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REVIEW ARTICLE

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Advancing ecohydrology in the 21st century: A convergence of opportunities

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Abstract

Nature-based solutions for water-resource challenges require advances in the science of ecohydrology. Current understanding is limited by a shortage of observations and theories that can further our capability to synthesize complex processes across scales ranging from submillimetres to tens of kilometres. Recent developments in environmental sensing, data, and modelling have the potential to drive rapid improvements in ecohydrological understanding. After briefly reviewing advances in sensor technologies, this paper highlights how improved measurements and modelling can be applied to enhance understanding of the following ecohydrological examples: interception and canopy processes, root uptake and critical zone processes, and up-scaled effects of land use on streamflow. Novel and improved sensors will enable new questions and experiments, while machine learning and empirical methods provide additional opportunities to advance science. The synergy resulting from the convergence of these parallel developments will provide new insight into ecohydrological processes and thereby help identify nature-based solutions to address water-resource challenges in the 21st century.

KEYWORDS

environmental sensing, measurement, machine learning, modelling, interception, critical zone processes, land use, streamflow

1 | INTRODUCTION

The interdisciplinary science of ecohydrology explores interactions between the structure and function of ecological systems and the movement and quality of fresh water. While aspects of this science have been investigated for over a century (Mackay, 2019), the field has experienced significant growth over the past two decades, highlighted by the establishment of a new field-specific journal in 2008 (Smettem, 2008). The past decade has also seen an explosion in our capability to sense and model the environment with the concomitant beneficial outcome of being able to better manage water resources. These advances in measurement and modelling have created new opportunities to address interesting and important ecohydrological questions, such as

- How do vegetation canopies and their communities interact with precipitation to affect the quantity and quality of water fluxes, along with their spatial and temporal variability?
- How do ecosystem processes in the critical zone—the thin, dynamic, and life-sustaining skin of the terrestrial earth that extends between the vegetation canopy, soil and groundwater (Grant & Dietrich, 2017)—affect the partitioning of soil moisture between the water that makes up transpiration and that which eventually becomes groundwater and streamflow?
- As we scale these processes, how do changes to the landscape affect the quantity, distribution, and quality of streamflow?

These science questions are not only fascinating in their own right but are also directly relevant to fundamental societal challenges laid out in the United Nations Sustainable Development Goals, such as access to clean water and sanitation, provision of food toward zero hunger, and protection of life on land (Brauman, Daily, Duarte, & Mooney, 2007; IPBES, 2019; Zalewski, 2000; Zalewski, 2014). In this paper, these questions—relating to canopy processes, belowground processes, and up-scaled effects—illustrate how recent improvements in measurement and modelling can accelerate scientific discovery. These advances in understanding can lead to decisions and policies that promote a more sustainable world (Figure 1).

2 | ADVANCES IN MEASUREMENT AND OBSERVATION

Observation of ecohydrological processes is challenging because of the scale of the systems (spanning submillimeter to global), the

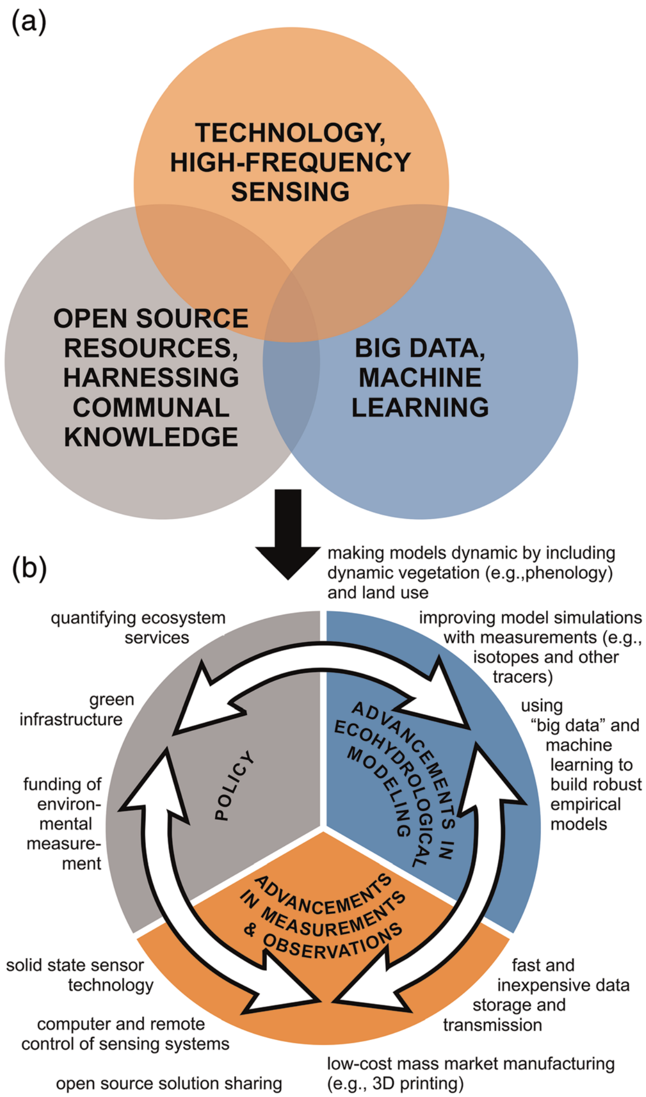

FIGURE 1 (a) The convergence of opportunities among high-frequency environmental sensing, open source resources, and machine learning in relation to (b) advancements in scientific understanding, measurements and observations, and modelling that will inform translation of ecohydrological science to policy

remoteness of key processes (e.g., headwaters and deep aquifers), and the breadth of informative and determinative parameters. Historically, advances have been slow because the commercial market for the required technologies has been small and, in some cases, existing sensing systems have been written into antiquated standard methods. However, in recent years, the technologies of sensing, housing, storing, transmitting, and disseminating data have been transformed in performance and cost, profoundly enhancing the ability to make environmental observations (e.g., Ensign et al., 2019; Tauro et al., 2018). In the section below, recent advances in the measurement of key state variables and information transmission pertinent to the physical environment surrounding vegetation are described. The aim here is not to provide an exhaustive list but rather a sampling of representative technologies gaining prominence and use in the field.

2.1 | Technological advances

2.1.1 | Solid state sensor technology

With the advent of mass technologies such as the smart phone and autonomous vehicles, the market demand for high-performance sensors has experienced tremendous growth. Many of these sensors are well suited for use in environmental applications. For example, the pressure sensors from diving watches are accurate to within 1 mm of pressure-head up to depths of 10 m, cost under US$10 each, and require only minimal energy (micro Amps; e.g., Stewart, Abou-Najm, Rupp, & Selker, 2012). Accelerometers, regularly used in smartphones and game controllers, are inexpensive and ubiquitous. Other examples include sensors for gases (e.g., CO as used by Huwald et al., 2012), turbidity, electrical conductivity, radiation (across the spectrum), temperature, humidity, global positioning system location, flow, fluid velocity, and many others. In each case, the combined accuracy, spatial and temporal resolution, energy efficiency, stability, and cost have all moved in favourable directions (see Sensorwiki.org for a comprehensive treatment of relevant microsensor technology).

2.1.2 | Computer control of sensing systems

Microcomputer systems such as the Arduino, Feather and Raspberry Pi, costing a few US$ and allowing for programmed logging and communication with very low power, have transformed the heart of environmental sensing systems (e.g., Nadeau et al., 2009). Perhaps even more importantly, these systems use high-level programming languages that are easily learned, and code can be shared and co-developed globally. Combined with version-controlled platforms such as GitHub, these advances provide the underpinnings for a transformative community-based approach for the development and dissemination of sensing systems (see Open-Sensing.org for examples of sensing systems based on these technologies).

2.1.3 | Data storage and transmission

Over the past decade, the challenges of storing and transmitting data have been partially solved. Historically, the most costly aspects of environmental sensing were mandatory scheduled site visits to retrieve data and verify system operation. Global telemetry now enables the remote acquisition of real-time data at much lower cost, allowing for new scales of observation. For example, the Trans African Hydro-Meteorological Observatory (TAHMO.org) now pays about US $0.25 per month per station to send up to one megabyte of data to the worldwide web from most African locations (Selker et al., 2020). Satellite communication complements telephonic systems in providing full global coverage, and, in 2019, we have seen the deployment of the first space-based LoRa telemetry, which is expected to dramatically reduce global data delivery costs from any point on earth (e.g., http://lacuna.space/). Moreover, other advanced systems are also presently under construction, such as the SpaceX Starlink, which has a constellation of 122 communication satellites in orbit https://www.spacex.com/news/2019/11/11/starlink-mission, as well as Amazon's Project Kuiper, which seeks to place 3,236 satellites in orbit for global connection to the internet.

2.1.4 | Fittings, fixtures, and housings

The maturation of mass-market 3-D printing has allowed economical and custom manufacturing of housings and fixtures; rather than requiring moulds costing on the order of US$100,000, these components can now be printed for US$5/kg. Further, these designs can be shared globally, so that anyone can have complex housings and fixtures created locally and at low cost. This technology can be used both commercially and in user-built contexts, in both cases offering important cost savings and accessibility of necessary elements for field-deployment of sensor systems.

