Ecological Processes

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Ecohydrological processes and ecosystem services in the Anthropocene: a review

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Abstract

The framework for ecosystem services has been increasingly used in integrated watershed ecosystem management practices that involve scientists, engineers, managers, and policy makers. The objective of this review is to explore the intimate connections between ecohydrological processes and water-related ecosystem services in human-dominated ecosystems in the Anthropocene. We synthesize current literature to illustrate the importance of understanding the ecohydrological processes for accurately quantifying ecosystem services under different environmental and socioeconomic settings and scales. Our synthesis focuses on managed ecosystems that are dominated by humans and explores how ecological processes affect the tradeoffs and synergies of multiple ecosystem services. We identify research gaps in studying ecological processes mainly including energy, carbon, water, and nutrient balances to better assess and quantify ecosystem services that are critical for sustaining natural resources for future generations. To better assess ecosystem services, future ecohydrological studies need to better account for the scaling effects of natural and anthropogenic stressors exerted on evapotranspiration and other water supply and demand processes. Future studies should focus on the bidirectional interactions between hydrological functions and services and human actions to solve real world problems such as water shortages, ecological degradation, and climate change adaptation.

Review

Introduction

Ecosystem services, the goods and services that ecosystems provide for human well-being (Alcamo et al. 2003; Millennium Ecosystem Assessment (Program) 2005), are increasingly used as a framework worldwide for the purposes of ecological restoration and conservation (Wei et al. 2017), watershed management (Falkenmark et al. 2004), and sustainable development policy making (Asbjornsen et al. 2015). Among the myriad of services provided by ecosystems, hydrological services such as water purification and water supply are considered the key to realizing other ecological services such as drinking water, recreation, and human health (Brauman et al. 2007; Keeler et al. 2012). Indeed, water is the most fundamental driver for ecological processes (Chapin et al. 2002) and is essential to all forms of life on Earth and human civilization (Gleick 2003). It is critical to understand how human-dominated ecosystems work in order to properly define and evaluate ecosystem services from both ecological and economical points of view (Boyd and Banzhaf 2007).

Unfortunately, ecosystem services are under serious threats and rapidly diminishing as a whole in the Anthropocene in many watersheds around the world (Falkenmark 2003; Jackson et al. 2001; Vitousek et al. 1997; Vorosmarty et al. 2000). Fresh water availability and supply are increasingly unreliable due to pollution of air, soil, and water; depletion of groundwater; shrinking snowpack and glaciers; sea level rise; and increased climate variability and change (Vorosmarty 2002; Vorosmarty et al. 2000). Increasing demands on ecosystem services such as clean water (Caldwell et al. 2012), fiber, bioenergy (Sun and Vose 2016), and recreational use of wildlands stress natural ecosystems and contribute directly to the decline of watershed hydrological services (Brauman et al. 2007; Vorosmarty 2002).

Ecohydrology, the study of interactions between ecological and hydrological processes (Porporato and Rodriguez-Iturbe 2013; Rodriguez-Iturbe 2000), has developed rapidly in the past two decades in response to watershed ecological degradation amid environmental changes worldwide (Asbjornsen et al. 2011) and is

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central to our understanding and quantification of water-related ecosystem services (Brauman et al. 2007; Wilcox et al. 2003a). Also, ecohydrological science has emerged as an important scientific field to address human influences on water resources and ecosystems under environmental changes ranging from urbanization to climate change (Gordon and Folke 2000; Vose et al. 2011; Wei et al. 2011; Zalewski 2000).

Our knowledge of ecohydrology is incomplete due to the complex nature of human-dominated ecosystems, which are constantly evolving in the Anthropocene (Sun and Vose 2016). Linking ecohydrological processes (e.g., energy, water, carbon, nutrient cycling) (Sun et al. 2011a; Wilcox et al. 2003a) to ecosystem services (e.g., carbon sequestration, water quality improvement, biodiversity conservation, regulation of water and nutrient cycles, urban heat island mitigation) (Sun et al. 2011b) is critical to properly quantifying ecosystem functions (Vose et al. 2011) and services (Brauman et al. 2007). A mechanistic understanding of ecosystem functions and potential interactions between ecosystem functions and services is especially important for projecting future ecosystem responses to climate change and variability (Sun et al. 2015b), land use change (Amatya et al. 2015), management options (Sun et al. 2015a), and human disturbances (e.g., wildland fires, urbanization).

