Watershed Services in the Humid Tropics: Opportunities from Recent Advances in Ecohydrology

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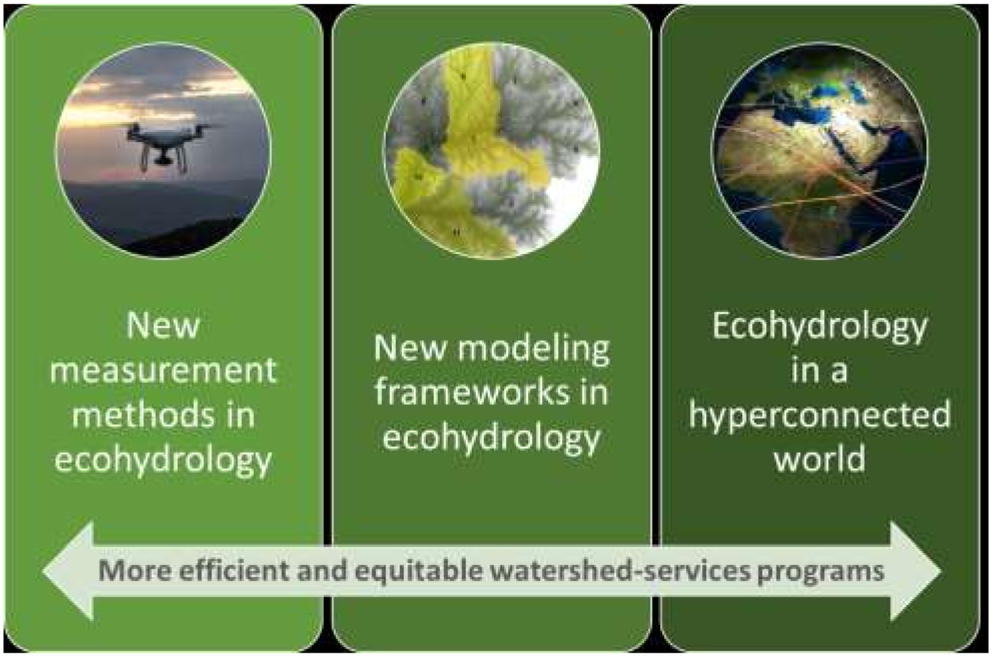
Abstract:

In response to increasing pressures on water resources, watershed-services management programs are implemented throughout the tropics. These programs aim to promote land management activities that enhance the quantity and quality of water available to local communities. The success of these programs hinges on our ability to i) understand the impacts of watershed interventions on ecohydrology; ii) model these impacts and design efficient management programs; and iii) develop strategies to overcome barriers to practical policy development, including resource limitations or the absence of baseline data. In this paper, we review opportunities in ecohydrological science that will help address these three challenges. The opportunities are grouped into measurement techniques, modeling approaches, and access to resources in our hyperconnected world. We then assess management implications of both the knowledge gaps and the new research developments related to the effect of land management. Overall, we stress the importance of policy-relevant knowledge for implementing efficient and equitable watershed-services programs in the tropics.

Keywords: investment in watershed services (IWS) programs; land management; ecosystem services; policy support; tropical mountains;

Graphical abstract:



1 Introduction

The humid tropics cover one-fifth of the Earth's land surface and generate the greatest amount of runoff of any biome globally (Fekete et al., 2002; Wohl et al., 2012). Three billion people worldwide live in humid tropical regions and depend on available water resources of tropical watersheds (State of the Tropics, 2014). Therefore, we need to properly manage watershed 'services', defined as the benefits that humans obtain from ecosystems at the scale of single watersheds or that are derived from processes occurring within the physiographic boundaries of a watershed. These services are essential to humans and range from water supply (e.g. for municipal, agricultural, or environmental uses) to water-risk mitigation (e.g. flood reduction and regulation of erosion) to cultural benefits (e.g. religious, recreation) and ecological functions (e.g. ecological flow regimes, contribution to the nutrient cycling or habitat creation).

Integration of landscape and water resources management is increasingly focused on the role of watershed services in tropical regions. Investment in Watershed Services (IWS) programs, land management planning based on watershed services such as national land use zonation, and natural capital assessments are well established or now emergent in these regions (Goldman-Benner et al., 2012; Bhalla et al 2013; Bremer et al., 2016). Here, we refer to these programs as "watershed-services programs", to encompass both IWS programs and other ecosystem-based planning processes. A successful example of IWS in the tropics is the Latin American Water Funds Partnership, which was created in 2011 to support the development of IWS programs in the region (Bremer et al., 2016). More than 20 land conservation programs participate in this initiative, producing and exchanging knowledge to improve the design and implementation of local programs. In India, the large scale watershed development initiative is an important component of the country's poverty alleviation and rural development programs with livelihoods being considered a "core objective" (Joshi, 2006). Globally, the advent of the sustainable development goals in the international political agenda also promotes the management of hydrologic services, in particular the objective to "protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes by 2020" (Target 6.6).

Despite the progress in existing IWS programs, practical barriers remain to the implementation of these programs around the world, often due to the lack of standardized assessment methodologies (e.g. Dougill et al., 2012; Bhalla et al 2015). Interventions promoted by watershed-services programs, such as conservation and protection of natural vegetation or restoration, including tree and grass planting, need to be carefully designed to account for local geology and ecohydrology. In particular, understanding the strength of the 'hydrologic signal' imposed by changes in land use is key to the implementation, monitoring, and success of watershed services programs (Guswa et al., 2014). For this, the scientific community needs to work closely with policy-makers to support the development of efficient and equitable management programs that rely on our best understanding of ecohydrological processes in a watershed.