2.2 | Transforming environmental sensing

While these technological advances are widely known, we are only now developing the community infrastructure to translate opportunity to reality. The Openly Published Environmental Sensing (OPEnS, found at Open-Sensing.org) community is creating a forum for the publication of solutions to diverse ecohydrological sensing problems, while many labs around the world are carrying out closely related work (e.g., Open-storm.org; Envirodiy.org). These platforms facilitate the continued evolution of successful systems, where users across the globe refine and republish improved and alternative systems. Even so, commercial entities will always be the primary means of making sensors broadly accessible, as most people will not have the time, equipment, or expertise to manufacture their own systems for outdoor deployment. Thus, the industry and forums such as OPEnS are actively exploring collaborations that nurture the creative output of instrument developers, while maintaining an environment where businesses can maintain viability. At this point, it appears that the "art" of building and supporting environmental sensing systems is so specialized that companies could succeed by focusing on the production and marketing of open-source designs. Interested readers are referred to Turner, Hill, and Caton (2020) for a full discussion of open source resources in ecohydrology.

An important platform for environmental sensors has arisen from the development of unmanned aerial systems with differential global positioning system accurate to 1 cm. These systems now provide for low-cost optical sensing, including photogrammetry, thermal-imaging, light detection and ranging, and hyperspectral imaging (e.g., Selker, Tyler, Higgins, & Wing, 2015). The ability to apply stereo-imagery methods, now often referred to as "structure from motion," allows millimetre-scale resolution of scenes spanning tens of kilometres (e.g., Carrivick, Smith, & Quincey, 2016). These same unmanned aerial system platforms can carry sensors for gas, radiation, dust, pollen, and many other parameters of great utility to ecohydrologists (e.g., Hill, Pypker, & Church, 2020; Schumacher & Christiansen, 2020; Toth & Jóźków, 2016).

Commercially available "multiparameter sondes" have been transformative in understanding the physical and chemical status of hydrological systems. These systems have typically been based on classical laboratory sensing approaches (e.g., ion-specific electrodes), adding important innovations in power management, calibration, and datalogging so that measurements can be effectively implemented over month-scale deployments. New sensing approaches, such as oxygen-sensitive fluorescent dye, have provided key capacity to measure dissolved oxygen with minimal recalibration required (e.g., Wang & Wolfbeis, 2014), and spectrolysers supply high-frequency stream chemistry data (e.g., Vaughan et al., 2017).

Laser technology has also affected instrumentation in hydrological sciences. Advances in laser spectroscopy have revolutionized the ability to quantify the stable isotopes of water (^{2}H and ^{18}O), dramatically lowering the per sample cost and enabling continuous in-field observations. These isotopes can be used to identify hydrological sources, track ecohydrological processes, and elucidate how different vegetation communities affect water partitioning between "green" and "blue" water fluxes (Dubbert & Werner, 2019; Tetzlaff et al., 2015). Laser disdrometers measure the fall velocity and diameter distribution of drop sizes of precipitation. Distributed temperature systems measure temperature along a fibre-optic cable with high spatial and temporal resolution. In all of these cases, the instrumentation is fundamentally complex and high cost, so the avenue for adoption has relied on manufacturers developing complete solutions. Collaboration between manufacturers and clients has been close, and many of the most important advancements have been driven by the needs of the user community. For example, CTEMPs.org has worked closely with distributed temperature sensing producers to develop distributed temperature sensing systems suited to environmental applications, to reduce power consumption, and to improve temporal and spatial resolution (e.g., Selker et al., 2006).

2.3 | Measurements and modelling

As ecohydrological knowledge and understanding expand, process-based representations increase in complexity as additional interactions and parameters are incorporated, for example, topography, hydrologic connectivity, soil texture, tree height, and canopy density (Band, Tague, Groffman, & Belt, 2001; Maxwell & Condon, 2016; Pringle, 2003). Utility of measurements to constrain model structures and parameter sets, which are associated with different subdomains of models (ecological, surface, subsurface, etc.), has been an increasing focus in model calibration. Multicriteria calibration increases the confidence that the dominant ecohydrological processes are being appropriately represented (Kelleher, McGlynn, & Wagener, 2017). Including measured data of different components of the ecohydrological system (water balance, energy balance, and carbon uptake) in the calibration process has been shown (Kuppel, Tetzlaff, Maneta, & Soulsby, 2018) to result in “the right answers for the right reasons” (Kirchner, 2006). Diverse data sources—made possible by advances in measurement—can help to reduce information redundancy and provide insight to the processes represented in a model (Clark, Kavetski, & Fenicia, 2011; Fatichi et al., 2016). As a corollary, model failure in adequately representing observed processes provides an opportunity to learn and improve conceptualizations (Birkel, Soulsby, & Tetzlaff, 2014).

To date, deductive reasoning has been the preferred strategy in ecohydrology, where process-based models are developed based on theory, and data are used to constrain parameters for a particular context. Consistent physics in the models provides a rationale for application to unobserved conditions, for example, prediction of the future or exploration of hypotheticals. Now, with the volume and complexity of big data being collected and shared, new methods are emerging to more fully realize the potential of these data. The core capacity of data-driven machine learning techniques is to quantify patterns in data that were not otherwise apparent, which can deepen conceptual understanding and feed into new theories.

Machine learning includes the automated identification of connections between measurements and outcomes, wherein signals in training data sets are identified and can be aggregated to obtain predictive models based purely on sets of observations. For example, Shortridge, Guikema, and Zaitchik (2016) claim that machine learning methods such as “random forest” provide significantly better predictions of streamflow compared with physical models. A significant challenge in using machine learning in ecohydrology, or any application, lies in the complexity of approaches. Many algorithms are available, and each varies in complexity, computation time, data needs, optimization, and effectiveness in pattern identification (Lange & Sippel, 2020). However, there is limited guidance on how to use these complex tools (Blair et al., 2019; Lange & Sippel, 2020; Olden, Kennard, & Pusey, 2012), and interdisciplinary training and collaboration between computer scientists and earth scientists are required to obtain a reliable and robust result (Ben-Hamadou & Wolanski, 2011). Machine learning tools have been made more accessible by automated software, for example, the Waikato Environment for Knowledge Analysis, Weka (Kotthoff, Thornton, Hoos, Hutter, & Leyton-Brown, 2017), an open-source user-friendly platform that identifies the most suitable algorithm and the hyperparameter settings based on the input dataset.

Currently, the number of applications in ecohydrology using this approach is limited, though new efforts are emerging. For example, boosted regression tree analysis identified the biotic and abiotic factors that affect variability in stemflow (Tanaka et al., 2017). In another example, factorial analyses on rainfall partitioning revealed new insights into processes that had hitherto been incompletely understood (Nanko, Hudson, & Levia, et al. 2016; Tanaka et al., 2015). As video (gigabytes per camera per day), hyperspectral images (terabytes per camera per day), fibre-optic sensors (gigabytes per sensor system per day), satellites (terabytes), and swarms of microsensing systems (gigabytes) provide massive and diverse data related to ecological and hydrological processes, the use of automated quantification of linkages between predictors and environmental responses will take a central place in the study and prediction of ecohydrological systems. These emerging techniques may challenge the historical preference for process-based modelling, and, if effort is dedicated to the opportunity, will result in new insights and greater understanding of these intrinsically complex systems.

2.4 | Measurement challenges

Measurement and modelling developments are not without their challenges, and we can only address the gap between opportunity and current practice by considering impediments to adoption. While technological advances have led to the development of novel and inexpensive sensors, increasing the number and accessibility of measurements is still challenged by issues of standardization, data curation, and resource allocation.

We are accustomed to plugging devices into our computers and having them work. This reflects the remarkable collaboration between peripheral makers and operating-system developers, and the substantial investment in making consumer electronics robust and reliable. The limited size of the environmental sensing market and the diversity of needs reduces the incentive for commercial interests to develop plug-and-play solutions. Further, as a community, we have not developed common standards for communication between sensors and data-communication systems. For example, the I2C protocol that many new sensors employ is limited to just one meter of cable between the sensor and the data system—a requirement that is often not met in environmental applications.

Data management, while no longer costly by way of raw storage, is challenging due to the need to properly describe, curate, and archive the information. Data unification efforts are underway at organizations such as the Consortium of Universities for the Advancement of Hydrologic Science, Inc., the National Ecological Observatory Network, the Long Term Ecological Research Network, FLUXNET, and the National Center for Atmospheric Research, among many others (see Richter et al., 2018). Nonetheless, the human effort required to maintain data integrity is large, and significant effort must be committed to data management. Although the biological community has developed inspiring infrastructure for sharing of DNA sequences, the complex and diverse nature of measurements in ecohydrology presents an additional challenge to the problem of accurate and accessible archiving of important data.

Even with new and low-cost sensors, resources are finite. Interesting challenges persist around issues of precision, resolution and coverage of spatial and temporal data, and how these issues relate to our scientific goals and questions. Should investments in measurements be targeted to testing specific hypotheses or to long-term monitoring to provide a baseline from which new hypotheses can be generated? What is the appropriate mix of cheaper sensors with low precision that can be deployed with wide spatial coverage versus more expensive and precise measurements? How can new technologies enhance and build upon existing measurement techniques? These are not issues of technology alone but will also be informed by (and inform) our scientific understanding and policy decisions (Figure 1).

