Received: 17 January 2018 | Accepted: 2 May 2018
DOI: 10.1002/hyp.13163

SCIENTIFIC BRIEFING

The importance of and need for rapid hydrologic assessments in Latin America

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Funding information
Administrative Department of Science, Technology, and Innovation of Colombia (COLCIENCIAS), Grant/Award Number: Diaspora Program

Abstract

Long-term observations are critical in hydrology to understand the dynamics of biological and physicochemical processes involved in and affected by the flux of water. Long-term observations have been employed to provide basic understanding of the water cycle (e.g., infiltration, evaporation, run-off generation, and groundwater–surface water interactions), but they are lacking in hydrologically relevant regions such as the Andes Mountains, including alpine watersheds. Although the call for long-term data acquisition in Latin America has been made, the establishment of long-term data collection centres remains logistically challenging. This ever-growing scientific gap hinders our understanding of differences and similarities in hydrological processes of tropical and temperate regions. Furthermore, technological advances such as in situ optical sensors for water quantity and quality remain cost-prohibitive for both short and long deployment at most existing research sites in Latin America, restricting researchers pursuing research funding or developing meaningful, intersite comparisons and syntheses. Here, we emphasize the importance of and need for rapid assessments (i.e., field campaigns conducted over a few days) for improved hypothesis development and mechanistic understanding of hydrological dynamics in Latin America. We report on rapid assessments conducted in the high-elevation mountains (>3,000 m) of Colombia. Our results highlight rapidly changing dynamics in nutrient retention potential and dissolved CO_2 (pCO_2), as well as highly variable spatial distribution of water quality parameters (N, C, P, Cl) in areas with varying land use. We present an initial examination of the effects of land-use change on stream nutrient dynamics in one of the most biodiverse and threatened ecosystems on Earth. We conclude that rapid assessments not only are necessary but also represent a cost-effective way to develop clear, testable hypotheses to advance a hydrologic research agenda in Latin America and work towards long-term hydrological knowledge and information for use by other scientists.

1 | INTRODUCTION

Long-term observations are critical in hydrologic science to understand the dynamics and heterogeneity of the biological and physicochemical processes involved in and affected by the flux of water (Tetzlaff, Carey, McNamara, Laudon, & Soulsby, 2017). Seminal studies in hydrology have used long-term measurements to enhance our basic understanding of the water cycle, including processes ranging from infiltration (Horton, 1933) to evaporation (Penman, 1948), to run-off generation (Hewlett & Hibbert, 1967), and groundwater–surface water interactions (Winter, Harvey, Franke, & Alley, 1998). Research networks such as the long-term ecological research sites and critical zone observatories in the United States and Antarctica, and the long-term ecological research Europe and TERENO observatories in Europe, are home to some of the richest ecological and hydrological datasets on Earth, bringing together diverse groups of researchers who apply new tools, explore new questions, and advance scientific knowledge.

In contrast to the well-established networks of the United States and Europe, much of the rest of the world lacks such infrastructure. Latin America, for instance, is home to a vast array of diverse landscapes and ecosystems that remain understudied (Veblen, Young, & Orme, 2007). In addition to a lack of scientific information, Latin America is experiencing rapid population growth. Most of the high-density cities in Latin America are located downstream of alpine systems (e.g., Bogotá, Lima, Quito, and Santiago de Chile), where deforestation, mining, and subsistence agriculture are the most dominant land-use disturbances (Grau & Aide, 2008). These disturbances are understood to affect hydrologic dynamics (both water quantity and quality), but effective monitoring programmes (*sensu* Lovett et al., 2007) in the region are often downplayed and environmental protection/remediation delayed or ignored due to inadequate administrative support and lack of control mechanisms (e.g., Toro, Requena, & Zamorano, 2010).

Despite remarkable progress in long-term observations and data acquisition in Latin America (e.g., Asbjornsen et al., 2011; Asbjornsen et al., 2017; Bruijnzeel, Mulligan, & Scatena, 2011; Gotsch et al., 2014; Moore, Orozco, Aparecido, & Miller, in press; Ogden & Stallard, 2013), the establishment and augmentation of long-term data networks remains logistically challenging, particularly at the highest elevations. This challenge results in an ever-growing scientific gap that hinders our understanding of differences and similarities between hydrological processes in tropical (e.g., tropical Latin America) and temperate (e.g., North America and Europe) regions (e.g., Boulton et al., 2008). This expanding gap includes topics such as the capacity of streams to take up and process carbon, nutrients and pollutants, the processes that govern the storage and transport of sediments, and the range of variability of in-stream processing (metabolism and geochemical) across elevation, latitude, and land-use gradients (Bernhardt et al., 2018). A literature search of published studies (ISI Web of Science) using the keywords "stream" and "nutrient" shows the disparity among studies conducted in North America and Europe versus those conducted in South/Latin America, including sites at high elevation (Figure 1a). When the comparison is limited to the term "stream metabolism," the difference is even more pronounced (Figure 1b). Similarly, we lack understanding of other key hydrologic processes in tropical regions, including the role of fog and condensation fluxes in the hydrologic cycle of mountainous areas (Hu & Riveros-Iregui, 2016; Scholl, Eugster, & Burkard, 2011); the seasonal variability of rainfall–run-off processes in tropical, alpine watersheds (Célleri & Feyen, 2009) and associated storage and buffering capacity (Buytaert et al., 2006); and the response of high-elevation watersheds to land management, climate change, and population growth (Buytaert & De Bièvre, 2012).