The objectives of this review are to explore the connections between ecohydrological processes and water-related ecosystem services and also to identify research gaps in studying ecological processes to better assess and quantify ecosystem services that are critical for sustaining natural resources (e.g., wood and water supplies) for future generations. We synthesize current literature to illustrate the importance of understanding the ecohydrological processes for accurately quantifying ecosystem services under different environmental and socioeconomic settings and scales. We focus on ecohydrological processes in human-dominated terrestrial and aquatic ecosystems and seek the mechanistic linkages between ecohydrological processes (e.g., water, carbon, energy balances) and key ecosystem services including water security, climate moderation, and carbon sequestration. In particular, we examine the coupling processes and balances of water, carbon, and energy fluxes in managed ecosystems that are dominated by people, and explore how these processes affect the tradeoffs and synergies of multiple ecosystem services.

Linkages among ecosystem services and ecohydrological processes

The Millennium Ecosystem Assessment (2005) report defines ecosystem services as benefits that people obtain from ecosystems (Fig. 1). This ecosystem services (ES) framework includes four broad categories: provisioning, regulating, cultural, and supporting services. Provisioning services refer to ecological functions providing food, fiber, water, oxygen, etc., for human well-being. Regulating services are ecosystems' roles in mediating fluxes of water, energy, nutrients, pathogens, etc., that are essential to humans' very existence (Brauman et al. 2007). Cultural services are those that provide enjoyment and enrich people's lives, such as recreational, esthetic, intellectual, and spiritual inspiration. Supporting services are considered as the underlying foundational ecosystem processes and thus are the most basic services that directly sustain the other three services (Fig. 1). Recent development in ES research recommends that final ecosystem services to people should be used to better quantitatively account for the role of nature to improve

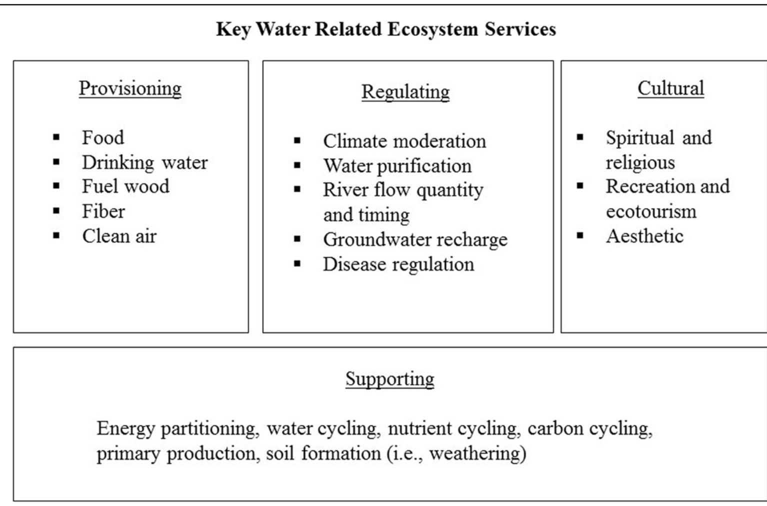

Fig. 1 Relationships between ecohydrological processes and key water-related ecosystem services (Modified from Millennium Ecosystem Assessment 2005)

human well-being from the economic perspective (Boyd and Banzhaf 2007).

Ecohydrological processes are closely connected to many water-related ecosystem services including climate moderation, water supply and quality, and flood mitigation (Ellison et al. 2012; Jackson et al. 2008; Sun et al. 2015a) at multiple scales from species to the globe (Fig. 2). As the key ecohydrological processes, energy, water, carbon, and nutrient cycles are closely coupled and the interconnectivity forms the basic supporting services to ecosystems (Brauman et al. 2007). Our discussion below focuses on these four processes as influenced by humans (Fig. 2).