Taken as a whole, advances in sensors, microcomputing, 3-D printing, unmanned aircraft, global telemetry, modelling, and data interpretation are slowly transforming our ability to understand eco-hydrological systems (cf. Levia et al., 2020). Improving the pace of translation of novel sensors to useful tools requires the adoption of clear and rigorous standards for meta-data and sensor interfaces. Global collaboration on these systems will be fundamental to success, with community efforts—such as Consortium of Universities for the Advancement of Hydrologic Science, Inc.'s Water Data Services—representing fundamental contributions to support these advancements. If these challenges are overcome, the synergies created by the convergence of opportunity among high-frequency environmental sensing, open source resources (both hardware and software), and machine learning have the potential and capability to help inform policies to mitigate the world's water problems (Figure 1). Such a convergence will change the way ecohydrologists perceive, tackle, and solve water-resource issues. No longer limited by small data sets, new insights into ecohydrological processes can be uncovered and lead to better environmental stewardship, thereby enabling ecohydrologists, water resource planners, and policy analysts to translate science into solutions (Figure 1).

3 | ADVANCING UNDERSTANDING AND REPRESENTATION OF ECOHYDROLOGICAL PROCESSES

3.1 | Canopy processes

Given the importance of interception loss as a component of total evapotranspiration from many of the globe's forests (see Carlyle-Moses & Gash, 2011), furthering our understanding of precipitation partitioning processes should result in a greater understanding of precipitation recycling. Precipitation recycling can generate and intensify the redistribution of water at scales far greater than the watershed scale (e.g., Nobre, 2014; van der Ent, Savenije, Schaefli, & Steele-Dunne, 2010) and is important for understanding water availability downwind (Ellison et al., 2017; Keys et al., 2012). Innovations in model predictions and measurement technologies discussed here will allow a more holistic approach to forest-water interactions connecting local, regional, and global scales and have important policy and management implications (Brubaker, Entekhabi, & Eagleson, 1993; Koster et al., 1986).

Canopy interception loss has long been understood to comprise evaporation from canopy storage both during and after a rain event (see Horton, 1919). Although one of the simplest concepts in ecohydrology, the controls on canopy-water storage and the mechanisms that result in the evaporation of intercepted rainfall are still not fully understood. Additionally, underlying assumptions known to be invalid in many cases continue to populate the interception literature and remain embedded in many canopy rainfall-partitioning models utilized today. For instance, the wetting of a canopy during small events of insufficient depth to saturate the canopy, or during the early stages of larger events, is represented as a "water-box"—in which no drainage occurs from the canopy until it reaches complete saturation—in Rutter-Gash type interception models (see Junior et al., 2019; Su, Zhao, Xu, & Xie, 2016; Valente, Gash, Nóbrega, David, & Pereira, 2020). However, interception theory has long recognized that canopy storage fills in an exponential manner with drainage occurring throughout the wetting phase of the rain event (see Leonard, 1967; Merriam, 1960).

Additionally, understanding the physical processes and atmospheric conditions leading to the evaporation of intercepted rainfall remains a formidable challenge (Carlyle-Moses & Gash, 2011; van Dijk et al., 2015). Rutter (1967) suggested that the energy required to sustain the evaporation of intercepted rainfall came from the air itself, that there is a downwards sensible heat flux and/or a decrease in the ambient air temperature within the canopy volume (van Dijk et al., 2015). Stewart (1977) argued that this downward sensible heat flux from above wetted canopies must involve large-scale advection from surrounding dry land areas. In contrast, Shuttleworth and Calder (1979) suggest that the lower atmosphere may already store sufficient sensible heat or that sensible heat being released by precipitation processes may maintain high evaporation rates from wetted canopies (van Dijk et al., 2015). Additionally, van Dijk et al. (2015) suggest that the use of conventional Penman-Monteith theory results in less interception loss than what should be expected based on experimental evidence from field studies (e.g., Cisneros Vaca, van der Tol, & Ghimire, 2018). This underestimation of canopy interception loss, and associated fluxes, has ramifications for climate and hydrological modelling. For example, van Dijk et al. (2015) suggest that rainfall generation downwind predicted by weather and climate models may be erroneous if water vapour and energy fluxes associated with interception loss are not considered by land-surface models. Similarly, Savenije (2004) states that underestimating interception loss may result in hydrological model errors, particularly when automated calibration leads to other parameter values being adjusted to compensate for errors in interception.

In order to more fully understand wetting and evaporative processes associated with canopy interception loss, precisely calibrated high-temporal resolution measurements of canopy partitioning of rainfall into interception loss and canopy drainage in the form of throughfall and stemflow are required (e.g., Iida et al., 2017; Iida, Shimizu, Shinohara, Takeuchi, & Kumagai, 2020). Sensor technologies, as discussed above, offer great promise in propelling our understanding of interception loss and understory precipitation dynamics. For example, laser disdrometers, such as those developed by Nanko, Hotta, and Suzuki (2006), allow for distinctions to be made between different throughfall types (free-throughfall, canopy-drip, and canopy-splash) and their relative quantitative importance (e.g., Levia et al., 2019;Levia, Hudson, Llorens, & Nanko, 2017; Nanko, Hudson, & Levia, 2016). By comparing the temporal characteristics of throughfall type and depth relative to rainfall, disdrometer technology can provide important insight into the wetting of the canopy during a rain event. Additionally, disdrometers may also provide insight into the role of larger raindrops on the interception loss process under differing forest and meteorological conditions. For example, the greater kinetic energy associated with larger raindrop diameters has been suggested by some (e.g., Calder, 1996) to delay canopy saturation and reduce maximum canopy storage, and by others (e.g., Dunkerley, 2009; Murakami, 2006) to increase evaporation because larger drops are subjected to greater splash. Disdrometers, along with other emerging sensor technology such as electromagnetic rain gauges (Bong-Joo et al., 2019) and piezoelectric rain gauges (Haselow, Meissner, Rupp, & Miegel, 2019), provide information on drop size and associated kinetic energy, as well as more precise measurement of event initiation, cessation, and intrastorm breaks.

Accelerometers that are mounted to a tree trunk can be used to determine canopy interception storage due to increases in the mass of the tree (van Emmerik et al., 2017) and may provide high-temporal resolution information about canopy-wetting dynamics. Other low-cost sensors that can be used to further our understanding of rainfall partitioning processes by the canopy include the Arduino-based stemflow sensor developed by Turner, Hill, Carlyle-Moses, and Rahman (2019). Leaf-wetness sensors determine the instantaneous time of stemflow initiation, while ultrasonic rangefinders measure the distance to the liquid surface within the reservoir. Average stemflow volume can be determined with a 10-s temporal resolution, and a series of these units measuring both throughfall and stemflow can be utilized to provide high temporal resolution understory rainfall measurements. These, in turn, provide greater understanding of the interactions between the canopy and lower portions of the critical zone (Carlyle-Moses et al., 2018).

3.2 | Critical zone processes

Vegetation partitions soil-water into “green” water fluxes that sustain biomass and “blue” water fluxes that supply groundwater recharge and streamflow (Evaristo, Jasechko, & McDonnell, 2015). Both a changing climate and changing landscapes can affect this partitioning. These interactions between water and vegetation occur in a dynamic feedback system within the critical zone where vegetation is influenced by the zone's structure and function, and, in turn, the critical zone is altered by the vegetation.

This dynamism—in vegetation growth, root structure, and plant physiology—is now being considered explicitly in ecohydrological models (e.g., RHESSys (Tague & Band, 2004), EcH_2O (Kuppel et al., 2018; Maneta & Silverman, 2013; Simeone et al., 2019), tRIBS-VEGGIE (Ivanov, Bras, & Vivoni, 2008), Cathy (Niu et al., 2014), Tethys-Chloris (Fatichi, Ivanov, & Caporali, 2012), and FLETCH2 (Mirfenderesgi et al., 2016)). These models explicitly integrate energy fluxes, water fluxes, and storage, as well as vegetation dynamics to capture feedback between ecosystem productivity, hydrology, and local climate. Still, a major remaining challenge is variation in temporal scales used to develop and calibrate models [i.e., short-to-midterm hydrological (e.g., streamflow and soil moisture) and ecological dynamics (e.g., seasonal phenology)] and their intended use—predicting long-term vegetation dynamics that affect water use. Fortunately, some work is beginning to ameliorate this challenge (Paschalis, Fatichi, Katul, & Ivanov, 2015).

Further advances in modelling ecohydrological processes in the critical zone will require robust data sets that can identify when models serendipitously yield plausible results, but for irrational or unjustifiable reasons. Stable isotopes and other conservative tracers can help resolve this dilemma. Isotopes and tracers can identify hydrological sources of water, elucidate how different vegetation communities affect water partitioning between “green” and “blue” water fluxes (Dubbert & Werner, 2019; Tetzlaff et al., 2015), and estimate the travel-time distributions, all of which can further constrain model representations (e.g., Botter, Bertuzzo, & Rinaldo, 2011; Calabrese & Porporato, 2015; Guswa, Rhodes, & Newell, 2007; Smith, Tetzlaff, Laudon, Maneta, & Soulsby, 2019). These data have also improved the representation of the celerity of hydrological fluxes, as well as the velocity of water particles and the mixing relationships within soils (Benettin, Kirchner, Rinaldo, & Botter, 2015; Birkel, Tetzlaff, Dunn, & Soulsby, 2011; McDonnell & Beven, 2014).

When integrated with explicit representation of vegetation dynamics, these tracer-aided modelling concepts can help resolve the influence of vegetation on ecohydrological partitioning (Douinot et al., 2019; Penna et al., 2018; Sprenger et al., 2018) and provide deeper insight into some of the most crucial phenomena of the ecohydrological system, such as from where in the subsurface plants extract their water (Piayda, Dubbert, Siegwolf, Cuntz, & Werner, 2017; Volkmann, Kühnhammer, Herbstritt, Gessler, & Weiler, 2016), over what spatial footprints (Geris, Tetzlaff, McDonnell, & Soulsby, 2017) and over what timescales (Brinkmann et al., 2018).

