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ECOHYDROLOGY OF TEMPERATE FORESTS

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21.1 Introduction

According to the Köppen climate classification, a temperate climate (C) has a mean air temperature between −3 °C and 18 °C in the coldest month, warm summers, cold winters, and intermediate levels of precipitation. The temperate climate zone represents about 18% of the Earth's total land area. It is also home to most of the human population with its land use dominated by agricultural crops (43%) and forests (33%) (www.esa-landcover-cci.org). Forests are an established part of the history and culture of the temperate zone (1).

Temperate forest (6.73 × 109 km^2) covers about 6% of the Earth's land surface and represents 17.4% of total forest area (3.89 × 1010 km^2 or 35% of all land areas). Temperate forests may consist of deciduous and/or evergreen trees representing important sources of global timber supplies. The largest areas of temperate forests are in eastern North America, western and central Europe, and Asia. However, important temperate forests are also found in western North America, Australia, New Zealand, South America, and South and central Africa (Figure 21.1).

The temperate forest climate is generally considered 'energy limited,' with a mean annual precipitation (P) of 1323 ± 575 mm, potential evapotranspiration (PET) of 956 ± 197 mm, dryness index (DI = PET/P) of 0.83 ± 0.35, evaporative index (ET/P) of 0.70 ± 0.19, and runoff ratio ((P-ET)/P) of 0.37 ± 0.31 (Figure 21.2). Most native temperate forests have been cut, and remaining fragments face multiple stressors from climate change, drought, insects, diseases, wildfire, and land use change. In many areas, the original temperate forests have been largely replaced by planted or regenerated forests.

In the temperate zone, large areas of planted forests originally designed for timber production or soil erosion control provide other ecosystem services, such as carbon sequestration, wildlife habitat, mitigating extreme climate (drought and floods), and biodiversity conservation. However, trade-offs of these wide range of ecosystem services are recognized (3). This chapter summarizes the current understanding of the ecohydrology of temperate forests, ranging from the individual tree to the watershed scale, in both unmanaged and managed forests. Such information is urgently needed in contemporary local forest management with multiple objectives including reducing wildfire potential, water supply, and enhancing ecosystem resilience to climate change.

DOI: 10.4324/9781003383918-24

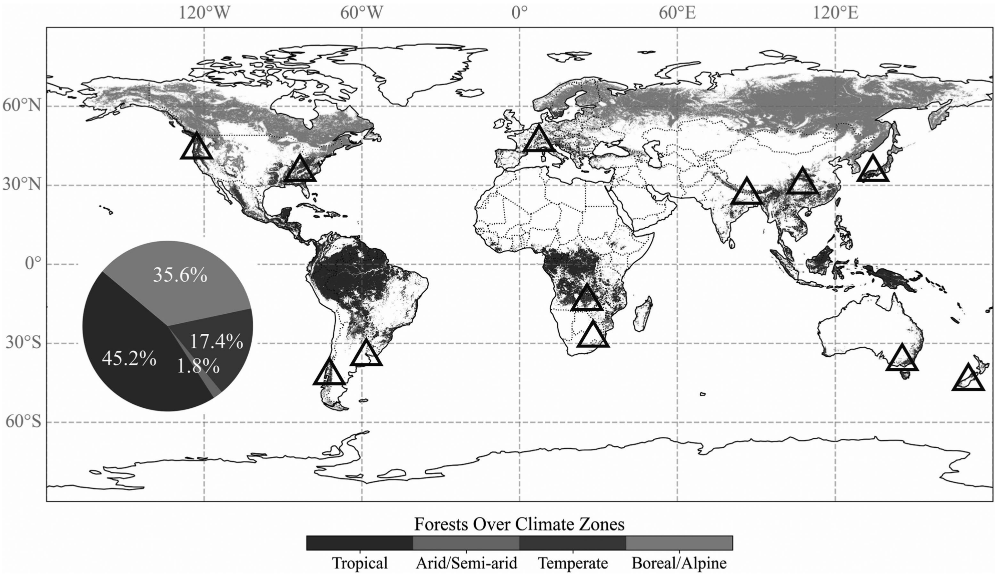

Figure 21.1 Distributions of world's forests across four major climate zones by the Köppen classification. Temperate forests represent about 17.4% of all forestlands and 6% of all lands on Earth (www.esa-landcover-cci.org). Over 30% of the temperate climate zone is covered by forests, which is less than the tropical zone (36%) or boreal climate (47%) zones. Triangles indicate regions reviewed or locations of contributing authors for this chapter.