Energy partitioning and climate moderation

Solar energy is the ultimate source of power driving the distribution and movement of water on Earth (Chapin et al. 2002; Jackson et al. 2008). However, ecosystems have tremendous influences on energy partitioning of solar energy to latent and sensible heat fluxes that are important for global climate and hydrology (Bonan 1999; Bonan 2008; Lee et al. 2011; Sun et al. 2010) and the distribution and characteristics of ecosystems (biomes). For example, forest canopies have a dense leaf cover (i.e., high leaf area index), resulting in a lower albedo and less reflection of radiation compared to grassland or surface with no vegetation cover (Sun et al. 2010). Forests consume more of the absorbed energy as latent heat during the evapotranspiration process (ET) than other land cover types (Lee et al. 2011). Consequently, forests often transmit more latent and sensible heat to the atmosphere, cooling locally compared to the grassland or unirrigated cropland (Jackson et al. 2008). Therefore, forests often cool the land surfaces (Ellison et al. 2017) more than urban land cover, grasslands, or bare land; thus, trees are helpful for mitigating urban heat island (UHI) (Shastri et al. 2017) and urban dry island (UDI) (Wang and Gong 2010) effects. Vegetated land cover acts as "air conditioners" because they use large amount of energy on ET, thus decreasing sensible heat and cooling the surrounding atmosphere (Hao et al. 2015). This may explain why UHI effects are especially evident in humid, wetland-dominated regions where converting natural or artificial wetlands (e.g., rice paddy field) that have high ET to urban uses can result in dramatic reductions in ET (Zhou et al. 2015a). The climate regulation functions of vegetation on local and regional climate are difficult to quantify empirically (Lee et al. 2011) but have been well-studied in many parts of the world using indirect methods such as remote sensing (Li et al. 2015) and simulation models (Jackson et al. 2005). The capture of hydropower,

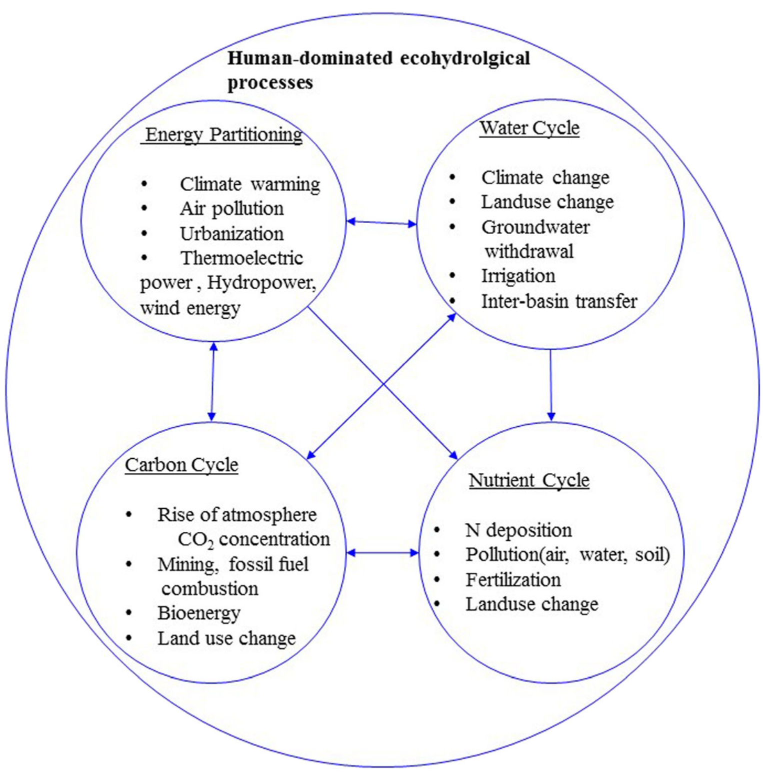

Fig. 2 A schematic overview of the inter-connected ecohydrological processes in human-dominated ecosystems. Human activities in the Anthropocene have permanently altered all aspects of the natural energy, water, carbon, and nutrient cycles by influencing the energy and material inputs to the biosphere, the hydrosphere, and the atmosphere

wind power, bioenergy, and thermoelectric power through human economic activities has great influences on energy flows and transformation in watershed ecosystems. Climate change mitigation and adaptation require novel approaches that partition energy and moderate climate in ways that foster human well-being.