3.3 | Effects of landscape change on amount, distribution, and quality of streamflow

Coupling aboveground and belowground processes across varied temporal and spatial scales is crucial to understanding streamflow amount, distribution, and quality. Observational studies indicate that an increase in forest cover (whether natural or plantation) leads to a decrease in overall water yield due to an increase in transpiration (e.g., Andréassian, 2004; Bosch & Hewlett, 1982; Brown, Western, McMahon, & Zhang, 2013; Brown, Zhang, McMahon, Western, & Vertessy, 2005; Bruijnzeel, 2004; Filoso, Bezerra, Weiss, & Palmer, 2017; Jackson, Jobbágy, & Nosetto, 2009). Increases in transpiration, coupled with increased infiltration, have also been shown to reduce peak flows but with variability in the magnitude of the response (e.g., Calder & Aylward, 2006; Dadson et al., 2017; Filoso et al., 2017). Effects of increased forest cover on baseflows and low flows are more uncertain—with even the directionality of the effect being unclear—due to interactions of increased flow regulation and transpiration (e.g., Dennedy-Frank & Gorelick, 2019; Devito, Creed, & Fraser, 2005; Filoso et al., 2017; Guswa, Hamel, & Dennedy-

Frank, 2017; Homa, Brown, McFarigal, Compton, & Jackson, 2013; Jensco & McGlynn, 2011; Laaha, Skoien, Nobilis, & Blöschl, 2013; Smakhtin, 2001). In all cases, predictions of the effects of landscape change on streamflow remain stubbornly imprecise. With respect to water quality, the story is similar. Scientific consensus is that forest cover reduces soil erosion, sediment load, nutrients, and pathogens relative to other land uses. Our ability to quantify precisely the effects of landcover change on water quality characteristics, however, remains limited (Jasper et al., 2013).

Direct application of new and improved ecohydrological methods relates to the emergence of ecosystem services as a framework for decision-making and design (Brauman et al., 2007; Guswa et al., 2014; Millennium Ecosystem Assessment, 2005; National Research Council, 2004; Pascual et al., 2017; USEPA Science Advisory Board, 2009). The Nature Conservancy has developed Water Funds with corporate and governmental partners throughout Latin America. Projects in Brazil, Colombia, Ecuador, Mexico, Panama, and Peru are designed to collect millions of dollars in fees from water users and to use those funds for watershed protection and improvement (Bremer et al., 2016; Goldman, Benitez, Calvache, & Ramos, 2010). Through its National Forest Conversation Program and Sloping Land Conservation Program, China has spent over US$50B dollars to incentivize land conversion to reduce erosion and flooding (Liu, Li, Ouyang, Tam, & Chen, 2008; Ouyang et al., 2016). As of 2018, payments for watershed services totalled over US$24B annually across more than 380 different programs in over 60 countries (Salzman, Bennett, Carroll, Goldstein, & Jenkins, 2018). Nature-based designs are also being developed to address wastewater treatment (Dotro et al., 2017; Jasper et al., 2013; Vymazal, 2010) and flood-damage mitigation (Opperman, 2014). For example, the Yolo bypass in California connects the Sacramento River to floodplains that store excess flood flows, provide habitat for fish and migratory birds, and offer recreational opportunities (Sommer et al., 2001). This manipulation of the landscape that results from new policies can be coupled with advances in measurement and modelling to improve ecohydrological understanding of the effects of landscape change on the amount, distribution, and quality of streamflow (Figure 1). A related problem concerns streamflow controls on the ecology of hosts and parasites of water-related diseases (Rinaldo, Gatto, & Rodriguez-Iturbe, 2018).

In urban environments, ecohydrologists and other scientists are increasingly called upon to assess the benefits and costs of trees and other green infrastructure for stormwater management, heat-stress mitigation, nutrient control, and many other benefits (e.g., Berland et al., 2017; Dadvand & Nieuwenhuijsen, 2019; Ellison et al., 2017; Keeler et al., 2019; Kuehni, Bou-Zeid, Webb, & Shokri, 2016; Ramamurthy & Bou-Zeid, 2014; Ramamurthy & Bou-Zeid, 2017; Rugel, Carpiano, Henderson, & Brauer, 2019; Zölch, Maderspacher, Wamsler, & Pauleit, 2016). Similarly, there is growing interest in understanding the potential for agricultural patterns and practices to provide cobenefits, such as for nutrient management, carbon storage, and groundwater recharge (e.g., Chaplin-Kramer et al., 2015; Dahlke, Brown, Orloff, Putnam, & O'Geen, 2018; Smith, Tetzlaff, Gelbrecht, Kleine, & Soulsby, 2020). Ecohydrologists working in agricultural and urban areas are confronted with very different environmental conditions than those in more natural ecosystems. Improvements in environmental sensing and empirical analysis will be essential to advancing understanding, and policy will both draw upon that understanding and feed into that understanding by promoting changes to landscapes from which we can gain new insight (Figure 1).

4 | CONCLUSIONS

Low-cost sensors, data-management tools, and analytical approaches provide opportunities to acquire, create, and interpret ecohydrological knowledge in new ways. We now have the ability to observe previously unobservable phenomena, to design new experiments, and to test new hypotheses. And, while controlled experiments with clear hypotheses will always remain the gold standard in science, the ability to observe the effects of landscape changes that are happening outside the realm of conventional scientific research can also enhance current understanding. Tools from data science enable us to sift through imperfect observations and discern signals—for example, what happens to low flows when forest is converted to agricultural use? If we implement best-management practices, how is water quality improved? Suddenly, routine and regular landscape manipulations become opportunities for advancing our knowledge. This new mode for science requires that we are willing to fund and support expanded measurement and observation and the analysis of hydrological impacts of landscape modifications that are outside scientists' control (Figure 1).

New hypotheses and ideas about the effects of landscape change on the amount, distribution, and quality of stemflow, streamflow, or root-water uptake that grow out of these empirical observations can be evaluated and tested with process-based models. Integrating multiple sources of data and observations from across multiple watersheds will improve model reliability (e.g., Clark et al., 2011; Fatichi et al., 2016; Kirchner, 2006). Coming full circle, such models can then be used to direct future experiments, monitoring, and observation to those landscape interventions that would result in the greatest increases to our scientific understanding. Additionally, advances in modelling can enable a hierarchy of models with clear trade-offs between complexity, data requirements, and precision of response. Simple or screening models could be used to evaluate future scenarios and questions of interest for communities and identify whether or not landscape interventions are likely to have an effect. More detailed models could then be used to interrogate those scenarios as needed to inform land-management decisions.

Convergence of climate and landscape changes with advances in measurements and modelling creates an important opportunity for the advancement of ecohydrological knowledge and understanding. Innovative technological developments facilitate the measurement of new environmental characteristics, and inexpensive ubiquitous sensors enable observation at resolutions and scales previously unavailable. Bringing these advances to bear on ecohydrological questions related to canopy processes, belowground processes, and the scaling-up of those processes will bring new insight to the interactions between ecological and hydrological systems, which, in turn, will help us address water-resource challenges in the 21st century.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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REFERENCES

Andréassian, V. (2004). Waters and forests: From historical controversy to scientific debate. *Journal of Hydrology*, *291*(1-2), 1–27. https://doi.org/10.1016/j.jhydrol.2003.12.015

Band, L. E., Tague, C. L., Groffman, P., & Belt, K. (2001). Forest ecosystem processes at the watershed scale: Hydrological and ecological controls of nitrogen export. *Hydrological Processes*, *15*(10), 2013–2028. https://doi.org/10.1002/hyp.253

Benettin, P., Kirchner, J. W., Rinaldo, A., & Botter, G. (2015). Modeling chloride transport using travel time distributions at Plynlimon, Wales. *Water Resources Research*, *51*(5), 3259–3276. https://doi.org/10.1002/2014WR016600

Ben-Hamadou, R., & Wolanski, E. (2011). Ecohydrology modeling: Tools for management. *Treatise on Estuarine and Coastal Science*, *10*, 301–328. https://doi.org/10.1016/B978-0-12-374711-2.01016-0

Berland, A., Shiflett, S. A., Shuster, W. D., Garmestani, A. S., Goddard, H. C., Herrmann, D. L., & Hopton, M. E. (2017). The role of trees in urban stormwater management. *Landscape and Urban Planning*, *162*, 167–177. https://doi.org/10.1016/j.landurbplan.2017.02.017

Birkel, C., Soulsby, C., & Tetzlaff, D. (2014). Developing a consistent process-based conceptualization of catchment functioning using measurements of internal state variables. *Water Resources Research*, *50*, 3481–3501. https://doi.org/10.1002/2013WR014925

Birkel, C., Tetzlaff, D., Dunn, S. M., & Soulsby, C. (2011). Using time domain and geographic source tracers to conceptualize streamflow generation processes in lumped rainfall-runoff models. *Water Resources Research*, *47*, W02515. https://doi.org/10.1029/2010WR009547

Blair, G. S., Henrys, P., Leeson, A., Watkins, J., Eastoe, E., Jarvis, S., & Young, P. J. (2019). Data science of the natural environment: A research roadmap. *Frontiers in Environmental Science*, *7*(August), 1–14. https://doi.org/10.3389/fenvs.2019.00121

Bong-Joo, J., Donggu, K., Chanjoo, L., Hyunjung, K., Sanghun, K., & Won, K. (2019). Preliminary of electromagnetic wave rain gauge for small areal precipitation measurement. *Geophysical Research Abstracts*, *21*, 1–1.