21.2 Distinctive elements of water balances and ecohydrological processes

21.2.1 Precipitation

Annual precipitation in temperate forests varies widely from less than 700 mm (e.g., Northern China) to over 2500 mm (e.g., southern Appalachians in the United States). Interannual change in P has a large effect on water yield because annual ET is relatively stable in temperate forests (4). Because the atmospheric DI for temperate forests is close to 1.0, declining precipitation can quickly shift temperate forests to water-limited conditions (Figure 21.2), reducing water yield.

21.2.2 Evapotranspiration

ET is central to ecohydrology because it links ecosystem energy, water, and carbon cycles. Globally, temperate forests may recycle half of incoming P as ET (5). However, ET at stand or watershed scales varies with climatic variables, soil properties, and plant biophysical characteristics. Most temperate forest rooting systems cannot access moisture below 100 cm depth (6) and thus can be vulnerable to chronic drought. Forest ET reduces water yield locally, but ET may become precipitation for areas downwind (7).

21.2.3 Change in soil water storage (ΔS)

Land use and climate change have produced long-term changes in soil water storage in many temperate forests (8). In many parts of the temperate zone, soil water and groundwater have declined

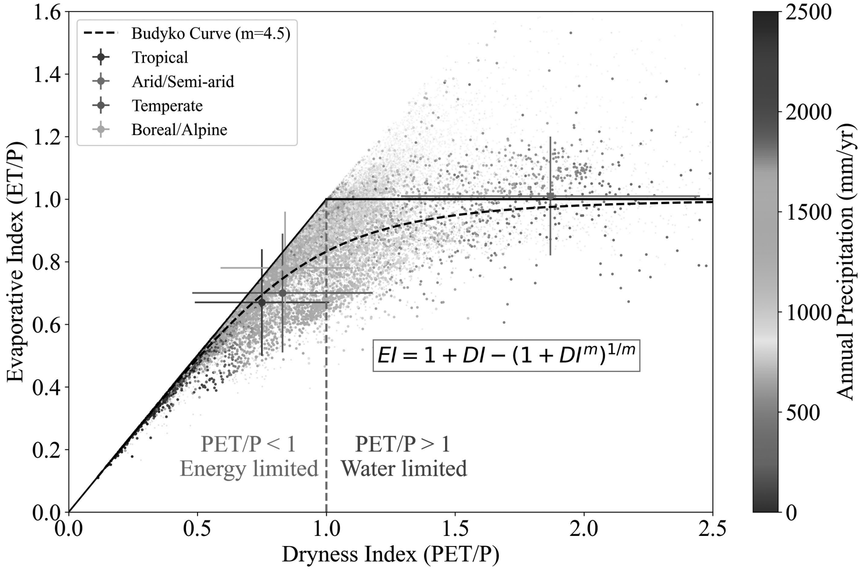

Figure 21.2 The Budyko framework shows relations between mean annual Evaporative Index (ET/P) versus Dryness Index (DI = PET/P) and climatic regimes for global forests as determined by the Global Land Evaporation Amsterdam Model (GLEAMS V3.7). The dashed line represents the Budyko curve (2) with a parameter m = 4.5 fitted for temperate forests. The data points are presented in grey scale by annual precipitation from the TerraClimate (https://www.climatologylab.org/terraclimate.html) with a grey scale bar on the right axis. The data points represent the estimated multi-year means for the period from 2001 to 2020 sampled across different climate zones at a 0.25-degree spatial resolution. The tropical forests receive most of precipitation followed by temperate forests, boreal forests, and forests in the arid/semi-arid region.

in response to increased ET associated with forest plantations (9), drought, and increased air temperature, while in other areas, soil water and groundwater have increased in response to deforestation and cropland expansion.

21.2.4 Water yield (Q)

Compared to other climate zones, the temperate climate promotes tree growth, forest establishment, and relatively high runoff (mean ~400 mm/year) (8,10,11). However, temperate forest water yield is sensitive to drought and forest change, and changes in both peakflow (floods) and baseflow (low flows) have important implications for aquatic ecosystems and water supplies. Human activities such as water withdrawals for irrigation and drinking water have altered water yield in many parts of the temperate zone. In general, water yield from temperate forests is less sensitive to deforestation than to forestation (10). Because of its high ET in fast-growing monocultural plantations, temperate forest Q is more sensitive than in tropical forests but less sensitive than in arid forests (10).

