17 Future Directions in Forest Hydrology

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17.1 Forest Hydrology: What Have We Learned?

17.1.1 Hydrological cycle in forests

Forest hydrology is a separate and unique branch of hydrology due to the special conditions caused by trees, and the understorey beneath them, comprising a forest. Understanding the forest, with trees that can grow over 100 m tall, may have crowns up to 20–30 m in diameter with roots 5–10 m deep and spread as widely as the crowns, and have lifespans from 50 to 5000 years, presents unique challenges to science. Forests cover approximately 26.2% of the world, with 45.7% of Latin America and the Caribbean being covered, 35% of East Asia and the Pacific, and 35% of the European Union. Canada and the USA combined account for only 6.8% of the world's forests, while Africa has even less at 5.7% (About.com, 2013). The wide distribution of forests makes it difficult to generalize about the role of trees and forest ecosystems in the global hydrological cycle.

The 16 chapters organized in this book deal with major hydrological processes such as runoff, drainage and evapotranspiration on various forest types from northern boreal forests to tropical forests, from snow-dominated temperate mountain forest watersheds to low-gradient humid coastal plain forests, small- to large-scale watersheds, and most other forest types including flooded and wetland forests. Most forests lose water through evaporation of precipitation intercepted by crowns (Chapter 3), with losses greatest for conifers in regions of frequent low-intensity rainfall separated by dry periods (Chapter 14). 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% (Chapters 2 and 6). In very cold continental climates (Chapter 16) 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 (Chapter 3), except on a single tree basis. Estimates of transpiration on a stand, hillslope or watershed basis cannot be separated from evaporation leading to the coined word 'evapotranspiration', which Savenije (2004) suggested hampers our understanding of the process. Although these are only a few of the problems associated with trying to explain forest hydrology that varies with temperature, rainfall, species, tree age, slope, drainage and soil type, this

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summary strives to outline some of the major findings across the forests of the world.

Figure 10.1 shows the distribution of forests spread over much of the earth. Tropical forests are concentrated in Africa, South America and South-East Asia; 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; and 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 temperature between 6 and 7°C (Körner and Paulsen, 2004). Likewise, forests are absent in regions of permafrost that occurs with mean annual air temperature below about −6°C (Smith and Riseborough, 2002). The other major limit to forest distribution is the balance of annual rainfall and potential evaporation. In the tropics forests are absent when rainfall is below 1000 mm (Staver *et al.*, 2011) yet in the arctic (61°N) forests are present with 260 mm of annual precipitation (Carey and Woo, 2001). In both the subtropical and temperate zones forests are also constrained by rainfall and evaporation, but patterns of forest are highly fragmented due to human land uses. As we see in the discussions in Chapters 1 and 5, the interaction of man with forest land and hydrology provides great incentive to resolve issues in forest hydrology. The long recorded history of European settlement may provide insight into variations due to long-term human–forest interaction. Similarly, Chapter 8 provides an overview of runoff dynamics of drained forests managed for silvicultural production.

While Chapters 9 and 10 deal with reviews of modelling tools and applications of geospatial technologies for understanding hydrological processes, impact assessments and decision support systems on forested landscapes, Chapter 15 addresses challenges in forest hydrological science for watershed management in the remainder of 21st century. Below we provide some critical highlights of what we learned from each chapter and where we go from here regarding various aspects of forest hydrological science, its applications, limitations, challenges, and opportunities for advancing it to address the issues of changing land use and climate change.

Boreal forests

Although absent in the southern hemisphere, boreal forests are the most widespread forests in the world. The type includes both maritime and continental climatic regions and tends to occur somewhat further south in eastern Eurasia and North America. Chapters 4 and 16, and related parts of Chapter 14, discuss the ways that forests cause snow hydrology to vary with temperature and winds during and shortly after the snow falls. In colder regions snow does not adhere to tree crowns as well and is easily dislodged by wind. On the ground it is subject to further wind distribution and sublimation (Chapter 16). In warmer and more maritime regions interception of snow is greater due to the tendency of snow near 0°C to adhere to foliage and there is 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 16). While snowmelt is the most important factor causing streamflow, in the southern areas rain-on-snow events are often associated with largest flows (Chapter 14). Streamflow may cease in small watersheds due to freezing in winter and/or increased evapotranspiration rates in the summer (Chapter 14), while flow beneath the ice in larger rivers is difficult to measure. Wetlands of this region are discussed quite extensively in Chapter 7 and data from Caribou-Poker Creek watershed in Chapter 14 illustrate one example of hydrology of this forest region.