What is unique about ecohydrology in the tropics? First, the tropics are home to unique ecosystems, influential climatic patterns, and distinct ecological processes. For example, the páramo ecosystem is a tropical alpine grassland found primarily in the Andes that has the capacity to provide reliable water supply to many Andean urban centers without the need for storage reservoirs (Buytaert et al., 2006; Figure 1). This function is largely dependent on the persistent low flux of liquid precipitation at high elevation, and the extremely porous soil-vegetation complex highly enriched in organic carbon – characteristics nearly unique to the tropics. Similarly, the unique meteorological processes of the Andean montane forests impose ecosystem dependence on fog drip precipitation, which is strongly influenced by geographic position relative to Amazonian forests (Célleri et al., 2009; Buytaert et al., 2006). Other unique mountain ecosystems include the Simien mountain ecosystems in Ethiopia (Liu et al 2008; Buytaert et al., 2011) and the montane shola forest-grassland ecosystems in the Western Ghats of India, which are perhaps 40,000 years old with endemic species whose closest relatives are found in the Himalayas (Bunyan et al., 2012; Das et al., 2015). Monsoonal precipitation in the Western Ghats in India can exceed 10,000 mm yr^{-1} and over 500 mm day^{-1} without significant overland flow (Krishnaswamy et al., 2006; Krishnaswamy et al., 2013).

Second, addressing the concerning issues of tropical land-use change in the tropics is challenging as most hydrologic research infrastructure and efforts remain located in temperate regions, with less attention toward tropical ecosystems (Wohl et al., 2012). This uneven geographic focus introduces substantial uncertainty in climate and hydrologic models within the tropics, and further exacerbates our lack of understanding of ecohydrological processes in tropical regions (Ponette-Gonzáles et al., 2014).

Third, the humid tropics are also hotspots of global biodiversity, thus providing a unique opportunity and challenge to link ecology with hydrology. Ecosystems in tropical mountains are also particularly vulnerable to climate change and loss of distinct ecohydrological moisture regimes (Beniston, 2003; Krishnaswamy et al., 2014).

This paper provides an overview of current challenges and opportunities in managing watershed services in tropical regions discussed at the AGU Chapman Conference on "Emerging Issues in Tropical Ecohydrology", held in Cuenca, Ecuador, June 5-9, 2016. Here we argue that growth in the study of tropical ecohydrology offers a great opportunity to i) evaluate the underlying biophysical processes that are responsible for current and future changes in watershed services in tropical regions; ii) assess the performance of existing hydrologic service-based management programs, including IWS programs; and iii) conceive and promote better practices to design, implement, and monitor such programs in the future. Importantly, we recognize that progress in ecohydrology has been made in very distinct areas thanks to advances in modeling capabilities, new technologies, and recent developments in social sciences. We seek to summarize key advances in each of these areas to improve the dialogue within the community and advance hydrologic services science.

In the next sections, we review the key challenges in ecosystem management to enhance or protect watershed services. We then provide a brief state of the art of ecohydrological techniques and approaches that can be used to inform the development of watershed-services programs. We conclude with management implications related to the design, implementation, and evaluation of watershed-services programs.

Figure 1. (A and B) Illustrations of the páramo ecosystem in Ecuador, and(C) high elevation Shola-grasslands in the Western Ghats, India, which generate streams providing hydropower and other hydrologic services despite a long dry season. These ecosystems unique to the tropics are hotspots of endemism.

2 Challenges for ecosystem management based on hydrologic services

Understanding the challenges and opportunities associated with watershed-based management is crucial to produce actionable science and develop efficient and equitable programs. Recently, the ecological and hydrological communities have summarized challenges and opportunities provided by the ecosystem services framework for their respective disciplines (Guswa et al., 2014; Birkhofer et al., 2015; Naeem et al., 2015). Associated knowledge gaps, with a focus on the tropics, can be grouped in three areas: 1) fundamental knowledge gaps on tropical ecohydrological processes; 2) integrated process modeling, including developing modeling frameworks and testable hypotheses specific to tropical regions; and 3) implementation and monitoring of watershed-services programs at local and global scales.

We summarize these gaps in Figure 2. Fundamental knowledge gaps in ecohydrology encompass the understanding of biological, chemical, and physical hydrological processes that occur at the multiple spatial and temporal scales of interest to management programs. Local-scale processes include the partitioning of precipitation between interception, infiltration, and evapotranspiration, as well as the biogeochemical exchanges between plants and their surrounding environment, above and below ground. Large-scale processes consider the watershed as a system and focus on the aggregated effects of biophysical processes that can be measured as water or nutrient flows (see Figure 2). At both scales, these processes need to be understood dynamically, i.e. under the influence of rapidly changing conditions such as land use or climate change. The temporal scales at which these processes occur are both short term (e.g. sub-hourly to daily) and long term (e.g. years to decades), and must be included when assessing ecohydrological change, field monitoring, and policy implications.

Next, reducing the limitations of current modeling approaches remains a major area of research. Modeling is often needed to implement and monitor programs. The multiplicity of models found in the literature, ranging from conceptual to hybrid to fully-distributed process-based models shows that multiple approaches are both possible and complementary. A major challenge for analysts is to decide on a tool with a structure and level of complexity aligned with modeling objectives and data availability, which are specific to each project. In addition, assessing the uncertainty in model outputs is difficult given the often limited number of available observations and inherent uncertainties in available data.