Bosch, J. M., & Hewlett, J. D. (1982). A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, *55*(1-4), 3–23. https://doi.org/10.1016/0022-1694(82)90117-2

Botter, G., Bertuzzo, E., & Rinaldo, A. (2011). Catchment residence and travel time distributions: The master equation. *Geophysical Research Letters*, *38*(11), L11403. https://doi.org/10.1029/2011GL047666

Brauman, K., Daily, G. C., Duarte, T. K., & Mooney, H. A. (2007). The nature and value of ecosystem services: An overview highlighting hydrologic services. *Annual Review of Environment and Resources*, *32*, 67–98. https://doi.org/10.1146/annurev.energy.32.031306.102758

Bremer, L. L., Auerbach, D. A., Goldstein, J. H., Vogl, A. L., Shemie, D., Kroeger, T., … Tiepolo, G. (2016). One size does not fit all: Natural infrastructure investments within the Latin American Water Funds Partnership. *Ecosystem Services*, *17*, 217–236. https://doi.org/10.1016/j.ecoser.2015.12.006

Brinkmann, N., Seeger, S., Weiler, M., Buchmann, N., Eugster, W., & Kahmen, A. (2018). Employing stable isotopes to determine the residence times of soil water and the temporal origin of water taken up by *Fagus sylvatica* and *Picea abies* in a temperate forest. *New Phytologist*, *219*(4), 1300–1313. https://nph.onlinelibrary.wiley.com/doi/abs/10.1111/nph.15255

Brown, A. E., Western, A. W., McMahon, T. A., & Zhang, L. (2013). Impact of forest cover changes on annual streamflow and flow duration curves. *Journal of Hydrology*, *483*, 39–50. https://doi.org/10.1016/j.jhydrol.2012.12.031

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., & Vertessy, R. A. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, *310*, 28–61. https://doi.org/10.1016/j.jhydrol.2004.12.010

Brubaker, K. L., Entekhabi, D., & Eagleson, P. S. (1993). Estimation of continental precipitation recycling. *Journal of Climate*, *6*(6), 1077–1089. https://doi.org/10.1175/1520-0442(1993)006<1077:EOCPR>2.0.CO;2

Bruijnzeel, L. A. (2004). Hydrological functions of tropical forests: Not seeing the soil for the trees? *Agriculture, Ecosystems and Environment*, *104*, 185–228. https://doi.org/10.1016/j.agee.2004.01.015

Calabrese, S., & Porporato, A. (2015). Linking age, survival, and transit time distributions. *Water Resources Research*, *51*(10), 8316–8330. https://doi.org/10.1002/2015WR017785

Calder, I. R. (1996). Dependence of rainfall interception on drop size. 1. Development of the two-layer stochastic model. *Journal of Hydrology*, *185*(1-4), 363–378. https://doi.org/10.1016/0022-1694(95)02998-2

Calder, I. R., & Aylward, B. (2006). Forest and floods: Moving to an evidence-based approach to watershed and integrated flood management. *Water International*, *31*(1), 87–99. https://doi.org/10.1080/02508060608691918

Carlyle-Moses, D. E., & Gash, J. H. C. (2011). Rainfall interception loss by forest canopies. In D. F. Levia, D. E. Carlyle-Moses, & T. Tanaka (Eds.), *Forest hydrology and biogeochemistry: Synthesis of past research and future directions*. Ecological Studies, 216. (pp. 407–424). Heidelberg: Germany, Springer-Verlag. https://doi.org/10.1007/978-94-007-1363-5_20

Carlyle-Moses, D. E., Iida, S., Germer, S., Llorens, P., Michalzik, B., Nanko, K., … Levia, D. F. (2018). Expressing stemflow commensurate with its ecohydrological importance. *Advances in Water Resources*, *121*, 472–479. https://doi.org/10.1016/j.advwatres.2018.08.015

Carrivick, J. L., Smith, M. W., & Quincey, D. J. (2016). Introduction to structure from motion in the geosciences. In J. L. Carrivick, M. W. Smith, & D. J. Quincey (Eds.), *Structure from Motion in the Geosciences*. Chichester: Wiley-Blackwell. https://doi.org/10.1002/9781118895818.ch1

Chaplin-Kramer, R., Sharp, R. P., Mandle, L., Sim, S., Johnson, J., Butnar, I., … Kareiva, P. M. (2015). Spatial patterns of agricultural expansion determine impacts on biodiversity and carbon storage. *PNAS*, *112*(24), 7402–7407. https://doi.org/10.1073/pnas.1406485112

Cisneros Vaca, C., van der Tol, C., & Ghimire, C. P. (2018). The influence of long-term changes in canopy structure on rainfall interception loss: A case study in Speulderbos, the Netherlands. *Hydrology and Earth System Sciences*, *22*, 3701–3719. https://doi.org/10.5194/hess-22-3701-2018

Clark, M. P., Kavetski, D., & Fenicia, F. (2011). Pursuing the method of multiple working hypotheses for hydrological modeling. *Water Resources Research*, *47*, W09301. https://doi.org/10.1029/2010WR009827

Dadson, S. J., Hall, J. W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., … Wilby, R. (2017). A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK. *Proceedings of the Royal Society A*, *473*(2199), 20160706. https://doi.org/10.1098/rspa.2016.0706

Dadvand, P., & Nieuwenhuijsen, M. (2019). Green space and health. In M. Nieuwenhuijsen, & H. Khreis (Eds.), *Integrating human health into urban and transport planning* (pp. 409–423). Cham: Springer. https://doi.org/10.1007/978-3-319-74983-9_20

Dahlke, H. E., Brown, A. G., Orloff, S., Putnam, D., & O'Geen, T. (2018). Managed winter flooding of alfalfa recharges groundwater with minimal crop damage. *California Agriculture*, *72*(1), 1–11. https://doi.org/10.3733/ca.2018a0001

Dennedy-Frank, P. J., & Gorelick, S. M. (2019). Insights from water simulations around the world: Watershed service-based restoration does not significantly enhance streamflow. *Global Environmental Change*, *58*, 101938. https://doi.org/10.1016/j.gloenvcha.2019.101938

Devito, K. J., Creed, I. F., & Fraser, C. J. D. (2005). Controls on runoff from a partially harvested aspen-forested headwater catchment, Boreal Plain, Canada. *Hydrological Processes*, *19*, 3–25. https://doi.org/10.1002/hyp.5776

Dotro, G., Langergraber, G., Molle, P., Nivala, J., Puigagut, J., Stein, O., & von Sperling, M. (2017). *Treatment wetlands, Vol. 7*. Biological wastewater treatment series. London, UK: IWA Publishing. https://doi.org/10.2166/9781780408774

Douinot, A., Tetzlaff, D., Maneta, M., Kuppel, S., Schulte-Bisping, H., & Soulsby, C. (2019). Ecohydrological modelling with EcH2O-iso to quantify forest and grassland effects on water partitioning and flux ages. *Hydrological Processes*, *33*(16), 2174–2191. https://doi.org/10.1002/hyp.13480

Dubbert, M., & Werner, C. (2019). Water fluxes mediated by vegetation: Emerging isotopic insights at the soil and atmosphere interfaces. *New Phytologist*, *221*(4), 1754–1763. https://doi.org/10.1111/nph.15547

Dunkerley, D. L. (2009). Evaporation of impact water droplets in interception processes: Historical precedence of the hypothesis and a brief literature overview. *Journal of Hydrology*, *376*, 599–604. https://doi.org/10.1016/j.jhydrol.2009.08.004

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., … Sullivan, C. A. (2017). Trees, forest, and water: Cool new insights for a hot world. *Global Environmental Change*, *43*, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002

Ensign, S., Arscott, D., Hicks, S., Aufdenkampe, A., Muenz, T., Jackson, J., & Bressler, D. (2019). A digital Mayfly swarm is emerging. *Eos*, *100*. https://doi.org/10.1029/2019EO116611

Evaristo, J., Jasechko, S., & McDonnell, J. J. (2015). Global separation of plant transpiration from groundwater and streamflow. *Nature*, *525*(7567), 91–94. https://doi.org/10.1038/nature14983

Fatichi, S., Ivanov, V. Y., & Caporali, E. (2012). A mechanistic ecohydrological model to investigate complex interactions in cold and warm water-controlled environments: 1. Theoretical framework and plot-scale analysis. *Journal of Advances in Modeling Earth Systems*, *4*(2) Quarter 2, M05002. https://doi.org/10.1029/2011MS000086

Fatichi, S., Vivoni, E. R., Ogden, F. L., Ivanov, V. Y., Mirus, B., Gochis, D., … Tarboton, D. (2016). An overview of current applications, challenges, and future trends in distributed process-based models in hydrology. *Journal of Hydrology*, *537*, 45–60. https://doi.org/10.1016/j.jhydrol.2016.03.026

Filoso, S., Bezerra, M. O., Weiss, K. C. B., & Palmer, M. A. (2017). Impacts of forest restoration on water yield: A systematic review. *PLoS ONE*, *12*(8), e0183210. https://doi.org/10.1371/journal.pone.0183210

Geris, J., Tetzlaff, D., McDonnell, J., & Soulsby, C. (2017). Spatial and temporal patterns of soil water storage and vegetation water use in humid northern catchments. *Science of the Total Environment*, *595*, 486–493. https://doi.org/10.1016/j.scitotenv.2017.03.275

Goldman, R. L., Benitez, S., Calvache, A., & Ramos, A. (2010). *Water funds: Protecting watersheds for nature and people*. Arlington, VA: The Nature Conservancy.