Temperate forests

The vast majority of temperate forests lie in the northern hemisphere, with other areas found in the South Island of New Zealand, southern and eastern Australia (including Tasmania), and Chile. These forest types have been studied 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 (Chapter 14) originate in temperate forest types. Nearly all of the runoff process studies cited in Chapter 2 occurred in temperate forests of North America, Europe, New Zealand and Australia. Likewise, the bulk of paired watershed research outlined in Chapter 12 also took place in those areas.

The most distinct characteristics of this forest region are a long dormant season due to low temperatures and extensive deciduous forests in the northern hemisphere. High evapotranspiration rates during late spring and summer generally result in a considerable deficit of soil moisture as precipitation minus evapotranspiration in late summer and early autumn. Precipitation during the winter may be stored as snow or as recharge of soil moisture, when forest vegetation is dormant and deciduous species are leafless. Streamflow is generally seasonal with highest flows during the spring, due to snowmelt, rain on snow, or high soil moisture.

The data in Chapter 14 demonstrate the wide variety of temperate forest hydrology associated with geographic and geological conditions. Marcell, Minnesota has hydrology similar to the boreal region with long cold winters due to its low relief and northern mid-continental location. Hubbard Brook, New Hampshire and Fraser, Colorado both have hydrology dominated by snowmelt despite Fraser being 5° further south. Snowmelt is a large component of runoff in Colorado due to elevation and mid-continental location. Strong maritime influences lessen the impact of snow accumulation and melt at the H.J. Andrews, Oregon and Casper Creek, California watersheds, as does the southern locations of Fernow, West Virginia and Coweeta, North Carolina. Pacific heavy winter rains create high runoff during the winter in the western watersheds while spring rains on moist ground are more likely to produce high runoff in the eastern ones. While high summer evapotranspiration is important in all four of these watersheds, the eastern watersheds are more likely to encounter runoff-producing summer thunderstorms and the occasional impact of tropical cyclones.

The above discussion of variations in forest hydrology of temperate North America is likely to be equally important in Europe (Chapter 5, this volume). However, experimental catchments have been more concentrated on temperate and alpine forests such as the Swiss Sperbel and Rappengraben, the German Eberswalde (temperate), the Welsh Plynlimon and German Harz (boreal). The review of European studies in Chapter 5 suggests that lack of large nationally owned forests and complex European policies precluded the type of coordinated collection of long-term basin-scale forest hydrological data as was presented in Chapter 14. Europe also has high mountains, maritime climatic regions, and more continental climatic regions in Eastern Europe and Russia. The exception to the generalization has been the work done in Scandinavia, much of which involves drainage of wetland forests as outlined in Chapter 8.

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. The second type occurs around the Mediterranean Sea, which gives this climatic type its common name. Mediterranean climate is also common in parts of south-western North America and southern Australia.

The northern and southern (in each hemisphere) edges of the subtropical zone have similarity to the temperate zone, with a winter season of plant dormancy and lower evaporative demands. With a Mediterranean climate lower winter evaporative demand combines with higher rainfall rates for a highly seasonal runoff pattern. The data from San Dimas, California in Chapter 14 exemplify forest hydrology of this climatic type. Although forest fires are common in all climate types, the dry summers of the Mediterranean type make the hydrological impacts of forest fire (Chapter 13) an important aspect in this region.

In eastern North America and Asia the subtropical climatic zone is also influenced by maritime climate from the Northern Tropical Convergence Zone during summer and autumn. Tropical cyclones (hurricanes and typhoons) are the most spectacular aspect of this influence, but higher summer rainfall is common (see Fig. 7.4 for example). Summer runoff is generally small or non-existent, as demonstrated by data from Santee, South Carolina (Chapter 14). Yet, rainfalls of 100–600 mm associated with tropical storms produce large areas (approaching 100%) of saturation-excess overland flow throughout coastal low-gradient watersheds.

Tropical forests

One important aspect of tropical forest hydrology is the lack of dormancy due to cold temperature. Trees are evergreen and transpire the entire year, as long as there is adequate rainfall. Tropical forests are divided into rainforests, with high year-round rainfall, and seasonal monsoonal forests with a pronounced dry season (see Plate 5). 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 bring into question the validity of principles that have been tested primarily in the temperate zone.