Finally, implementing ecosystem-based watershed management programs remains a challenge because the benefits provided by these programs is inherently site-specific. While these programs have obvious similarities (e.g., by using ecosystem knowledge to inform land management policies), they also, inevitably, range in their specific goals and decision contexts (Bremer et al., 2016). For instance, some programs may be concerned with the absolute value of groundwater recharge under a given land use change to structure their payment system, while others may only require a general assessment of best places to target their interventions (Guswa et al., 2016). In addition, designing ecosystem-based program requires interpretation of ecohydrological knowledge to derive relevant information to policy-makers: scientific breakthroughs do not serve policy needs if "knowledge brokers" are not translating them into practical terms (Partidario and Sheate, 2014; Lehmann et al., 2014). Monitoring and evaluation of these programs can further add complications given the costs of instrumentation or personnel needs, despite these steps being recognized as fundamental to the success of watershed-services programs as the structure itself (Naeem, et al., 2015).

Figure 2. List of challenges in applying ecohydrological knowledge to the design and implementation of watershed-services programs, from fundamental science gaps, to modeling, to

practical implementation challenges.

Fundamental knowledge gaps related to ecohydrological processes	Modeling challenges	Practical challenges and implementation
Knowledge gaps related to **local processes**: – Partitioning between interception, infiltration, evapotranspiration, nutrient and erosion generation processes in Tropical ecosystems (e.g. Páramo) – Water and chemical exchanges between soil, vegetation, and the atmosphere Knowledge gaps related to **watershed processes**: – Surface and subsurface flow processes – Contaminant transport – Effects of landscape heterogeneity on ecohydrological functions – Impact of climate variability (e.g. ENSO cycles) on ecohydrological processes and functions Knowledge gaps related to the **responses to global environmental change**: – Ecohydrologic responses to land management or direct human modifications – Responses to climate change	Developing **adequate models**: – Adequacy between model complexity and purpose of the decision context – Output variable measurable and common to multiple ecosystem services – Comprehensive to encompass larger-scale climate drivers such as ENSO cycles Assessing **modeling uncertainty**: – Quantifying uncertainty in data-scarce environments – Resources to assess robustness of outputs – Use of multiple modeling approaches to assess/reduce uncertainties **Collecting data** in resource-scarce or remote environments	Designing **efficient and equitable** management programs: – Variability in goals and decision contexts across programs – Translating data from ecohydrological analyses into information used to meet socio-political objectives – Using analytical framework from ecohydrological knowledge/modeling, when alternative frameworks may be better suited to local culture Designing **monitoring and evaluation** programs: – Absence of baseline data – Limited resources (human and economic) to implement monitoring

3 Opportunities in ecohydrology of tropical systems

In the following sections, we highlight new opportunities in ecohydrology that offer potential to inform watershed-services programs in the tropics. We organize these opportunities around three major themes: measurement techniques, modeling frameworks, and access to information in our hyperconnected world.

3.1 Measurements for ecohydrology

Plot-scale measurements

Plot-scale measurements and field observations represent the cornerstone of ecohydrology. Typically, plot-scale observations are made by direct observations of various components of the water cycle (e.g., rainfall, discharge, storage), quantification of chemical fluxes (e.g., sediment and nutrient export), and characterization of plant-soil interactions (e.g., including quantification of mass exchange). Tropical soils differ from temperate soils in that they are often highly weathered, often deep, have unique macropores (Putty and Prasad, 2000) and current pedotransfer functions are not appropriate for use in tropical soils (Hodnett and Tomasella, 2002) given that micro-aggregation in high-clay ferrosols results in much more rapid drainage compared to soils of similar clay contents in temperate regions.

Key insights in the tropics relate to the hydrological functions of undisturbed soil (Bruijnzeel, 2004) and their evolution with land use change (Molina et al., 2007; Roa-García et al., 2011). Direct implications for land management can be drawn from empirical data, for example on the impact of land use change on runoff (Tobón et al., 2010; Ghimire et al., 2014). In addition, plot-scale studies have been used to understand soil-vegetation interactions in tropical ecosystems. A recent study suggested that plant water use is more strongly related to nutrient distribution in the soil than water availability in montane cloud forests (Goldsmith et al., 2012). Other researchers have observed that upslope tree water use was more strongly coupled with environmental variables than low-slope trees in a tropical montane cloud forest (Berry et al., 2016), highlighting that caution is needed when upscaling such processes from single trees to forest stands to catchments (Seyfried and Wilcox, 1995). With regards to the seasonality of flow, studies have shown that tropical seasonality can induce a shift to a more stable deep soil water source along dry seasons (Romero-Saltos et al., 2005) and exhibit hydraulic redistribution (Oliveira et al., 2005).

In general, an increasing number of studies show that the magnitude of hydrologic processes or their responses to change may significantly differ from intensively-studied ecosystems (e.g. in temperate climates). Therefore, plot-scale efforts should be sustained to provide mechanistic explanations of patterns observed at the watershed scale, which are critical to improve spatially distributed catchment models (Wohl et al., 2012).