Water cycle and supply

The energy partitioning function directly affects the hydrological cycle since ET is a major water loss in the water balance of ecosystems (Bonan 2008), especially in arid and semi-arid regions (Hao et al. 2016; Zhou et al. 2015b; Zou et al. 2010). Ecosystems regulate streamflow quantity (Sun et al. 2011b) and even timing (Hewlett et al. 1977; Hewlett and Helvey 1970) by altering the evapotranspiration and groundwater recharge processes. For example, deforestation generally decreases ET and thus increases streamflow (Andreassian 2004) and peak flow rates (Bruijnzeel 2004), while afforestation generally increases ET (Jackson et al. 2005), raises shallow groundwater tables (Sun et al. 2000), and reduces streamflow quantities, especially when fast growing exotic tree species are used (Brown et al. 2013; Calder 2007). The effects of vegetation on water supply are more pronounced in water-limited regions than water unlimited (energy-limited) regions (Sun et al. 2015a). For example, deforestation in areas with precipitation formation dominated by cloud could reduce interception of precipitation and thus reduce streamflow (Ponette-Gonzalez et al. 2015). In a special case, extensive deforestation in snow-dominated Northern Angara region in Russia caused a deceased in river flow by about 10–20 mm over the first two decades following clearcutting the deciduous forests (Onuchin et al. 2017). The reason was that clearcutting reduced snow accumulation compared to non-disturbed forests. Disturbance events such as wildfire not only affect evapotranspiration but also reduce the rate of infiltration into the soil, leading to enhanced streamflow in regions with a Mediterranean or semi-arid climate (Hallema et al. 2017). The streamflow regulation functions of forests depend on many watershed factors including background climate, forest structure (i.e., species composition, ages), soil properties such as hydraulic conductivity (Wilcox et al. 2003b), geology, and watershed size (Calder et al. 2007). It appears that the hydrological regulation functions of forests are scale-dependent, and most of our knowledge is derived from small watershed vegetation manipulation experiments, and we lack empirical data about the role of vegetation in influencing streamflow of large river systems.

Carbon cycle and ecosystem productivity

Changes in the water cycle directly affect ecosystem productivity (Xu et al. 2014) and aboveground and belowground carbon cycles through plant transpiration (Sun et al. 2011b), soil heat and moisture dynamics that affect ecosystem respiration (Biederman et al. 2016; Zhang et al. 2017b), and surface and subsurface flows that determine soil water availability to plants. Ecosystems do not generate water, but they modify the quantity, quality, and timing of water cycles. Global measurements of carbon and water fluxes using the eddy covariance method (Baldocchi et al. 2001; Chu et al. 2017) in recent decades clearly show that ecosystem primary productivity and ecosystem respiration are closely coupled with evapotranspiration processes (Sun et al. 2011b). At the leaf level, plant stomata play a critical role in regulating both water and CO_2 fluxes in ecosystems. Both soil moisture and temperature are key controls to soil respiration and photosynthesis through plant physical and physiological mechanisms(Baldocchi et al. 2006). Wetland hydroperiod, the fluctuation of wetland water level, is a major control to greenhouse gas emissions in wetland ecosystems (Dai et al. 2012; Hunter et al. 2008; Mitsch et al. 2010). The quantity of dissolved organic carbon (DOC) that is transported laterally through water flows is often considered to be small when compared to vertical flux exchange between the land and the atmosphere for most watersheds. However, lateral hydrologic carbon fluxes in water and sediment are an important food sources for aquatic organisms and can represent a significant component of net primary productivity for coastal wetlands (Chu et al. 2015).

Nutrient cycles and water quality

Ecosystems improve water quality by regulating nutrient cycling through various physical (i.e., dilution, uptake), chemical (phytoremediation, transformation), and biological processes (microorganism activities) (Chapin et al. 2002). Nutrient cycling in ecosystems is closely linked to water availability, movement, and carbon cycles in plants, soils, groundwater, and streams. For example, the N cycle is critical for understanding global change effects on ecosystem productivity (Aber and Federer 1992) and eutrophication of aquatic systems. Nitrogen deposition and rising atmospheric CO_2 concentrations have been identified as the two major factors controlling changes in forest productivity and carbon sequestration functions in Europe (de Vries 2009; de Vries and Posch 2011) and eastern USA (Tian et al. 2012), even surpassing the effects of climate change in some regions. Soil moisture affects soil C and nitrogen cycles through the processes of mineralization, leaching, plant uptake, and denitrification processes (Glazebrook and Robertson 1999). Plant photosynthetic capacity, which is strongly controlled by leaf nitrogen concentration, directly affects leaf biomass and litter production and thus ET and water yield, which in turn feedback to influence water and carbon cycles (Ollinger et al. 1998). Sediment is a major non-point source pollutant in many river systems that greatly increases water treatment cost for domestic use. Vegetated riparian buffers that serve as barriers of surface runoff often provide cost-effective management practices to slow down overland flow, trap sediment, and take up excess nutrients (Boggs et al. 2016; Endreny 2002). These buffer zones are also used as wildlife corridors (Lees and Peres 2008) and recreation greenways for people to enjoy in urban areas (Henry et al. 1999).