The 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 fluctuation throughout the year. Despite multi-layered evergreen forests interception losses can be low as 9% of rainfall in the Amazonian rainforest (Lloyd and Marques, 1988).

Seasonal monsoons are most typically associated with India and South-East Asia, but seasonality is fairly high between 15° and 20° north and south latitude, associated with seasonal movement of the Inter-Tropical Convergence Zone (Plate 5). During the rainy season these regions may have high-intensity rainfall over sustained periods. Bonell and Gilmour (1978) found surface runoff and rainfall intensity were factors in forest hydrology of northern Australia, in contradiction to Hewlett *et al.*'s (1977) contention that rainfall intensity did not explain streamflow volume or peak discharge in humid temperate forests (see Chapter 1). Elsenbeer (2001) suggested that occurrence of surface runoff on tropical watersheds was determined by rainfall intensity and vertical conductivity of subsurface soil layers (see Chapter 6).

17.2 Where Do We Go from Here?

17.2.1 What will forest hydrology become?

Forest hydrology emerged as an effort to understand how human changes to the forests altered the amount of water in our rivers during floods and droughts. Now humans are changing both landscape and (likely) climate. At the same time forests are an integral component of the landscape and maintaining their functional integrity is necessary for the sustainability of both ecosystems and societies (Amatya *et al.*, 2011). There is an urgent need for better understanding of the linkages between trees, forests and water, for awareness raising and capacity building in forest hydrology, and for embedding this knowledge and research findings in policies (Hamilton *et al.*, 2008; Chapter 5, this volume). Many of the challenges of the coming decades discussed in the context of Europe and the south-eastern USA (Chapters 5 and 15) are equally applicable for many 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. Over the next century the role of forests in mitigating climate change may become the greatest challenge. As we see in Chapter 3, forest carbon assimilation and transpiration are controlled by the same physiological mechanism, stomatal opening. Rapidly growing forests can provide sustainable carbon-neutral energy. Trees also assimilate carbon and can sequester that carbon for centuries to millennia. However, intake of CO_2 requires exposing internal leaf tissue to the atmosphere, with transpiration occurring when vapour pressure is lower. Only by understanding the variation in water use per unit of assimilated carbon can we understand and manage forests to balance growth for wood products, energy production and carbon assimilation with water use.

In addition to carbon assimilation, streamflow from forested watersheds produces high-quality water requiring minimal treatment for drinking-water. Forests play a role in aquifer recharge by affecting the processes by which rain is partitioned into recharge and runoff. Although those processes have been well defined (Chapter 2), understanding how climate, forest characteristics and geology determine the pathways and quantities of water movement, from crowns to stream or aquifer, 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 their pathways on both natural and managed forests, while considering the contribution of other land uses (Amatya *et al*., 2015).

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 always apply universally. We have given examples of contrasting situations; for example, cutting forests of 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, the underlying principles must be found by extending research into all forested regions.

17.2.2 Evaporation and transpiration

Evapotranspiration (ET), the word that is dear to the hearts of many forest hydrologists and land and water managers, reveals how very little we really know about the principles that drive movement of water from forests into the atmosphere. ET accounts for the greatest flow in most forested ecosystems (Chapter 3), but is measured well only on particular forest stands and/or watersheds where there is no loss of water from the watershed, other than that measured at the weir. ET has been estimated for nearly every paired watershed experiment, but always as the residual in water balance so that it includes all the errors and unknowns. ET measurement (or lack of direct measurement) may well be the reason for the '$R^2 = 0.8$' dilemma posed in Chapter 1. Does rainfall and evaporative potential (PET) explain about 80% streamflow in all forests? Until we can quantify how actual evaporation (E) and transpiration (T) change with forest characteristics, climatic drivers and weather conditions, we may have no hope of doing better than $R^2 = 0.8$, regardless of the model form we use.

E and T measurements may be the most rapidly expanding part of forest hydrology. Sapflow measurements have great potential for understanding the relationship of forest ecology to hydrology. Wide differences in sapflow are evident between different tree species and sizes as can be seen in Plate 2. Understanding how these species differences relate to autecology of those species will become a productive avenue for future research. Also, new remote sensing techniques of airborne, or ground-based, LiDAR (Vauhkonen *et al*., 2016), addressed in Chapter 10, may produce better estimates of crown dynamics than diameter at breast height and leaf area index. Such advances will potentially allow understanding landscape-scale ET. Novel approaches like 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, can also be explored for forest systems.