Grant, G. E., & Dietrich, W. E. (2017). The frontier beneath our feet. *Water Resources Research*, *53*(4), 2605–2609. https://doi.org/10.1002/2017WR020835

Guswa, A. J., Brauman, K. A., Brown, C., Hamel, P., Keeler, B. L., & Sayre, S. S. (2014). Ecosystem services: Challenges and opportunities for hydrologic modeling to support decision making. *Water Resources Research*, *50*(5), 4535–4544. https://doi.org/10.1002/2014WR015497

Guswa, A. J., Hamel, P., & Dennedy-Frank, P. J. (2017). Potential effects of landscape change on water supplies in the presence of reservoir storage. *Water Resources Research*, *53*(4), 2679–2692. https://doi.org/10.1002/2016WR019691

Guswa, A. J., Rhodes, A. L., & Newell, S. E. (2007). Importance of orographic precipitation to the water resources of Monteverde, Costa

Rica. *Advances in Water Resources*, *30*, 2098–2112. https://doi.org/10.1016/j.advwatres.2006.07.008

Haselow, L., Meissner, R., Rupp, H., & Miegel, K. (2019). Evaluation of precipitation measurements methods under field conditions during a summer season: A comparison of the standard rain gauge with a weighable lysimeter and piezoelectric precipitation sensor. *Journal of Hydrology*, *575*, 537–543. https://doi.org/10.1016/j.jhydrol.2019.05.065

Hill, D. J., Pypker, T., & Church, J. (2020). Applications of unpiloted aerial vehicles (UAVs) in forest hydrology. In D. F. Levia, D. E. Carlyle-Moses, S. Iida, B. Michalzik, K. Nanko, & A. Tischer (Eds.), *Forest-water interactions*. Ecological Studies, 240. (p. 55). 85, Cham, Switzerland: Springer Nature. https://doi.org/10.1007/978-3-030-26086-6_3

Homa, E. S., Brown, C., McFarigal, K., Compton, B. W., & Jackson, S. D. (2013). Estimating hydrologic alteration from basin characteristics in Massachusetts. *Journal of Hydrology*, *503*, 196–208. https://doi.org/10.1016/j.jhydrol.2013.09.008

Horton, R. E. (1919). Rainfall interception. *Monthly Weather Review*, *47*, 608–623. https://doi.org/10.1175/1520-0493(1919)47<603:RI>2.0.CO;2

Huwald, H., Selker, J. S., Tyler, S. W., Calaf, M., van de Giesen, N. C., & Parlange, M. B. (2012). Carbon monoxide as a tracer of gas transport in snow and other natural porous media. *Geophysical Research Letters*, *39*, L02504. https://doi.org/10.1029/2011GL050247

Iida, S., Levia, D. F., Shimizu, T., Tamai, K., Nobuhiro, T., Kabeya, N., … Araki, M. (2017). Intrastorm scale rainfall interception dynamics in a mature coniferous forest stand. *Journal of Hydrology*, *548*, 770–783. https://doi.org/10.1016/j.jhydrol.2017.03.009

Iida, S., Shimizu, T., Shinohara, Y., Takeuchi, S., & Kumagai, T. (2020). The necessity of sensor calibration for the precise measurement of water fluxes in forest ecosystems. In D. F. Levia, D. E. Carlyle-Moses, S. Iida, B. Michalzik, K. Nanko, & A. Tischer (Eds.), *Forest-water interactions*. Ecological Studies, 240. (pp. 29–53). Cham, Switzerland: Springer Nature. https://doi.org/10.1007/978-3-030-26086-6_2

IPBES. (2019). In E. S. Brondizio, J. Settele, S. Diaz, & H. T. Ngo (Eds.), *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Bonn, Germany: IPBES Secretariat.

Ivanov, V. Y., Bras, R. L., & Vivoni, E. R. (2008). Vegetation-hydrology dynamics in complex terrain of semiarid areas: 1. A mechanistic approach to modeling dynamic feedbacks. *Water Resources Research*, *44*(3), W03429. https://doi.org/10.1029/2006WR005588

Jackson, R. B., Jobbágy, E. G., & Nosetto, M. D. (2009). Ecohydrology in a human-dominated landscape. *Ecohydrology*, *2*, 383–389. https://onlinelibrary.wiley.com/doi/abs/10.1002/eco.81

Jasper, J. T., Nguyen, M. T., Jones, Z. L., Ismail, N. S., Sedlak, D. L., Sharp, J. O., … Nelson, K. J. (2013). Unit process wetlands for removal of trace organic contaminants and pathogens from municipal wastewater effluents. *Environmental Engineering Science*, *30*(8), 421–436. https://doi.org/10.1089/ees.2012.0239

Jensco, K. G., & McGlynn, B. (2011). Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resources Research*, *47*(11), W11527. https://doi.org/10.1029/2011WR010666

Junior, J. A. J., de Mello, C. R., de Mello, J. M., Scolforo, H. F., Beskow, S., & McCarter, J. (2019). Rainfall partitioning measurement and rainfall interception modelling in a tropical semi-deciduous Atlantic forest remnant. *Agricultural and Forest Meteorology*, *275*, 170–183. https://doi.org/10.1016/j.agrformet.2019.05.016

Keeler, B. L., Hamel, P., McPhearson, T., Hamann, M. H., Donahue, M. L., Meza Prado, K. A., … Wood, S. A. (2019). Social-ecological and technological factors moderate the value of urban nature. *Nature Sustainability*, *2*, 29–38. https://doi.org/10.1038/s41893-018-0202-1

Kelleher, C., McGlynn, B., & Wagener, T. (2017). Characterizing and reducing equifinality by constraining a distributed catchment model with regional signatures, local observations, and process understanding. *Hydrology and Earth System Sciences*, *21*, 3325–3352. https://doi.org/10.5194/hess-21-3325-2017

Keys, P. W., van der Ent, R. J., Gordon, L. J., Hoff, H., Nikoli, R., & Savenije, H. H. G. (2012). Analysing precipitationsheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences*, *9*, 733–746. https://doi.org/10.5194/bg-9-733-2012

Kirchner, J. W. (2006). Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. *Water Resources Research*, *42*, W03S04. https://doi.org/10.1029/2005WR004362

Koster, R., Jouzel, J., Suozzo, R., Russell, G., Broecker, W., Rind, D., & Eagleson, P. (1986). Global sources of local precipitation as determined by the Nasa/Giss GCM. *Geophysical Research Letters*, *13*(2), 121–124. https://doi.org/10.1029/GL013i002p00121

Kotthoff, L., Thornton, C., Hoos, H. H., Hutter, F., & Leyton-Brown, K. (2017). Auto-WEKA 2.0: Automatic model selection and hyperparameter optimization in WEKA. *Journal of Machine Learning Research*, *18*, 1–5. https://doi.org/10.1007/978-3-030-05318-5_4

Kuehni, S. M., Bou-Zeid, E., Webb, C., & Shokri, N. (2016). Roof cooling by direct evaporation from a porous roof layer. *Energy and Buildings*, *127*, 512–528. https://doi.org/10.1016/j.enbuild.2016.06.019

Kuppel, S., Tetzlaff, D., Maneta, M. P., & Soulsby, C. (2018). What can we learn from multidata calibration of a process-based ecohydrological model? *Environmental Modelling & Software*, *101*, 301–316. https://doi.org/10.1016/j.envsoft.2018.01.001

Laaha, G., Skoien, J. O., Nobilis, F., & Blöschl, G. (2013). Spatial predictions of stream temperatures using top-kriging with an external drift. *Environmental Modeling and Assessment*, *18*(6), 671–683. https://doi.org/10.1007/s10666-013-9373-3

Lange, H., & Sippel, S. (2020). Machine learning applications in hydrology. In D. F. Levia, D. E. Carlyle-Moses, S. Iida, B. Michalzik, K. Nanko, & A. Tischer (Eds.), *Forest-water interactions*. Ecological Studies, 240. (pp. 233–257). Cham, Switzerland: Springer Nature. https://doi.org/10.1007/978-3-030-26086-6_10

Leonard, R. E. (1967). Mathematical theory of interception. In W. E. Sopper, & H. W. Hull (Eds.), *International symposium on forest hydrology* (pp. 131–136). Oxford: Pergamon Press.