Knowledge gaps, research needs, and challenges to linking ecohydrological processes and ecosystem services

Although Ecosystem Services have been increasingly valued by both land managers and policy makers, there are various confusions about the mechanisms how ecosystems' function remains (Table 1). Some misconceptions come from "traditional wisdoms" and some from poorly informed science, but most are a result of deficient sciences. In addition, a lack of understanding of the connections between ES and nature's responses to human actions contributes to the slow recognition of nature's benefits. Table 1 provides an example of how perceptions about the influence of forests on water may vary among different disciplines and ecosystem service users.

Understanding tradeoffs and synergies among ecosystem services

Ecosystem processes such as energy, water, carbon, and nutrient cycling are interconnected in a rather complex way as discussed earlier. Similarly, many ecosystem services valued by people are highly interdependent. For example, growing trees for timber production or bioenergy requires consuming large amounts of fresh water and nutrients (Watkins et al. 2015), creating tradeoffs between two important ecosystem services, water supply and biological carbon sequestration (Jackson et al. 2005; Su et al. 2012; Wang et al. 2017). Consequently, enhancing one ecosystem service can negatively affect another. This kind of carbon-water tradeoff appears to be most pronounced in dry regions where water is limited and more valued than in humid regions (Sun et al. 2006). The carbon-water interactions occur in humid "water-rich" regions as well, but the tradeoffs in ecosystem services in terms of water supply and carbon sequestration are minimal.

Ecosystem service synergies occur when one service enhances another. For example, restoration of vegetation on degraded lands may increase ecosystem productivity such as litter fall and soil organic matter, and in turn, productive vegetation with multiple canopy layers helps enhance water infiltration and groundwater recharge (Ilstedt et al. 2007; Ilstedt et al. 2016), thereby reducing soil erosion and nutrient loss to aquifers and improving stream water quality. In addition to soil quality improvement, reforestation on degraded lands may increase baseflow and low flows in the dry seasons due to the improvement of soil infiltration capacity and groundwater recharge (Bruijnzeel 2004; Garcia-Chevesich et al. 2017; Liu et al. 2016).

The balance between positive and negative tradeoffs and synergistic relationships among various ecosystem services can shift depending on environmental conditions. For example, compared to grasslands, forests generally cool the air in tropical and temperate regions, but may warm the local atmosphere (Li et al. 2015) due to differences in evapotranspiration and albedo across the climate gradient. The regional contrast has important implications for reforestation in climate change mitigation by sequestering atmospheric CO_2 or/and reflecting shortwave ration (sunlight) to the atmosphere. Similarly, a reforestation study in western Africa suggests that an optimum forest coverage can be achieved to minimize the negative impacts of increased tree transpiration and maximize the positive effects of improved rainfall infiltration for groundwater recharge (Ilstedt et al. 2016).

Understanding the complex interactions among multiple ecohydrological processes is essential for developing models that can be used to understand and predict the tradeoffs or synergies among ecosystem services under a changing environment (Calder et al. 2009; Sun et al. 2011b). These models are inherently complex because they must include feedbacks among key physical,

Table 1 A comparison of common differences in perceptions among different ecosystem users about forests and water and potential policy implications

People	Interest in forests	Perception to forest and water relationship	Policy implications
Farmers	Competition for land	Trees compete for water; shade reduces crop production	Remove trees for crops
Foresters	Timber, fuels	Trees = clean water; soil erosion control	Trees are great, the more trees the better
Hydrologist/climatologists	Important land surface	High water users, soil erosion control	Play a small, but important role in the hydrological cycle
Hydraulic engineers	Hillslope and bank stability	Climate, not forests control river flow	Neutral, forests not important
Ecologists	Productivity, Biodiversity	Water as a limiting factor	Forests are key ecosystems
Land managers	Ecosystem services	Many perceptions, none dominant	Integrated management

biogeochemical, and ecological processes and socioeconomic systems. Empirical data quantifying the feedbacks of ecological processes are rare and require long-term observations. Process-based simulation models are currently limited but are emerging so that ecosystem services can be effectively evaluated.