Scaling E and T measurements over plot, hillslope, watershed and regional space presents another challenge. Sapflow produces an accurate estimate of transpiration for a single tree. Eddy-covariance towers sample integrated areas depending on fetch. Water balance works only for gauged basins with minimal deep seepage. Remote sensing from satellites can measure worldwide data for estimates of evapotranspiration but their current resolution limits application on plot or small watershed scale unless high-resolution images with ground-truthing are used (Chapter 10). A method is needed to integrate and compare results from these methods such that E and T can be measured at any scale appropriate to a societal need.

17.2.3 Condensation

Condensation is the process that is least pursued in forest hydrology despite the fact that it may represent an important part of water exchange. Makarieva *et al*. (2014) have put forward the thoery that air passage over forests yields more rainfall since forest areas with the highest evaporation drive both upwelling and condensation. However, rather than merely influencing the moisture content in the air that is passing over a forest, the process of evapotranspiration can impact regional atmospheric dynamics by enhancing rainfall and thus modifying large-scale pressure gradients. They argue that this, in turn, enhances and stabilizes precipitation in a positive feedback loop.

Scientists at the WSL Birmensdorf (Herzog *et al*., 1995) carried out long-term experiments on water exchange in Norway spruce in an alpine environment based on measurements of diurnal variation in stem radii. A daily temporary decline in sapflow at mid-crown before midday was observed but not explained. This phenomenon could be linked to effects of condensation before the onset of transpiration as measured in the shrub zone above the treeline (de Jong, 2005). In future, measurement techniques shedding more light on condensation and evapotranspiration such as radial stem variations should be more fully expoited (Zweifel, 2015).

Coordinated simultaneous measurements of evaporation, transpiration and atmospheric dynamics are needed to determine the linkage of local and regional air mass transfer and movements in relation to local precipitation.

17.2.4 Runoff processes

We have a good qualitative understanding of processes that produce runoff from rainfall on forested systems. Basic processes, depicted in Figs 2.2, 6.5, 9.1 and 9.3, reveal a common understanding of alternative paths of rainfall to streamflow. However, quantitative estimates of flow pathways are dependent on the location of the research site. Where paths have been altered by human intervention, providing artificial drainage to provide trafficability and increased tree growth on poorly drained soils (Figs 8.1 and 8.2), we find quantitative analysis requires alternative hydraulic conductivity estimates for differing stages of the forest regeneration cycle. Most of our quantitative understanding has come from isotope or geochemical tracer analysis to streamflow. An outstanding discussion of the use and limitations of isotopes can be found in Klaus and McDonnell (2013). 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).

A path to developing a unified explanation of forest subsurface processes is beginning to emerge. McDonnell (2013) began to explore an idea that subsurface processes may behave in a manner similar to infiltration-excess overland flow. As discussed in Chapter 2, incoming rain may travel in several alternative pathways to become streamflow. Vertical flow to groundwater represents the highest-gradient pathway. Jackson *et al*. (2014) present an elegant mathematical depiction of partitioning between vertical and slope-parallel flow above an impeding layer based on ratios of lateral and vertical gradients and hydraulic conductivities with the thickness of saturated material above the impeding layer. This analysis is similar to the arguments made by Elsenbeer (2001) for classifying tropical soils that would produce overland flow. The analysis is exact only for planar slopes with slope-parallel impeding layers, but does express an idea that could be more inclusive of conditions normally found in forested systems. Uchida *et al*. (2005) developed a decision tree to evaluate the prevalence and flow rate of hillslopes, dominated by pipeflow, based on both rainfall amount and intensity. Their decision tree depends on quantity of rain to initiate pipeflow and intensity of rain, in relation to maximum pipeflow rate, to determine the rate of hillslope pipeflow. In the case of pipeflow both vertical and slope-parallel hydraulic conductivities are functions of active soil macropores and pipes.

17.2.5 Merging forest hydrology and ecohydrology

As defined by Smettem (2008):

> Ecohydrology seeks to understand the interaction between the hydrological cycle and ecosystems. The influence of hydrology on ecosystem patterns, diversity, structure and function coupled with ecological feedbacks on elements of the hydrological cycle and processes are central themes of ecohydrology. The scope covers both terrestrial and freshwater ecosystems and the management of our relationship with the environment.