Isotope tracing

Hydrologic studies involving water isotope ratios ($^{18}O/^{16}O$, $^{2}H/^{1}H$) over the past 60 years have led to a number of key advances in our understanding of tropical hydrologic processes. Tropical isotope hydrology has helped pinpoint plant water sources and assess water mixing in soil profiles (Meinzer et al., 1999; Lamontagne et al., 2005; Goldsmith et al., 2012; Evaristo et al., 2016), quantify threshold rainfall intensities that must be exceeded to recharge groundwater aquifers (Vogel and Van Urk, 1975; Jones and Banner, 2003; Jasechko and Taylor, 2015; Sánchez-Murillo and Birkel, 2016), partition vapor flows into physical evaporation and plant transpiration fluxes (Dincer et al., 1979; Yepez et al., 2003), calculate fractions of streamflow comprised of recent rainfall (Buttle and McDonnell, 2005; Mosquera et al., 2016; Muñoz-Villers et al., 2016), and calibrate models of flow processes at the subsurface (Windhorst et al., 2014; Birkel and Soulsby, 2016). The usefulness of isotopic tracer data in ecohydrology relies on measurable differences in the isotopic compositions of waters in a study area. Regional isotopic variations are produced by variable isotopic compositions of catchment inputs (i.e., rain, fog, and snow), or modifying processes that take place within the catchment or aquifer such as evaporation, mixing, and water-rock interactions. Unlike the extratropics, where precipitation $\delta^{18}O$ is often linearly related to atmospheric temperatures, tropical precipitation $\delta^{18}O$ is often related significantly to precipitation rates (Dansgaard, 1964). Further, intra-annual variations in precipitation isotope contents are generally more subdued in the tropics relative to sites at higher latitudes (Jasechko et al., 2014).

These tropical-extratropical differences in precipitation isotope variations indicate that some of the isotope-related tools developed in the extratropics may require adaptations prior to application in the tropics. For example, isotope-based approaches designed for regions with distinct winter versus summer precipitation $\delta^{18}O$ variations may be inappropriate for regions with multi modal precipitation (e.g. Jasechko et al., 2014; Jasechko and Taylor, 2015). Adapting approaches applied in the extratropics—where the great majority of published field studies have taken place (Burt and McDonnell, 2015)—may help to accelerate development of isotope-based approaches targeted for low latitude settings. With further experience, isotopic techniques may prove valuable to understand processes in the field of tropical hydrology: in particular, they will support the re-evaluation of some long-standing conceptualizations of water and solute mixing and movements within the critical zone (McDonnell, 2014), and an improved understanding of the impacts of land clearing on recharge, runoff and nutrient fluxes may benefit from isotope-based approaches that are designed to calculate the age of water and solutes (Butman et al., 2015).

Remote sensing

Remote sensing and geographical information science serve to capture, process, and analyze spatially-referenced observations, obtained from sensors in space and on the ground (Chen et al., 2016). They provide a cost-effective source for biophysical variables and methods for characterizing spatial patterns of climate, soil and vegetation in the tropics (Vivoni, 2012). For example, new satellite products have been used to better quantify precipitation patterns, a key input in the watershed-scale water balance (Campozano et al. 2016; Carrillo-Rojas et al., 2016). This is particularly important for the tropics, which tend to be less well instrumented than the temperate zone. Satellite images can also be coupled with ground observations to facilitate downscaling spatial data (Hunink et al., 2014), to test and improve quality of satellite images (Glenn et al., 2007; Manz et al., 2016), and to characterize the interplay among different sources of information.

In the past two decades, observations from space have experienced significant and ongoing improvement. Spatial resolution of images decreased from 80 m for Landsat 1 in 1970s, to 30 m for Landsat 7 in 1990s, and recently to 0.31 m for WorldView 3 in 2015 (Chen et al., 2016). Temporal returns decreased from 16 days (Landsat series) to daily returns for MODIS (spatial resolution of 250m to 1000m). Spectral bandwidth has increased from panchromatic (1 band, black and white images), to multispectral (4+ bands) and hyperspectral bands (100+ bands). Sensors are now designed to capture a wide range of the electromagnetic spectrum ranging from the visible to the infrared, thermal and microwave wavelengths.

Although there is great potential for use of remotely sensed information in tropical regions, its application faces several challenges. As in other regions, it is important to conduct ground validation of remotely-sensed information since algorithms used globally may yield large errors (e.g. for precipitation, as shown by Manz et al. 2017). One impediment is the frequent cloud coverage over the tropics, which reduces the capacity of several techniques to consistently collect useful observations at regular time intervals. To address this issue, unmanned aerial vehicle (UAV) systems offer a promising technology since they fly below cloud coverage. In addition, their spatial resolution is sub-centimeter, the temporal resolution can be managed on-demand, and the spectral resolution is continuously improving with the miniaturization of multispectral and hyperspectral cameras (Anderson and Gaston, 2013; Colomina and Molina, 2014; Teodoro and Araujo, 2016). Early initiatives using UAVs for ecohydrological research include high-resolution data within eddy covariance footprints, spatial distribution of terrain attributes related to vegetation conditions (Vivoni, 2012; Vivoni et al., 2014), biomass (Bendig et al., 2015), and vegetation health monitoring (Michez et al., 2016).