Recent technological advances such as in situ optical sensors for water quantity and quality – which remain cost-prohibitive even in developed countries – are not readily affordable for environmental monitoring in Latin America. This lack of access to cutting-edge technology places researchers at a disadvantage in the pursuit of the development of meaningful, intersite comparisons and syntheses and, paradoxically, in the pursuit of research funding. Because this situation may remain in place for the foreseeable future, a different and pragmatic approach is critically needed.

In this paper, we exemplify the importance of and need for rapid assessments (i.e., field campaigns conducted over a few days) for improved hypothesis development and mechanistic understanding of hydrological dynamics in Latin America, specifically along the Andes Mountains. At the continental scale, South America has 28.3% of the world's freshwater resources and is second to Asia (28.5%) and far ahead of Europe (15.2%) and North and Central America combined (17%; FAO, 2003). Rapid assessments are common in hydrology and are regularly used to evaluate various processes, including water quality of rivers (Chessman, 1995), the ecological condition of wetlands (Fennessy, Jacobs, & Kentula, 2007), or the source of pollution to large water bodies (Scheren, Zanting, & Lemmens, 2000). It has been recently shown that periodic sampling is a useful tool in

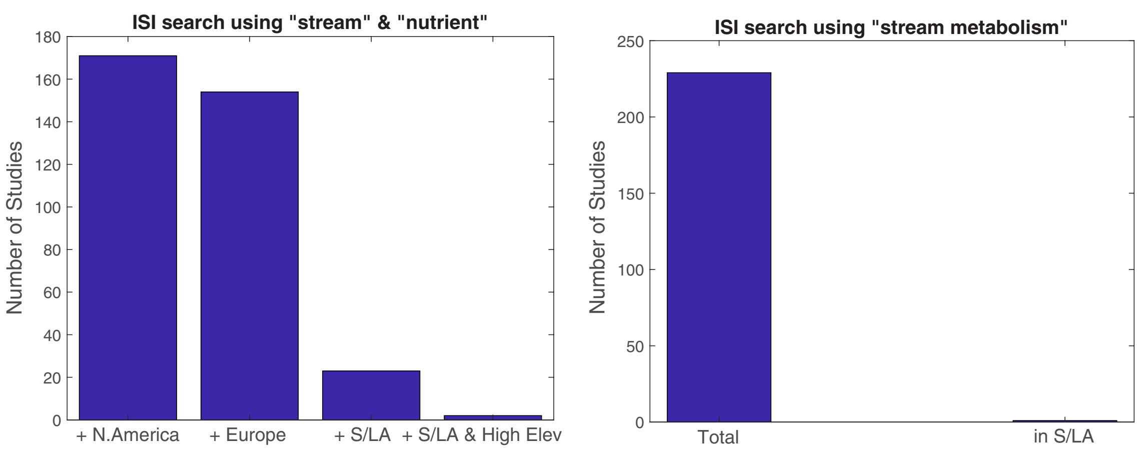

FIGURE 1 (Left) Literature search of published studies (ISI Web of Science) using the keywords "stream" and "nutrient" across various geographic regions, including North America, Europe, South/Latin America (S/LA), and high-elevation studies in S/LA for all years. (Right) Literature search of published studies (ISI Web of Science) using the keyword "stream metabolism" for all studies compared with South/Latin America

characterizing the long-term behaviour and spatial variability of water chemistry of multiple headwater catchments (Abbott et al., 2018). The same study concluded that the spatiotemporal variability in water chemistry across the sampled catchments is more stable than previously thought on seasonal to decadal timescales. Here, we report on rapid assessments at two high-altitude mountains (>3,000 m) in Colombia, combining synoptic sampling with automated sensor technology to investigate: (a) effects of land-use change and management on water quality; (b) dynamics of dissolved CO_2 and potential for evasion along headwater streams; and (c) dynamics of stream metabolism and nutrient retention capacity of high-altitude, tropical streams. We focus specifically on the high-elevation tropics, because it is a region where observations are critically lacking in Latin America (Figure 1a). We conclude that rapid assessments are important and practical tools to develop clear, testable hypotheses to advance a hydrologic research agenda in the region and close the knowledge gap between hydrologic understanding in tropical and temperate regions.