Scale effects

Ecosystem services are often evaluated at a specific spatial (e.g., plot, watershed, regional, global) and temporal scale (e.g., a few hours to years). The scale context is important in identifying how ecological processes control ecosystems services and how to best evaluate these relationships. For example, reforestation or afforestation of land that previously supported short stature vegetation cover with shallow roots (non-irrigated croplands or grasslands) or planting fast-growing exotic trees that are more productive and use more water than native species, may lead to a reduction in water yield per unit of land area (Farley et al. 2005). However, the potential "negative" effects of planted forests on ecosystem services (e.g., reducing water supply) observed at a forest stand or small watershed scale may not be directly extrapolated to large basins or regions because hydrologic flows at these larger scales represent the integration of mixed land covers/land uses and other landscape components such as wetlands (Amatya et al. 2015). For example, planting trees in a small area, such as 10% of the entire basin, the negative hydrological effects on water yield may not be manifested at the watershed outlet, especially during the first few years when the trees are young with low leaf area index (Yang et al. 2017). The size and severity of land use disturbances matter at the watershed scale. A recent review study suggests that the increase in annual water yield associated with forest cover loss is significantly correlated to forest cover change at both small (< 1000 km^2) and large (> 1000 km^2) watershed scales, but the correlation between water yield responses to forest cover gain is statistically inconsistent at different scale (Zhang et al. 2017a). Temporal scales also matter in assessing hydrologic responses to land cover change. A study in the highlands of Veracruz, Mexico, showed that conversion of cloud forest to pasture led to increases in peak flows and decreases in dry-season flow, while reforestation with pines could either increase or decrease water yield depending largely on stand age and the timing of specific management practices (Asbjornsen et al. 2017).

Another example of scale effects on ecosystem services can be demonstrated by the influence of forests on ET (Ellison et al. 2017). As discussed, forests generally have higher ET than grasslands due to higher amount of biomass and deeper root systems in forests than grasslands (Jackson et al. 1996) and use deeper soil water resources (Asbjornsen et al. 2008). When evaluated at the watershed scale, the higher ET from forests resulting in lower water yield than grasslands is considered negative in terms of water supply to downstream water users. However, when the influences of forests on hydrology are evaluated at the "airshed" or regional scale, water vapor generated from forests located in one watershed may be considered as water supply via precipitation inputs to watersheds located downwind (van der Ent et al. 2010). Such a water supply function at the regional scale and the local cooling effects of trees can be considered as "positive" rather than negative services (Ellison et al. 2012; Ellison et al. 2017). In tropical Amazon Basin in Brazil and Peru, large areas of forests are important in cycling moisture between the land and the atmosphere and large-scale clearing of natural forests may have modified local climate and hydrology (Garcia-Chevesich et al. 2017). Observations of ecohydrological processes are linked to the spatial and temporal scales at which they were studied; therefore, the valuation of ecosystem services such as flood risk assessment, runoff abatement, and erosion control depends largely on the ability to identify connections across these scales (Hallema et al. 2016).

Disconnect between ecological status and ecosystem service delivery

Ecological or environmental status such as water quantity and quality and ecosystem service delivery are not the same. Our knowledge on the connection between the ecological status, processes, functions, and ecosystem service delivery is lacking. For example, a water body may be more polluted as people add more pollutants to it, but as a result, ecological processes that remove pollutants are generally doing more; thus, the service values also increase. Ecosystem service values may vary depending on the amount of supply and demand and thus are not static. An ecosystem service may increase even as its supply decreases if demand increases. For example, the value of providing drinking water service may increase relatively during a drought or peak water withdrawal seasons when water demand of water supply increases. Ecosystem services must be evaluated base on the practical uses for human welfare accounting (Boyd and Banzhaf 2007). Understanding the ecological processes related to the demand and supply of final ecosystem services is helpful to achieve this goal.