21.3 Global case studies

Forest hydrology research around the world has addressed many hydrologic effects of land use change in the relatively densely populated temperate zone, including conversion to/from forest, agriculture, and pasture and management of forests. Compared to other climate zones, literature on temperate forest ecohydrology is abundant, mostly from developed countries (11). Much of what is known about ecohydrology is derived from the classic paired watershed experiments (12), which show that deforestation or forest harvest decreases ET and thus generally elevates peakflow, baseflow, and total water yield (see examples in Figure 21.3), while reforestation or afforestation on degraded grasslands or croplands generally has the opposite effects. Hydrologic responses to forest change also vary by tree species, precipitation type, soil disturbances, and watershed characteristics (8). Less is known about forest restoration effects, especially on baseflow or dry-season flow response (13). Process studies using water stable isotope ratios, heat pulse sapflow sensors, eddy covariance, and high-resolution remote sensing methods extend understanding of watershed studies. Below we review major temperate forest ecohydrology by continent, focusing on ecohydrological processes at stand and watershed scales that are most relevant to forest management in response to climate change and variability.

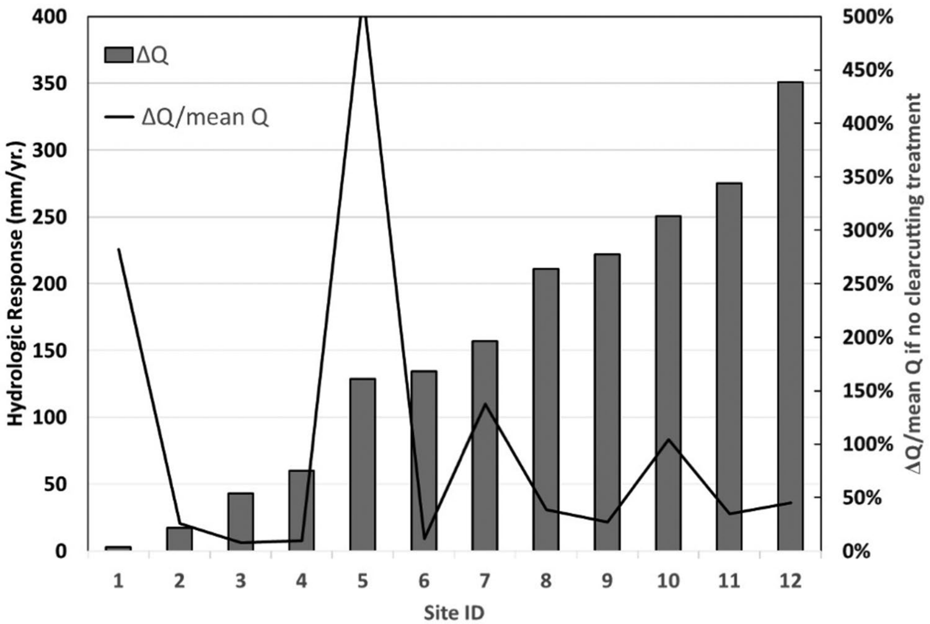

Figure 21.3 Mean annual absolute (ΔQ), measured water yield (Qt) of watershed subject to clearcutting treatment minus water yield (Q) predicted if no treatment occurs, and relative response (ΔQ/Q) during the first three years post deforestation under temperate climates for selected classic 'Paired Watershed Experiments' results from the United States, Australia, and Japan. There is a wide range of water yield responses in both absolute change (up to 350 mm) and relative change (up to 500%) in water yield due to differences in background climate (precipitation and PET) and watershed characteristics (e.g., leaf area, topography, disturbance history of the reference uncut watershed). Site ID 1 = Australia Dons Catchment, 2 = Australia Willbob Watershed, 3 = US Caspar North Fork, 4 = US Fernow Watershed 1, 5 = Australia Germans Creek, 6 = US H J Andews W3, 7 = US Hill Forest, 8 = US Carteret, 9 = US Coweeta Hydrological Laboratory Watershed 17, 10 = Australia Picaninny Catchment, 11 = Japan Fukuroyamasawa Experimental Watershed B, and 12 = US Hubbard Brook Watershed 2.

