long-term data but also utilizes various innovative methodologies including the ground-based and remote-sensing-based data backed by process-based models.

Our ability to model large-scale processes has been limited by our ability to collect data that appropriately reflects and integrates parameter variability. 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 (Sun *et al.*, 2016, 2023). Recent advancements in monitoring with high-resolution sensors and mapping technology using LiDAR, satellite imageries, stable isotopes for partitioning water flux sources (Good *et al.*, 2015; Klaus *et al.*, 2015) and other sensor technologies, together with rapidly advancing computational techniques, should also be used as opportunities to address these complex processes. Global water models are being used not just for policy and science but also to drive publicly available information services, although predictions still show considerable differences between models (Gnann *et al.*, 2023).

17.3 Meeting Forest Management Needs

UNESCO's World Water Development Report (UN Water, 2024) noted that water demand continues to grow, even as half of the world's population is already experiencing water stress for at least part of the year. Global water demand has doubled since 1960 and is expected to increase by an additional 20–25% by 2050, with demand in sub-Saharan Africa expected to increase a staggering 163% (Kuzma *et al.*, 2023a; b). Climate change and natural variability may reduce water availability, even in areas unaccustomed to drought. These conditions may put strong pressure on forest managers to sustain and even increase water yields of forested watersheds for municipal and other downstream uses, while water stress leaves the forest itself more vulnerable to dieback, pests and fire (Grant *et al.*, 2013). At the same time, carbon sequestration initiatives typically favor afforestation, longer rotations and increased stocking (Kaarakka *et al.*, 2021) that will increase ET and forest water use (Farley *et al.*, 2005; Jackson *et al.*, 2005).

To develop tools to manage complex and sometimes competing interactions, we should not only advance forest hydrological science for understanding complex interactions but also learn to scale currently available research and model results to define reasonably achievable benchmarks of water quantity and quality. As the world demands an increased clean water supply and wood, energy and carbon storage from forests, forest hydrology becomes equally critical to sustainably providing services while protecting water resources.

From a recent list of 23 unsolved problems in hydrology (Blöschl *et al.*, 2019), one could get discouraged at the vast number of processes we do not understand and research questions to address within forest hydrology. What hydrological laws control catchments and how do they vary with scale? What causes spatial heterogeneity in hydrological processes? Why is runoff more sensitive to land use/land cover in some watersheds than others? How do we adapt models to changing vegetation dynamics? However, there is room to be hopeful that the coming years will bring many advances as our ability to collect and share data at relevant scales has greatly increased, and analysis of these large data sets will follow. The next decades promise a confluence of advanced instrumentation, computational power and analysis tools to put better understanding within our reach.

17.4 Conclusions

In its century of existence, forest hydrology has come a long way in quantifying the relationship between the world's forests and its water. The approaches have used field studies, modeling and remote sensing. There is a rapid escalation of information available due to both satellite measurement of hydrological variables and new ground-based approaches, which may change our basis approach to research. The issues of climate change and rising Earth temperatures are creating new research issues.

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