Socio-hydrological processes and ecosystem services

The values of ecosystem services are assessed based on human needs that are often diverse and vary across a spectrum of socioeconomic status, human management options, and environmental resource availability (Brauman et al. 2007). Worldwide, humans have a tremendous impact on watershed ecohydrological processes for several reasons: hydraulic engineering such as building dams for generating powers, inter-basin transfers for meeting irrigation and domestic water demands, urbanization and land use change, and human population growth and rise of standard of living. The anthropogenic impacts on ecohydrological processes are often dramatic and permanent and can exceed those from natural forces such as climate variability (Hao et al. 2015; Zhang et al. 2016). Therefore, it is important to understand the coupling processes between people and water, i.e., the coupled human-water system, in order to meet human needs of hydrological services while maintaining watershed resource sustainability (Srinivasan et al. 2017).

Socio-hydrology is proposed as a new water science that focuses on studying cross-scale bidirectional interactions of society and hydrological cycles and the co-evolution of human-water systems (Sivapalan et al. 2012). One of the key goals of socio-hydrology is understanding the meaning and value of water to human well-being in the context of biophysical and human interactions (Sivapalan et al. 2014). Therefore, sociohydrology is consistent with the call for understanding sustainability by studying coupled human-natural systems (Elshafei et al. 2015) and offers a new framework to link ecohydrological processes with ecosystem services that are meant to value nature that serves society (Daily et al. 2000). Socio-hydrology is considered a fundamental science for the practice of modern integrated water resource management (IWRM) that traditionally focused on sustainably managing water for people (Liu et al. 2015) but with less attention on the feedbacks of human actions on watershed ecosystem functions (Srinivasan et al. 2017).

Ecohydrology as an interdisciplinary science aims at understanding the interactions between hydrology and ecosystems. As discussed, humans are one of the important components of human-dominated ecosystem in the twenty-first century (Zalewski 2015). Human activities have shaped almost all aspects of natural ecosystems and present increasing challenges to the integrity of ecosystems that people depend on. Understanding the ecohydrological processes for the purposes of maximizing ecosystem services must consider the social-hydrological processes that involve not only physical processes but also cultural, political, socioeconomical, and ethical mechanisms (Sivapalan et al. 2014). Thus, an important knowledge gap and direction for future ecohydrological research is to include the integration of socio-hydrology to more fully explore the role of humans in shaping ecohydrological processes.

Integrated simulation models for ecosystem service assessments are lacking. Models to quantify ecosystem services require integration of both ecological process models and economical and sociological models at the right scale using a uniform terminology. Existing models in different disciplines vary in objectives, inputs, and outputs. However, they are complementary in that ecological and economic models are quantitative but much information about human systems is qualitative. It remains a challenge to integrate and link these models to fully understand ecosystem tradeoffs and human-nature interactions.

Conclusions

The ecosystem service framework offers an effective way to connect nature to people's well-being. From many perspectives, water is at the core of this linkage; thus, it is vital to understand the human-impacted ecohydrological processes in order to properly manage the inevitable tradeoffs or "win-win" synergies among the diverse ecosystem services provided by nature in the Anthropocene (Elshafei et al. 2015). We have identified several significant knowledge gaps and research opportunities that may help to guide efforts linking ecohydrological processes and ecosystem services at multiple scales. Future ecohydrological studies need to better account for the scaling effects of natural and anthropogenic stressors exerted on evapotranspiration and other water supply and demand processes. Most importantly, future studies should focus on the bidirectional interactions between hydrological functions and services and human actions to solve real-world problems such as water shortages, ecological degradation, and climate change adaptation. The newly proposed socio-hydrology calls for novel approaches to understanding human-water systems and achieving societal sustainable development (Sivapalan et al. 2012). Improved quantitative understanding of the linkages between ecohydrological processes and many facets of ecosystem services is consistent with the goals of the emerging socio-hydrology science addressing water issues relevant to human well-being including the physical, cultural, and socioeconomic values of water.

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Authors' contributions
GS designed and drafted the manuscript. DH and HA contributed to the revision of the first draft. All authors have read and approved the final manuscript.

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