New sensors and data loggers

With an increasing awareness of the value of long-term datasets (Burt, 2003; Holmes, 2006) and high-resolution data to improve our understanding of hydrological processes and management of water resources (Bowes et al., 2009; Neal et al., 2012; Lloyd et al., 2016), a growing number of studies deploy *in-situ* sensors to measure relevant parameters with high temporal frequency (Sandford et al., 2007; Pellerin et al., 2009; Sherson et al., 2015). Recently, the cost of commercially available sensors has stimulated the development of alternative low-cost, robust sensors and data loggers: open-source software, electronics and off-the-shelf hardware store items, combined with low-cost microcontrollers (Pearce, 2012). For example, low-cost water quality sensors have been developed and tested for parameters such as pH and conductivity, temperature, toxicity and turbidity (Tuna et al., 2013; Banna et al., 2014; Chapin et al., 2014; Murphy et al., 2015; Yagur-Kroll et al., 2015), although few sensors have actually been deployed in the field. Off-the-shelf cameras have also been applied successfully to record water level (Gilmore et al., 2013) and discharge (Bradley et al., 2002; Tsubaki et al., 2011), plant phenology (Crimmins and Crimmins, 2008; Nijland et al., 2014) and cloud cover (Scholl, 2015). To compile data, wireless sensor networks can also be used to provide connected and sometimes real-time data on a range of environmental parameters within an area (Kido et al., 2008; Zia et al., 2013).

Currently, the application of low-cost sensors in the tropics remains limited (Cama et al., 2013; Hund et al., 2016). Examples include the FreeStations, an open source hardware weather stations, which have been deployed in more than a dozen sites across the tropics (www.policysupport.org/freestation). Because they are low cost, lightweight, easily installed and modular, they remove many of the barriers to deployment and maintenance in tropical (montane) environments. Data from these FreeStations are uploaded to the server and contribute to the temporal and spatial open-access database used in policysupport.org tools such as WaterWorld[1]. Another example is the Trans-African Hydro-Meteorological Observatory (TAHMO[2]) project, which seeks to install 20,000 robust, low-cost ground-based weather stations in partnership with schools, communities and national meteorological services across Africa.

Due to their versatility and low cost, new sensors offer great promise to address knowledge gaps in ecohydrology (Brown et al., 2016), including monitoring of the effect of land use change (e.g. interventions in IWS programs). Low-cost but robust sensors are particularly important now that official hydrological monitoring networks are in decline in many countries (Lanfear and Hirsch, 1999; Vorosmarty et al., 2001) and in tropical montane settings where sensor networks remain sparse (Jarvis and Mulligan, 2011). Barriers to implementation include the lifetime, statistical

[1] www.policysupport.org/waterworld
[2] tahmo.org

validation, robustness and accuracy, which remain in many cases low compared to commercial sensors. In addition, wireless sensors relying on batteries can be limited due to the short lifetime of batteries at high altitude.

3.2 Modeling change in ecohydrology

A major challenge in modeling relates to the available data to test and calibrate these models, which is the focus of the next section on watershed monitoring. Next, we present the advances in the field of socio-ecohydrology, which provides a novel perspective on modeling needs and objectives, and conclude with some examples of model adaptation for the tropics.

Monitoring change: Paired-watershed experiments and regional studies

Understanding watershed behavior is a major objective of hydrologic research and paired-watershed experiments have long been used for that purpose. These experiments began in the early 20th century as a mechanism to understand the effects of land use and/or land cover change (particularly forest cover) on the water balance at the catchment scale (Bosch and Hewlett, 1982; Neary, 2016) by comparing two catchments with similar biophysical characteristics (Brown et al., 2005). After a calibration period, one of the catchments is subjected to a treatment (e.g. deforestation or afforestation) and the other remains as a control. Paired-watershed studies have been useful to “substitute space for time” in hydrological monitoring, for example to understand the effects of forest regeneration (Bren et al., 2010) or watershed development on water and sediment fluxes (Wemple et al., 2007; Neary, 2016; Ochoa-Tocachi et al., 2016b), the function of riparian buffers (Scott, 1999), or for developing appropriate hydro-biogeochemical models (Cosby et al., 1996).

The objective of paired-watershed studies conducted in the tropics include research on the conversion of rainforest to forest plantations (Bruijnzeel, 1990; Malmer, 1996), deforestation

(Bruijnzeel, 1990; Neill et al., 2001; Le Tellier et al., 2009; Wilcke et al., 2009; Deegan et al., 2011), water yield of forest and non-forest native vegetation (Chandler and Walter, 1998; Mark and Dickinson, 2008), impacts of agriculture and grazing (Chandler, 2006; Ogden et al., 2013), impact of roads and logging operations (Grayson et al., 1993; Sidle et al., 2006), impact of shifting cultivations (Gafur et al., 2003), hydrologic function of wetlands (Mosquera et al., 2015), ecohydrologic controls on runoff (Crespo et al., 2011), nutrient fluxes (Câmara et al., 2000; Stallard, 2011; Gücker et al., 2016;), water quality and macroinvertebrates (Ometo et al., 2000), and in general about the effects of land use change (Ochoa-Tocachi et al., 2016b). As the these studies reveal, paired-watershed studies can be useful for informing watershed-services programs as they help identify the potential changes in hydrological services through land degradation or land use change, e.g. reduction in annual and seasonal flows, or degradation of water quality (e.g. sediment and nutrient fluxes) that can increase the cost of downstream water treatment.

A well-known limitation of paired-catchment studies is that it may be difficult to separate the effect of land intervention from other watershed characteristics, which inevitably slightly differ between two watersheds. Using a nested catchment approach and regional studies help to overcome this issue and reduce uncertainty about the effect of the intervention. Measuring internal fluxes within the catchments, with nested catchments, can prove useful to explain the differences in observations at the outlets (Mosquera et al., 2015; Salemi et al., 2015). An integration of point, hillslope and watershed observations can provide stronger evidence of ecohydrologic processes, and nested watershed approaches can provide information at different spatial scales (Mori et al., 2015; Correa et al., 2016). At a larger scale, ecohydrologists can use regionalization approaches, gaining insights on the hydrological behavior of watersheds over large areas. Regionalization approaches allow watershed-services programs to benefit from insights gained in similar environmental settings (e.g. iMHEA network, Célleri et al., 2009; Ochoa-Tocachi et al., 2016a).