Levia, D. F., Carlyle-Moses, D. E., Iida, S., Michalzik, B., Nanko, K., & Tischer, A. (Eds.) (2020). *Forest-water interactions*. Ecological studies series, No. 240. (p. 628). Switzerland AG: Springer Nature. https://doi.org/10.1007/978-3-030-26086-6

Levia, D. F., Hudson, S. A., Llorens, P., & Nanko, K. (2017). Throughfall drop size distributions: A review and prospectus for future research. *WIREs Water*, *4*, e1225. https://doi.org/10.1002/wat2.1225

Levia, D.F., Nanko, K., Amasaki, H., Giambelluca, T.W., Hotta, N., Iida, S., Mudd, R.G., Nullet, M. A, Sakai, N., Shinohara, Y., Sun, X., Suzuki, M., Tanaka, N., Tanatsirin, C., & Yamada, K. (2019). Throughfall partitioning by trees. *Hydrological Processes*, *33*(12), 1698-1708. https://doi.org/10.1002/hyp.13432

Liu, J., Li, S., Ouyang, Z., Tam, C., & Chen, X. (2008). Ecological and socioeconomic effects of China's policies for ecosystem services. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(28), 9477–9482. https://doi.org/10.1073/pnas.0706436105

Mackay, D. S. (2019). Ecohydrology: What's in a name? *Eos*, *100*, 1–7. https://doi.org/10.1029/2019EO123093 Published on 13 May 2019

Maneta, M. P., & Silverman, N. L. (2013). A spatially distributed model to simulate water, energy, and vegetation dynamics using information from regional climate models. *Earth Interactions*, *17*, 1–44. https://doi.org/10.1175/2012EI000472.1

Maxwell, R. M., & Condon, L. E. (2016). Connections between groundwater flow and transpiration partitioning. *Science*, *353*, 377–380. https://doi.org/10.1126/science.aaf7891

McDonnell, J. J., & Beven, K. (2014). Debates—The future of hydrological sciences: A (common) path forward? A call to action aimed at understanding velocities, celerities and residence time distributions of the headwater hydrograph. *Water Resources Research*, *50*(6), 5342–5350. https://doi.org/10.1002/2013WR015141

Merriam, R. A. (1960). A note on the interception loss equation. *Journal of Geophysical Research*, *65*, 3850–3851. https://doi.org/10.1029/JZ065i011p03850

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis (pp. 155)*. Washington, DC: Island Press.

Mirfenderesgi, G., Bohrer, G., Matheny, A. M., Fatichi, S., Moraes Frasson, R. P., & Schäfer, K. V. R. (2016). Tree level hydrodynamic approach for resolving above ground water storage and stomatal conductance and modeling the effects of tree hydraulic strategy. *Journal of Geophysical Research: Biogeosciences*, *121*, 1792–1813. https://doi.org/10.1002/2016JG003467

Murakami, S. (2006). A proposal for a new forest canopy interception mechanism: Splash droplet evaporation. *Journal of Hydrology*, *318*, 72–82. https://doi.org/10.1016/j.jhydrol.2005.07.002

Nadeau, D. F., Brutsaert, W., Parlange, M. B., Bou-Zeid, E., Barrenetxea, G., Couach, O., … Vetterli, M. (2009). Estimation of urban sensible heat flux using a dense wireless network of observations. *Environmental Fluid Mechanics*, *9*(6), 635–653. https://doi.org/10.1007/s10652-009-9150-7

Nanko, K., Hotta, N., & Suzuki, M. (2006). Evaluating the influence of canopy species and meteorological factors on throughfall drop size distribution. *Journal of Hydrology*, *329*, 422–431. https://doi.org/10.1016/j.jhydrol.2006.02.036

Nanko, K., Hudson, S. A., & Levia, D. F. (2016). Differences in throughfall drop size distributions in the presence and absence of foliage. *Hydrological Sciences Journal*, *61*, 620–627. http://doi.org/10.1080/02626667.2015.1052454

National Research Council. (2004). *Valuing ecosystem services: Toward better environmental decision-making*. Washington, D.C: National Academic Press.

Niu, G.-Y., Paniconi, C., Troch, P. A., Scott, R. L., Durcik, M., Zeng, X., … Goodrich, D. C. (2014). An integrated modelling framework of catchment-scale ecohydrological processes: 1. Model description and tests over an energy-limited watershed. *Ecohydrology*, *7*(2), 427–439. https://doi.org/10.1002/eco.1362

Nobre, A. D. (2014). The future climate of Amazonia, scientific assessment report (Sponsored by CCST-INPE, INPA and ARA, São José dos Campos, Brazil). https://www.ccst.inpe.br/wp-content/.../11/The_Future_Climate_of_Amazonia_Report.pdf

Olden, J. D., Kennard, M. J., & Pusey, B. J. (2012). A framework for hydrologic classification with a review of methodologies and applications in ecohydrology. *Ecohydrology*, *5*(4), 503–518. https://doi.org/10.1002/eco.251

Opperman, J. J. (2014). *A flood of benefits: Using green infrastructure to reduce flood risks*. Arlington, VA: The Nature Conservancy.

Ouyang, Z., Zheng, H., Xiao, Y., Polasky, S., Liu, J., Xu, W., … Daily, G. C. (2016). Improvements in ecosystem services from investments in natural capital. *Science*, *352*(6292), 1455–1459. https://doi.org/10.1126/science.aaf2295

Paschalis, A., Fatichi, S., Katul, G. G., & Ivanov, V. Y. (2015). Cross-scale impact of climate temporal variability on ecosystem water and carbon fluxes. *Journal of Geophysical Research: Biogeosciences*, *120*(9), 1716–1740. https://doi.org/10.1002/2015JG003002

Pascual, U., Balvanera, P., Diaz, S., Pataki, G., Roth, E., Stenseke, M., … Yagi, N. (2017). Valuing nature's contributions to people: the IPBES approach. *Current Opinion in Environmental Sustainability*, *26-27*, 7–16. https://doi.org/10.1016/j.cosust.2016.12.006

Penna, D., Hopp, L., Scandellari, F., Allen, S. T., Benettin, P., Beyer, M., … Kirchner, J. W. (2018). Ideas and perspectives: Tracing terrestrial ecosystem water fluxes using hydrogen and oxygen stable isotopes–challenges and opportunities from an interdisciplinary perspective. *Biogeosciences*, *15*, 6399–6415. https://doi.org/10.5194/bg-15-6399-2018

Piayda, A., Dubbert, M., Siegwolf, R., Cuntz, M., & Werner, C. (2017). Quantification of dynamic soil-vegetation feedbacks following an isotopically labelled precipitation pulse. *Biogeosciences*, *14*, 2293–2306. https://doi.org/10.5194/bg-14-2293-2017

Pringle, C. (2003). What is hydrologic connectivity and why is it ecologically important? *Hydrological Processes*, *17*, 2685–2689. https://doi.org/10.1002/hyp.5145

Ramamurthy, P., & Bou-Zeid, E. (2014). Contribution of impervious surfaces to urban evaporation. *Water Resources Research*, *50*(4), 2889–2902. https://doi.org/10.1002/2013WR013909

Ramamurthy, P., & Bou-Zeid, E. (2017). Heatwaves and urban heat islands: A comparative analysis of multiple cities using a high-resolution numerical model. *Journal of Geophysical Research: Atmospheres*, *122*(1), 168–178. https://doi.org/10.1002/2016JD025357

Richter, D. D., Billings, S. A., Groffman, P. M., Kelly, E. F., Lohse, K. A., McDowell, W. H., … Zhang, G. (2018). Ideas and perspectives: strengthening the biogeosciences in environmental research networks. *Biogeosciences*, *15*, 4815–4832. https://doi.org/10.5194/bg-15-4815-2018

Rinaldo, A., Gatto, M., & Rodriguez-Iturbe, I. (2018). River networks as ecological corridors: A coherent ecohydrological perspective. *Advances in Water Resources*, *112*, 27–58. https://doi.org/10.1016/j.advwatres.2017.10.005

Rugel, E. L., Carpiano, R. M., Henderson, S. B., & Brauer, M. (2019). Exposure to natural space, sense of community belonging, and adverse mental health outcomes across an urban region. *Environmental Research*, *171*, 365–377. https://doi.org/10.1016/j.envres.2019.01.034

Rutter, A. J. (1967). An analysis of evaporation from a stand of Scots pine. In W. E. Sopper, & H. W. Hull (Eds.), *International symposium on forest hydrology (813 pp.)*. Oxford: Pergamon Press.

Salzman, J., Bennett, G., Carroll, N., Goldstein, A., & Jenkins, M. (2018). The global status and trends of Payments for Ecosystem Services. *Nature Sustainability*, *1*, 136–144. https://doi.org/10.1038/s41893-018-0033-0

Savenije, H. H. (2004). The importance of interception and why we should delete the term evapotranspiration from our vocabulary. *Hydrological Processes*, *18*, 1507–1511. https://doi.org/10.1002/hyp.5563

Schumacher, J., & Christiansen, J. R. (2020). LiDAR applications to forest-water interactions. In D. F. Levia, D. E. Carlyle-Moses, S. Iida, B. Michalzik, K. Nanko, & A. Tischer (Eds.), *Forest-water interactions*. Ecological Studies, 240. (pp. 87–112). Cham, Switzerland: Springer Nature. https://doi.org/10.1007/978-3-030-26086-6_4

Selker, J. S., Selker, F., Llamas, R., Kruger, A., Niemeier, J., Abou Najm, M. R., … McCulloh, K. (2020). Lessons in new measurement technologies: From instrumenting trees to the Trans-African Hydro-meteorological Observatory. In D. F. Levia, D. E. Carlyle-Moses, S. Iida, B. Michalzik, K. Nanko, & A. Tischer (Eds.), *Forest-water interactions*. Ecological Studies, 240. (pp. 131–144). Cham, Switzerland: Springer Nature. https://doi.org/10.1007/978-3-030-26086-6_6

Selker, J. S., Thévenaz, L., Huwald, H., Mallet, A., Luxemburg, W., van de Giesen, N., … Parlange, M. B. (2006). Distributed fiber optic temperature sensing for hydrologic systems. *Water Resources Research*, *42*(12), W12202. https://doi.org/10.1029/2006WR005326