21.3.1 North America

Since the 1930s, hydrologic research on temperate forests in North America has focused on hydrologic response to forest management, climate, and environmental policy using long-term paired watershed experiments (14–17). For example, in the marine west coast climate (wet winters, dry summers) of the Pacific Northwest, paired watershed studies at the H.J. Andrews Experimental Forest, the South Umpqua Experimental Forest, and the Alsea watershed study demonstrated that harvest of old-growth conifers and replacement with plantations of native species increased water yield and peak discharges over multiple decades (18), but higher transpiration rates of young trees produced dry-season lowflow deficits that emerged within one to two decades and persisted for half a century (19). In the mesic climates (wet winters, wet summers) of eastern North America, similar paired watershed studies and eddy covariance measurements have examined forest hydrological processes in second-growth forests and intensively managed plantations on various landscapes from the steep mountains to flat coastal plains (20–22). For example, research at the Coweeta Hydrological Laboratory in North Carolina has contributed the Variable Source Area Concept (23) and quantified hydrologic response to forest regrowth on mountain farmland, conversion of deciduous to conifer forest, hemlock woolly adelgid outbreaks, and fire (24). The eastern and western regions show consistent trends of hydrologic response to forest cover change with contrasting seasonality and magnitude due to differences in precipitation patterns and forms (Figure 21.3).

21.3.2 South America

Ecohydrology research in South America has grown dramatically since 2000 and is primarily focused on the effects of the rapid expansion of plantation forestry using introduced *Eucalyptus* and pine species. Forest plantations have replaced native forest, agriculture, and pasture in Brazil and Chile and native grassland in Uruguay, with significant effects on streamflow (25). Watershed studies in the marine west coast (wet winters, dry summers) climate of south-central Chile have shown that forest plantations of non-native Radiata pine (*Pinus radiata*) and *Eucalyptus spp* reduced streamflow over the 2000 to 2020 period coinciding with a mega-drought (26, 27). Paired watershed experimental studies on forest industry land and private protected areas (28, 29) indicate that native forest restoration and streamside vegetation buffers with native forests may mitigate or reverse reductions in baseflow associated with forest plantations and drought. Widespread fires since 2010 have produced additional changes in temperate forest ecohydrology in south and central Chile. Paired watershed studies on forest industry lands in the mesic climate of Uruguay have shown that replacement of native grasslands with forest plantations of loblolly pine (*Pinus taeda L.*) and *Eucalyptus spp* increased ET and surface soil hydrophobicity, but reduced annual water yield and groundwater recharge (30–32).

However, little research has addressed native forests in temperate South America. Thinning of 60-year-old, second-growth, native *Nothofagus* forests increased dry-season baseflow (33). Native drought-adapted *Araucaria* forests in Brazil have lower interception than other forest types and higher streamflow than in managed forest plantations (34, 35).

21.3.3 Europe

European ecohydrological research has combined watershed studies with process studies in forests in a wide range of climatic conditions ranging from cool, moist spruce- and pine-dominated forests to warm, seasonally dry deciduous and coniferous forests on a continent that has lost half its native forests in the past 6,000 years. Long-term watershed studies have documented effects of grassland conversion to forest plantations (36, 37) and long-term recovery as atmospheric deposition has declined (38). Process studies have quantified effects of canopy interception; and species-specific rooting patterns on spatial patterns of soil moisture (39) and the effects of precipitation timing and canopy interception on runoff (40).

Recent ecohydrological research in Europe has examined effects of increasing droughts and heatwaves on groundwater recharge and streamflow (41). Process studies have quantified effects of multiple droughts on the resilience of beech forests (42) and differences in drought vulnerability among tree species and in dominant trees versus suppressed trees (43). Other isotope-based investigations in temperate Central-European forests revealed complex patterns of water use during drought (44). Detailed measurements of growth and transpiration in German and Swiss forests demonstrated efficient use of winter soil moisture by trees, providing resilience to drought (45).

21.3.4 Asia

Temperate forests in East Asia are commonly found in China, Japan, Korea, Nepal, and India (Figure 21.1). In Japan, early small, paired watershed experiments demonstrated that afforestation and reforestation reduced streamflow (46). Recent Japanese forest hydrology studies focus on the effects of thinning of mature conifer plantations (47) and converting conifer plantations to native broadleaf forests to alleviate droughts and floods (48). Ecohydrology research in China has examined effects of large-scale forestation programs initiated in the late 1990s in response to floods and sedimentation in large rivers (49). Techniques such as remote sensing, eddy covariances, sapflow, water stable isotopes ratios, and modelling have been used to examine canopy interception, transpiration, and overland flow in planted forests (50, 51). Reported effects of afforestation and reforestation on hydrology in China vary with climate and forest structure and composition (52). In the dry areas of northern China, large-scale afforestation and reforestation and associated bioengineering (e.g., terraces) not only reduced soil erosion but also reduced soil moisture, baseflow, and watershed streamflow (9) due to increased ET. Ecohydrology research in South Korea has focused on effects of large-scale forest rehabilitation since the 1970s (53). A long-term watershed study demonstrated that a native conifer plantation reduced water yield compared to an old natural broad-leaved forest, and thinning of the plantation produced only temporary increases in water yield (54). Forest ecohydrology research in Nepal is scarce and has been focused on comparing plot-scale water balances between native forests and small community-planted forests (55, 56). In northwest India, a watershed study documented the cessation of baseflow from a degraded forest but continued perennial flow from a largely undisturbed native forest (57).