Approaches developed in socio-ecohydrology

The importance of interactions among human, land uses and ecosystems has been widely recognized in ecology (Elmhagen et al., 2015). The notion of ecosystem services itself assumes a set of values that are shared by groups of “beneficiaries”. Socio-hydrology is an emerging field aiming to understand co-evolution between human and water systems (Troy et al., 2015). It focuses on the development of interdisciplinary approaches to provide options for addressing competing interests at the science–policy interface (Wheater and Gober, 2013; Gober and Wheater. 2014), which makes its development relevant to watershed-services programs.

In an early effort, Falkenmark and Folke (2002) set out important themes of socio-ecohydrology. They stressed the importance of “doing things right” but also “doing the right thing” in an environmental ethics perspective (Falkenmark and Folke, 2002). Therefore, in addition to the ecohydrological properties of ecosystems, socio-economic, culture, and governance factors are crucially important (Calder, 2000; Ostrom, 2009). To support this change, neo-classical economic development perspectives are complemented by ecological economics approaches, which incorporate a broader range of values in ecological services assessments (Matthews, 2002; Farber et al., 2006). New participatory methods are also being developed for generating democratic options based on social-ecological system dynamics (Walker et al., 2002; Kok, 2009; Gober et al., 2010; Bakker, 2012). Examples of these approaches are emerging, although evaluation of long-term effects is still rare (Gómez-Baggethun et al., 2014), given the recent history of this field. IWS programs in the Latin American Water Funds Partnership will provide useful empirical data for socio-ecohydrology since a number of the explicitly state community engagement in the key objectives of their programs (Bremer et al., 2016). In addition, citizen science and the recent trends in distributed monitoring and hydrological information systems (Buytaert et al., 2016) provides opportunities to better understand the dynamics between traditional water managers and the civil society.

Adapting ecohydrologic models to the tropics

Insights gained from all the techniques presented above, from small-scale measurements to watershed and regional studies, allow for the development of new models in the tropics. Ecohydrologists have long recognized that many modeling tools were inadequate for applications in tropical watersheds (Ponette- González et al., 2014), due to the differences in dominant processes in this region. For example, the Soil Water Assessment Tool (SWAT) commonly relies on the curve number method to estimate runoff generation, without recognition that this empirical method has not been extensively tested in tropical watersheds, where infiltration excess runoff is rarely dominant (White et al., 2017). Similarly, fog capture is a significant input to the water balance in many montane tropical regions (Mulligan, 2013), but is rarely represented in models due to its insignificance in temperate climate.

These model inadequacies may be addressed by modifying existing model structures, e.g. enhancing the SWAT model with different runoff generation routines, as illustrated by White et al. (2010) in the Ethiopian highlands and more recently by Hoang et al. (2017). Alternatively, new models can be developed that focus on dominant processes in the tropics, for example fog capture is a major component of the FIESTA model, which was later incorporated in the WaterWorld model (Mulligan, 2013).

3.3 Ecohydrology in a hyperconnected world

Citizen science

An alternative to the traditional methods of data gathering is the involvement of citizens or the non-scientific community – also called citizen science. Involvement ranges from participatory process in research design and on-site monitoring to creating large online communities for data collection and performing scientific tasks. This method has successfully been applied in many conservation projects, especially in ornithology (Sullivan et al., 2009; Dickinson et al., 2012; Tulloch et al., 2013), but is increasingly applied in hydrology as well (e.g. Breuer et al., 2015;

Lowry and Fienen 2013).

The majority of citizen science projects in hydrology are located in non-tropical countries (Buytaert et al., 2014), but there are some examples of projects whereby the local community is actively involved in tropical environments, including several projects in Ethiopia (Liu et al., 2008; Zemadim et al., 2013; Walker et al., 2016), Tanzania (Gomani et al., 2010), South Africa (Kongo et al., 2007), the Andean region (Célleri et al., 2009) and in Bolivia (Le Tellier et al., 2009). In most cases, studies conclude that the involvement of the local community improves the positive perception of local communities towards research and avoids issues such as vandalism. Furthermore, local knowledge is useful in the design of a monitoring network (Gomani et al., 2010; Zemadim et al., 2013) and involvement also often raises awareness of environmental issues and encourages active participation in sustainable management of their resources (Liu et al., 2008; Walker et al., 2016).

One of the challenges of citizen science is engagement and motivation of data collectors. Whereas in developed countries, the motivation mainly comes from increasing one's personal scientific knowledge, environmental concern or curiosity (Buytaert et al., 2014), in tropical ecosystems located in developing countries, where livelihoods depend on natural resources, information on individual benefits may be sought before citizens invest their time and resources. Therefore, careful planning on how to engage these people and keep them motivated on the long term is required. However, combining citizen science monitoring with an IWS program, from which the local community will benefit in the long run, could significantly increase the willingness of people to participate. Despite concerns about quality of collected data (Le Tellier et al., 2009; Conrad and Hilchey, 2011), data collected through citizen science has proven to be of significant value in increasing understanding of how a system works (e.g., Kongo et al., 2010; Walker et al., 2016) and is a good alternative to high-cost or labor and maintenance intensive monitoring programs. A key implication of the shift to a "polycentric monitoring and governance approach" is that knowledge and power relationships are redistributed from traditional water management actors to the civil society, including non-technical advocacy groups (Buytaert et al., 2016).