Selker, J. S., Tyler, S. W., Higgins, C., & Wing, M. (2015). Drone squadron to take earth monitoring to new heights. *Eos*, *96*(19), 8–11. https://doi.org/10.1029/2015EO035405

Shortridge, J. E., Guikema, S. D., & Zaitchik, B. F. (2016). Machine learning methods for empirical streamflow simulation: A comparison of model accuracy, interpretability, and uncertainty in seasonal watersheds. *Hydrology and Earth System Sciences*, *20*, 2611–2628. https://doi.org/10.5194/hess-20-2611-2016

Shuttleworth, W. J., & Calder, I. R. (1979). Has the Priestly-Taylor equation any relevance to forest evaporation? *Journal of Applied Meteorology*, *18*, 639–646. https://doi.org/10.1175/1520-0450(1979)018<0639:HTPTEA>2.0.CO;2

Simeone, C., Maneta, M. P., Holden, Z. A., Sapes, G., Sala, A., & Dobrowski, S. Z. (2019). Coupled ecohydrology and plant hydraulics modeling predicts ponderosa pine seedling mortality and lower treeline in the US Northern Rocky Mountains. *New Phytologist*, *221*, 1814–1830. https://doi.org/10.1111/nph.15499

Smakhtin, V. U. (2001). Estimating continuous monthly baseflow time series and their possible applications in the context of the ecological reserve. *Water SA*, *27*, 213–217. https://doi.org/10.4314/wsa.v27i2.4995

Smettem, K. R. J. (2008). Welcome address for the new 'Ecohydrology' journal. *Ecohydrology*, *1*, 1–2. https://doi.org/10.1002/eco.2

Smith, A., Tetzlaff, D., Gelbrecht, J., Kleine, L., & Soulsby, C. (2020). Riparian wetland rehabilitation and beaver re-colonisation impacts on discharge and water quality in a lowland agricultural catchment. *Science of the Total Environment*, *699*, 134302. https://doi.org/10.1016/j.scitotenv.2019.134302

Smith, A., Tetzlaff, D., Laudon, H., Maneta, M., & Soulsby, C. (2019). Assessing the influence of soil free-thaw cycles on catchment water storage–flux–age interactions using a tracer-aided ecohydrological model. *Hydrology and Earth System Sciences (HESS)*, *23*, 3319–3334. https://doi.org/10.5194/hess-2019-84

Sommer, T., Harrell, B., Nobriga, M., Brown, R., Moyle, P., Kimmerer, W., & Schemel, L. (2001). California's Yolo Bypass: Evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. *Fisheries Magazine*, *26*(8), 6–16. https://doi.org/10.1577/1548-8446(2001)026<0006:CYB>2.0.CO;2

Sprenger, M., Tetzlaff, D., Buttle, J., Laudon, H., Leistert, H., Mitchell, C., … Soulsby, C. (2018). Measuring and modelling stable isotopes of mobile and bulk soil water. *Vadose Zone Journal*, *17*(1), 170149. https://doi.org/10.2136/vzj2017.08.0149

Stewart, J. B. (1977). Evaporation from the wet canopy of a pine forest. *Water Resources Research*, *13*, 915–921. https://doi.org/10.1029/WR013i006p00915

Stewart, R., Abou-Najm, M. R., Rupp, D. E., & Selker, J. S. (2012). Measurement tool for dynamics of soil cracks. *Vadose Zone Journal*, *11*, vzj2011.0048. https://doi.org/10.2136/vzj2011.0048

Su, L., Zhao, C., Xu, W., & Xie, Z. (2016). Modelling interception loss using the revised gash model: A case study in a mixed evergreen and deciduous broadleaved forest in China. *Ecohydrology*, *9*, 1580–1589. https://doi.org/10.1002/eco.1749

Tague, C. L., & Band, L. E. (2004). RHESSys: Regional Hydro-Ecologic Simulation System—An object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling. *Earth Interactions*, *8*(9), 1–42. https://doi.org/10.1175/1087-3562(2004)8<1:RRHSSO>2.0.CO;2

Tanaka, N., Levia, D., Igarashi, Y., Yoshifuji, N., Tanaka, K., Tantasirin, C., … Kumagai, T. (2017). What factors are most influential in governing stemflow production from plantation-grown teak trees? *Journal of Hydrology*, *544*, 10–20. https://doi.org/10.1016/j.jhydrol.2016.11.010

Tanaka, N., Levia, D. F., Igarashi, Y., Nanko, K., Yoshifuji, N., Tanaka, K., … Kumagai, T. (2015). Throughfall under a teak plantation in Thailand: A multifactorial analysis on the effects of canopy phenology and meteorological conditions. *International Journal of Biometeorology*, *59*(9), 1145–1156. http://doi.org/10.1007/s00484-014-0926-1

Tauro, F., Selker, J. S., van de Giesen, N., Abrate, T., Uijlenhoet, R., Porfiri, M., … Grimaldi, S. (2018). Measurements and Observations in the XXI century (MOXXI): innovation and multi-disciplinarity to sense the hydrological cycle. *Hydrological Sciences Journal*, *63*(2), 169–196. https://doi.org/10.1080/02626667.2017.1420191

Tetzlaff, D., Buttle, J., Carey, S. K., McGuire, K., Laudon, H., & Soulsby, C. (2015). Tracer-based assessment of flow paths, storage and runoff generation in northern catchments: a review. *Hydrological Processes*, *29*(16), 3475–3490. https://doi.org/10.1002/hyp.10412

Toth, C., & Jóźków, G. (2016). Remote sensing platforms and sensors: A survey. *Journal of Photogrammetry and Remote Sensing*, *115*, 22–36. https://doi.org/10.1016/j.isprsjprs.2015.10.004

Turner, B., Hill, D. J., Carlyle-Moses, D. E., & Rahman, M. (2019). Low-cost, high-resolution stemflow sensing. *Journal of Hydrology*, *570*, 62–68. https://doi.org/10.1016/j.jhydrol.2018.12.072

Turner, B., Hill, D. J., & Caton, K. (2020). Cracking "open" technology in ecohydrology. In D. F. Levia, D. E. Carlyle-Moses, S. Iida, B. Michalzik, K. Nanko, & A. Tischer (Eds.), *Forest-water interactions*. Ecological Studies, 240. (pp. 3–28). Cham, Switzerland: Springer Nature. https://doi.org/10.1007/978-3-030-26086-6_1

United States Environmental Protection Agency, 2009. *Valuing the protection of ecological systems and services*, EPA-SAB-09-012, 121 pages.

Valente, F., Gash, J. H., Nóbrega, C., David, J. S., & Pereira, F. L. (2020). Modelling rainfall interception by an olive-grove/pasture system with a sparse tree canopy. *Journal of Hydrology*, *581*, 124417. https://doi.org/10.1016/j.hydrol.2019.124417

van der Ent, R. J., Savenije, H. H. G., Schaefli, B., & Steele-Dunne, S. C. (2010). Origin and fate of atmospheric moisture over continents. *Water Resources Research*, *46*(9), W09525. https://doi.org/10.1029/2010WR009127

van Dijk, A. I. J. M., Gash, J. H., van Gorsel, E., Blanken, P. D., Cescatti, A., Emmel, C., … Wohlfahrt, G. (2015). Rainfall interception and the coupled surface water and energy balance. *Agricultural and Forest Meteorology*, *214-215*, 402–415. https://doi.org/10.1016/j.agrformet.2015.09.006

van Emmerik, T., Steele-Dunne, S., Hut, R., Gentine, P., Guerin, M., Oliveira, R. S., … van de Giesen, N. (2017). Measuring tree properties and responses using low-cost accelerometers. *Sensors*, *17*(5), 1098. https://doi.org/10.3390/s17051098

Vaughan, M. C. H., Bowden, W. B., Shanley, J. B., Vermilyea, A., Sleeper, R., Gold, A. J., … Schroth, A. W. (2017). High-frequency dissolved organic carbon and nitrate measurements reveal differences in storm hysteresis and loading in relation to land cover and seasonality. *Water Resources Research*, *53*(7), 5345–5363. https://doi.org/10.1002/2017WR020491

Volkmann, T. H., Kühnhammer, K., Herbstritt, B., Gessler, A., & Weiler, M. (2016). A method for in situ monitoring of the isotope composition of tree xylem water using laser spectroscopy. *Plant, Cell & Environment*, *39*(9), 2055–2063. https://doi.org/10.1111/pce.12725

Vymazal, J. (2010). Constructed wetlands for wastewater treatment: Five decades of experience. *Environmental Science and Technology*, *45*, 61–69. https://doi.org/10.1021/es101403q

Wang, X., & Wolfbeis, O. S. (2014). Optical methods for sensing and imaging oxygen: materials, spectroscopies and applications. *Chemical Society Reviews*, *43*, 3666–3761. https://doi.org/10.1039/C4CS00039K

Zalewski, M. (2000). Ecohydrology-the scientific background to use ecosystem properties as management tools toward sustainability of water resources. *Ecological Engineering*, *16*, 1–8. https://doi.org/10.1016/S0925-8574(00)00071-9

Zalewski, M. (2014). Ecohydrology and hydrologic engineering: Regulation of hydrology-biota interactions for sustainability. *Journal of Hydrologic Engineering*, *20*(1), A4014012. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000999

Zölch, T., Maderspacher, J., Wamsler, C., & Pauleit, S. (2016). Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. *Urban Forestry & Urban Greening*, *20*, 305–316. https://doi.org/10.1016/j.ufug.2016.09.011

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