21.3.5 Oceania (Australia, New Zealand)

Temperate zone ecohydrology research in Australia and New Zealand has focused on the effects of wildfire and management of native *Eucalyptus* and non-native *Pinus (e.g.,* Radiata pine*)* forests. Watershed studies in New Zealand demonstrated that native forest had the lowest stormflow yields, lowest peakflows, and highest low flows compared to pasture, invasive gorse (*Ulex europaeus*) or forest plantations of *Pinus radiata* in part due to higher interception by pines (58, 59). Wildland fires and droughts are increasingly affecting woodlands/forests and water resources in Australia, and recent ecohydrology research has examined effects of ‘mega-fires’ on water supplies (60). After severe fire, reductions in transpiration and interception increase streamflow (e.g., 61, 62), but high soil moisture deficits may counteract these increases, leading to a wide range of streamflow responses after fire (63). Post-fire regeneration also strongly influences streamflow response: dense even-aged stands regenerating after severe fire produced large reductions in streamflow compared to pre-fire forests (64), but less severe fire, less dense regeneration, and/or potential tree species shifts moderate these effects (65).

21.3.6 Africa

Temperate forests on the African continent are confined to Zambia (Luangwa river), southern Angola, Malawi, Zimbabwe, a small part of South Africa (the Limpopo province), and east coastal areas of the island of Madagascar (Figure 21.1). Paired watershed studies initiated in South Africa in 1936 produced unequivocal evidence that the fast-growing plantations of *Eucalyptus* and *Pinus spp.* reduced total annual and dry-season streamflows, but also that flow reductions became progressively smaller as trees grew past the rotation length (up to 30 to 45 years for *Pinus radiata* and >13 years for *Eucalpytus grandis*) (66–68).

In a river basin in Zambia, a multi-decadal study linked a reduction in forest cover to a reduction in both wet- and dry-season streamflow (69). Studies using streamflow records, remote sensing, and modeling in Malawi have documented reductions in river flow associated with increasing area of forest plantations (70) and loss of woodlands (71). In Zimbabwe, studies combining remote sensing, modelling, and analysis of streamflow documented reduced river flow associated with clearing of native forest and shrub land (72) and increased water yield associated with reduced forest plantation cover (73). Process studies in Southern Africa have shown that native tree species use substantially less water and grow more slowly than non-native plantation tree species (*Pinus radiata*) (74, 75).

21.4 Summary and research outlook for ecohydrology of temperate forests

Our review on temperate forest ecohydrology for six continents has demonstrated that while intensively managed forest plantations reduce stream water temperature, soil erosion and sedimentation, and flooding relative to agricultural or pasture lands they also provide lower water yield relative to these land uses and lower low flows during dry seasons or dry periods in comparison to native, relatively undisturbed forests. Fast-growing, evergreen, often densely planted forests have higher rates of interception and transpiration than other land cover types, especially during dry periods in dry regions. The elevated water losses by plantations often overwhelm the enhanced infiltration resulting in reduced groundwater recharge (76, 77). Interest is growing in forest restoration for hydrology (13), including the goal to provide increased dry-season streamflow, but more research is needed to examine how native tree species and native forest regeneration improve soils and hydrology. More work also is needed to investigate how young and old trees of native and non-native species respond to wildfire and to extreme heat and drought events. In addition, empirical field studies are needed on hydrology of native forests and hydrological recovery from degraded lands, especially those in the developing countries where data are lacking (56). Modern technology, such as high-resolution remote sensing, modelling, isotope tracers, sapflow measurements, and new monitoring sensors, should be integrated to better understand ecohydrological processes at multiple scales (78). Watershed studies can be redirected to explore effects of native forest restoration (28), and integrated approaches linking hydrology, ecology, and tree physiology are essential to document ecohydrological patterns at multiple scales (79). Temperate forest ecosystem services are becoming increasingly important for sustainable development as the world's population continues to rise, and global climate change intensifies. Adequate protection and sound management of existing temperate forests, plantations, and native forests, based on ecohydrological principles, are critical to ensuring the health and productivity of the biome.

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