Leveraging globally-available data

Another opportunity in our hyperconnected world is the enhanced international collaboration, with scientists being able to share knowledge and contribute to global data platforms. Examples include the CUAHSI[3] platform, which offers access to hydrologic datasets from universities around the world, or the iMHEA[4] network, collecting and curating hydrologic information in the Andes. Global datasets allow researchers to gain new insights into the water balance and its evolution through time (e.g. Jaramillo and Destouni, 2015). They also serve to develop and test global models, such as WaterWorld (Mulligan, 2013) or WaterGAP (Alcamo et al., 2003), which can then be modified to represent the particular dynamics found in tropical ecosystems. For example, a new module is currently being developed to represent cloud forest dynamics in WaterGAP, for its application in Latin America.

The development of information networks and platforms has implications for the design of monitoring and experimental strategies, which should facilitate regional comparisons and therefore generalization of local findings (Ochoa-Tocachi et al., 2016a). Robust and consistent methodology for data analyses is critical to interpret these datasets (Adams and Fowler, 2006). As noted earlier, wireless and low-cost sensor networks are also becoming more common, facilitating the development of dense network deployment and real-time monitoring (Jin et al., 2014; Krause et al., 2015). Recent advances in user platforms to access satellite imagery open up a wide range of possible research topics. For example, Google Earth Engine users can access archival data from a large number of sources (Donchyts et al., 2016). This promises a "golden-age" for data fusion (combining satellite with UAV and ground-based measurements) to enable researchers to integrate disparate data sources to identify ecohydrological functions and processes. This is especially important in tropical ecohydrology given the pace of land use change and the profound interannual differences that can result from climate variability (e.g.

[3] www.cuahsi.org
[4] www.condesan.org/imhea

ENSO cycles) and climate change.

4 Management implications

4.1 Managing complex ecosystems

Designing efficient and equitable watershed-services programs in the tropics requires extensive knowledge of local ecohydrologic systems. Many ecosystems are unique to these regions and their behavior significantly differs from better-studied temperate systems. For example, northern South America is unlike any other tropical region because of the unique combination of climatic and orographic forcings. First, due to the elevations imposed by the Andes, mean annual air temperatures can be as low as 4ºC (Hofstede et al., 1995). Second, similar to other humid tropical systems, the annual distribution of precipitation in the region is controlled by the meridional oscillation of the intertropical convergence zone, leading to a bi-modal distribution of precipitation throughout the year and an average annual precipitation above 2000 mm/year (Poveda et al., 2006). Ecosystems like the páramo regulate the water resources of communities at lower elevations yet they remain poorly characterized and managed in an ad-hoc way (Ponette-González et al., 2014; Ochoa-Tocachi et al., 2016b). They remain poorly characterized and studies that systematically combine direct observations, modeling, and citizen science are virtually not existent. We believe that it is feasible to use techniques that are already at hand – and widely applied in temperate regions – to examine both the hydroclimatic responses and the coupling of human-natural dynamics of this unique ecosystem. Because ecosystem services from páramos are often being managed by local entities (e.g., local water supply companies or community-level associations), it is of vital importance to engage such entities in meaningful discussions and long-term planning for research.

While maintaining or restoring water is usually the primary objective for land management, soil management is often considered important. Mossy and other organic rich soils are naturally dominant of high-elevation regions of the tropics and mediate shallow subsurface storage and the spatial and temporal delivery of water (Mosquera et al., 2016), carbon (C), nitrogen (N), and phosphorous (P) to streams. When these soils are disrupted by conversion to, or intensification of agriculture and grazing, there is an associated change in shallow subsurface storage, hydrologic flowpaths, and the delivery of sediments and nutrients to streams.

For both water services and soil conservation, the key implication of these knowledge gaps is to provide incentives to better characterize these systems, with metrics that are relevant to management. In fact, the complexity of hydrological processes means that the management of hydrologic services is unlikely to be efficient with the use of simple land-use and land-cover proxies (Ponette-González et al., 2014). Progress has been made towards utilizing global data products towards catchment classification in data-scarce regions (Auerbach et al., 2016), which provides a key organizational framework for modeling tropical ecohydrological processes and managing tropical watersheds. On the contrary, local knowledge on water fluxes and robust modeling approaches need to be used to design programs. As argued in Section 3.1, a number of measurement methods are available to improve our knowledge of surface and subsurface flow processes, climate drivers, soil-vegetation-water exchanges, and the impact of land-use or climate change on these processes.

4.2 Producing policy-relevant knowledge

In addition to fundamental knowledge gaps in tropical ecohydrology, two other barriers hinder the design of efficient and equitable watershed-services programs: the inevitable limitations of existing monitoring networks and the scarcity of modeling tools that address specific program needs. In both cases, the target variables include both biophysical (e.g. flow rates, water quality) and socio-economic variables (e.g. water use from relevant parties, costs and benefits from water services). In line with the scope of this paper, we focus here on the biophysical data only but note that new approaches developed in socio-ecohydrology will be critical to guide ecohydrological research. For example, the development of indicators and proxies to quantify human impacts on the biosphere is critical to help translate ecohydrologic science into actionable knowledge.