That definition also fits forest hydrology as a subset of that wider discipline. Jackson *et al*. (2009) cited the Swiss watershed experiments discussed in Chapters 1 and 5 as early ecohydrological experiments. One could argue that afforestation and some deforestation experiments are examples of ecohydrology since they deal with transformation of grassland to/from forest.

Bonnell (2002) also pointed out that ecohydrology was not a completely new science but does incorporate new connections between hydrological processes and stream hydrobiology. Coupling with the stream hyporheic process is new and has not been addressed in earlier studies of hillslope subsurface flow phenomena. The wider science of ecohydrology can couple forest hydrology with wider studies of the interaction of forests with more arid grasslands as well as wetlands and streams.

Ecohydrology may provide the tools needed to answer the century old question of 'do forests bring rain or merely respond to increased rain?' This question may become more important in tropical forests. Over much of the tropics the balance between forest, savannah or grassland is not determined climatically but may be in ecological alternative states that may be easily altered by fire or fire exclusion as well as many other human activities. If forest cover increases rainfall then a change in biome may become difficult to reverse (Staver *et al*., 2011).

17.3 Broader Dimensions of Forest Hydrology

Advancing forest hydrology is critical to forest ecosystem management, as it drives contaminant cycling and loading dynamics in the soil, through plants, animals, precipitation inputs, and surface and subsurface flow networks that support downstream water quality, besides serving as a reference for assessing developmental impacts. Although it is understood that water yield and timing are affected by forest management, the duration and spatial scale of these effects merit further investigation (NRC, 2008).

Vose *et al*. (Chapter 15) state that:

> Projections indicate a future of increasing pine plantations and expansion of fast-growing species for carbon sequestration and bioenergy, but landscape-scale effects on water yield and quality, and the magnitude of potential trade-offs between managing for carbon and water, have not been systematically explored across time and space (Jackson *et al*., 2005; King *et al*., 2013).

The challenge of addressing forest hydrology and managing forests at large spatial scales requires also an understanding of large-scale processes and interactions with landscapes within and outside, usually accomplished by modelling approaches. However, the uncertainties in the variability of field circumstances, measurements and the modelling approaches must also be considered (Harmel *et al*., 2010).

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). Recent advancements in monitoring 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 increased computing speed, should also be used as opportunities to address these complex processes. This will allow further investigation of the relationships between forest ecohydrological processes and remote sensing products which are currently poorly understood.

Jones *et al*. (2009) emphasized a need to address forest hydrology as a landscape hydrology that embraces the interactive effects of various land-based activities on water supplies. In order to improve the efficiency and effectiveness of designing landscapes to ensure sustainability, models commensurate with those available for agricultural lands are needed to characterize the biological, chemical and physical processes of forested lands. The fact that the hydrology and water quality of undisturbed forested lands are generally used as a baseline reference (Chapter 14) for determining anthropogenic impacts adds further emphasis to the importance of testing and, where necessary, further developing models for application to forested catchments.

The scope of forest hydrological science has to 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 that 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 also serve as valuable benchmarks for advancing forest hydrological science and addressing emerging forest and water issues of the 21st century.

17.3.1 Meeting forest management needs

Global water demand is expected to increase 55% by 2050, primarily in developing countries (WWAP, 2014), where rising standards of living are likely to also increase demand for wood products and energy. 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 somehow 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). As cities grow, large forested municipal watersheds will have to be managed to meet as yet undefined benchmarks of both water yield and water quality, experiences described by Barten *et al*. (2012). Climate change mitigation and energy security initiatives will rely on increased forest biomass growth and utilization. As increasing forest growth requires higher water uptake on a plant basis, forest managers will need reliable planning tools to manage these requirements from a tree to a landscape basis. To develop these tools, we not only should advance forest hydrological science for understanding complex interactions but also must learn to scale currently available research and model results to define reasonably achievable benchmarks of water quantity and quality. We must also understand forest management practices and estimation techniques that allow such benchmarks to be achieved within the constraints of the forest owner. Challenges include changes in forests and water yield associated with climate change, land-use change, resistance of the public to forest modification, and the ever-present effects associated with disturbances such as fires, the age distribution of forests, insects and diseases, and forest regeneration impacts besides the natural ones. As the world demands more clean water supply, wood, energy and carbon storage from forests, forest hydrology becomes equally critical to sustainably providing services while protecting water resources.

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