Monitoring networks are key to the design and implementation of management programs. First, local monitoring data help overcoming the barriers related to incomplete system understanding and low confidence in models. The availability of monitoring data prior to the establishment of a program is extremely useful to design robust plans and increase the chances of success for the program (Naeem et al., 2015). An example of such pro-active and data-based planning is the Latin American Water Fund Partnership, whose members helped establish or connect monitoring networks in Latin America, with the aim to improve management and make the case for the importance of watershed investments (Higgins and Zimmerling, 2013; LAWFP, 2016). Second, monitoring networks have long been recognized as essential assets for adaptive management (Higgins and Zimmerling, 2013). Acquiring data and continuously testing the key assumptions underlying a program may help redirect funding or focus areas for interventions. Socio-economic data on the impact of the program on livelihoods also help assess that programs promote equity in the area.

In parallel to acquiring of monitoring data, producing robust predictions of future water resources is critical to the successful program development. As noted in Figure 2, successful ecohydrologic modeling is hindered by data availability and the challenges associated with assessing uncertainty in ecosystem services modeling (Hamel and Bryant, 2017). It is indeed difficult to leverage the accessibility of recent research, if model outputs essentially cannot be compared to each other. Therefore, consistency in the data and types of models used regionally would dramatically accelerate the generation and reuse of information. This approach was taken by a recent project, ClimateWIse[5], which aims to improve our understanding the value of ecohydrological tools to inform the design of watershed-services programs in tropical mountains.

4.3 Practical challenges

In practice, the transfer of ecohydrological knowledge to policy and management is limited by several constraints, which we summarize as follows:

[5] environment.umn.edu/discovery/gwi/our-work/climatewise

1. The complexity of managing hydrologic services for various spatial scales: for example, evapotranspiration is associated with reduction in usable water at local spatial and temporal scales (Bruijnzeel, 2004) but contributing to vital hydro-climatic services at larger spatial scales due to contribution to rainfall (Spracklen et al., 2012). In addition, extrapolating from small homogeneous areas to large mixed landscapes is challenging because of scale effects and spatial thresholds of hydrologic processes such as ground-water contribution to baseflow (Bruijnzeel, 2004).
2. The complexity of managing hydrologic services for various temporal scales: for example, forest degradation may increase water availability in the short-term (e.g. through an increase in surface runoff that fills irrigation tanks) but it leads to complex trade-offs and reduction in other ecosystem services in the future (Lele et al., 2008; Mehta et al., 2008).
3. The trade-offs between water services and other services (e.g. carbon, nutrients), given the increasing demand for climate change mitigation using vegetation (Malmer et al., 2010).
4. The uncertainty introduced by climate change, e.g. the shifts in hydrologic pathways under diverse land use/land cover due to intensification of the hydrological cycle (Bonell et al., 2010; Krishnaswamy et al., 2013).
5. The legal and ethical limits to manipulating vegetation for water services in biodiversity hotspots or landscapes that provide multiple ecosystem services.
6. Socio-economic feasibility of managing for water services at local scale (farm) versus using economic productivity at larger scales (e.g. basin) to divert management of ecosystem services at local scales (e.g. Le Maitre et al., 2007).

Despite these challenges, there are a few examples of existing knowledge of land management effects on ecohydrology informing policy and management, some of them dating back to several decades. In the Western Ghats mountains of South West India, concerns over reduced dry-season flow has led to policy decisions to discourage plantations of exotic Acacia and eucalyptus on montane grassland and elsewhere (Sikka et al., 2003; Rangan et al., 2010). The tropical forested

Western Himalayan Uhl catchment, situated between 2133 m to over 4900 m and upstream of a hydropower project, was the site of an important forest hydrologic experiment between 1934 and 1947. In this period, grazing by over 95,000 sheep and goats was stopped, and river discharge and rainfall gauged. Although no conclusive evidence for the negative impact of grazing on winter discharge was found, important lessons were drawn related to robust monitoring design (Saberwal, 1999).

The experience of transforming landscapes or sites (grassland or degraded/deforested land) for ecosystem services such as some form of wood product or biomass and for watershed protection has usually been attempted with quick growing non-native species, and in other cases with species that have become invasive well beyond the sites where they were initially introduced. In India, this has resulted in serious concerns about impacts on soil moisture, groundwater table and dry-season flow (Sikka et al., 2003; Srinivasan et al., 2015). These concerns are finally starting to influence policy and management of landscapes for enhancing hydrologic services in India.

5 Conclusions

In this paper, we synthesized the current knowledge gaps and barriers to the implementation of successful land management programs in the tropics. Key knowledge gaps span all scales of study for ecohydrology: from soil-vegetation-atmosphere interactions to land surface hydrology and groundwater dynamics. This lack of knowledge in tropical ecohydrology is in part explained by the disproportionate amount of studies available in these regions compared to temperate areas. Fortunately, the variety of tools developed for ecosystems globally can be used to rapidly expand ecohydrological knowledge in the tropics. In particular, the extensive use of remote sensing data, isotope techniques, and new sensors, combined with more traditional plot-scale monitoring and modeling, will help researchers to comprehend the potential impact of watershed-services management. We also argued that our hyperconnected world increases accessibility to data at an unprecedented rate: in addition to leveraging citizen engagement, researchers may use globally available data and benefit quasi-instantly from lessons learnt in other tropical environments. However, these opportunities do not come without a cost: making use of these data is contingent on scientific knowledge to be presented in an effective way to their peers. Given the potential of watershed-services program in the tropics, we call for ecohydrologists to consider the implications of their work for watershed-services programs. The challenges summarized here may help situate their work and make their findings directly relevant to a sustainable management of natural ecosystems.

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