2 | METHODS

2.1 | Site description

This study was conducted in two high-elevation páramo sites near Bogotá, Colombia (Figure 1). Páramos are alpine grasslands broadly present in South America and also present at smaller scales in Central America, Africa, and Indonesia (Hamel et al., 2017; Hofstede, 1995). Páramos extend from Venezuela to Peru creating an orographic barrier for trade winds moving northwestward from the Amazon, which captures atmospheric moisture and facilitates the initiation of many of the main tributaries of the Amazon and Orinoco Rivers. The first site is a second-order stream (Chucua Creek) in the preserved Chingaza Natural National Park (4°40′ N 73°47′W), a 77-km^2 national park located 35 km east of Bogotá. The second site is a third-order stream (Guandoque Creek) located in the ~60-km^2 Guerrero Páramo, 60 km northwest of Bogotá (5°12′N 74°00′W). Both creeks start in small wetland complexes located in alpine areas (i.e., above the treeline) and extend downstream as well-defined stream channels. Land cover for the non-impacted site is composed mainly of páramo coverage, including *Espeletia sp*. shrubs and dense grassland. Land cover for the impacted site includes similar páramo coverage but only near and around the wetland complexes. Downstream from the wetlands' land cover is mainly pasture (*Pennisetum clandestinum*) and potato crops (*Solanum tuberosum*) with portions of bare soil between planting rotations. Intense agricultural activity has been conducted in the impacted site for over 40 years (Peña-Quemba, Rubiano-Sanabria, & Riveros-Iregui, 2016). Both sites are underlain by the Guadalupe Group, a late Cretaceous sequence of shales and sandstones, which extend along much of the Bogotá Savanna and the eastern flank of the Colombian Andes (Moreno-Torres & Ruiz-Rodriguez, 2016). Hereafter, we will refer to these sites as the non-impacted (Chingaza) and impacted (Guerrero) sites. Both sites have similar climatic regimes but contrasting land cover (Figure 2). The highest precipitation at both sites occurs between May and July with a short dry season that extends from December to early April. Mean annual precipitation at both sites ranges between 1,800 and 2,000 mm (IAvH, 2012; Sanchez, Posada,

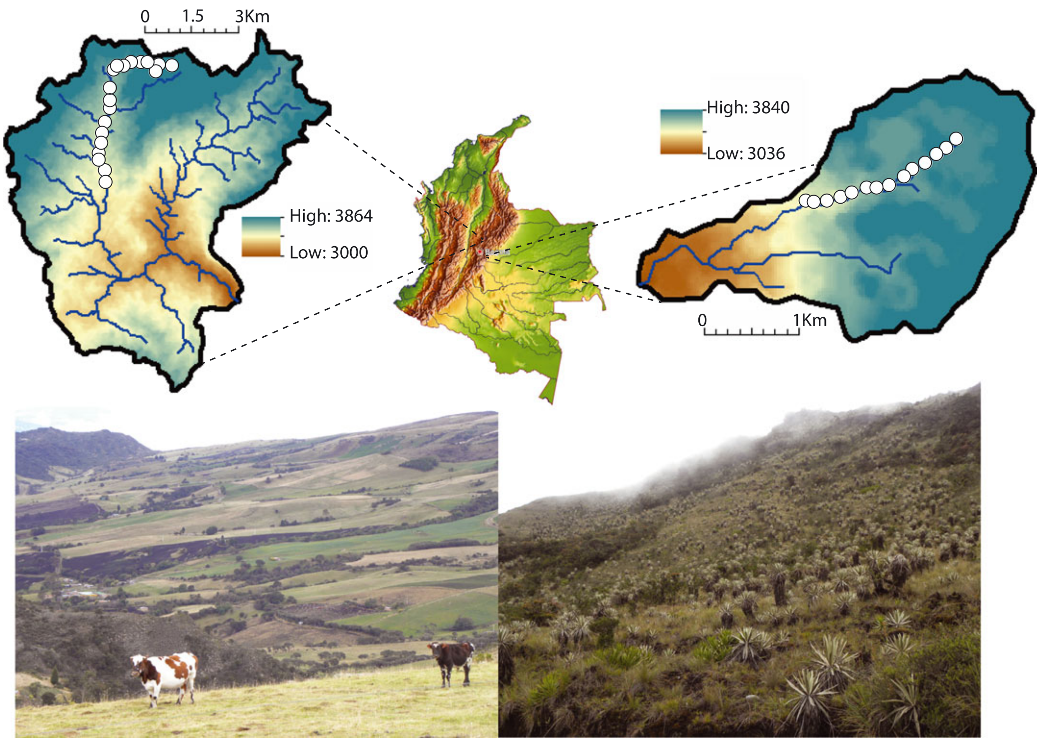

FIGURE 2 (Top panel) Locations of the impacted (Guerrero, left) and the non-impacted (Chingaza, right) páramos in central Colombia. Sampling locations along the Guandoque Creek and Chucua Creek are shown as white circles. (Bottom panel) Land cover comparison of the same two sites. The impacted site's land cover (left) includes intensive potato farming, grazing, and bare soil between planting rotations, whereas the non-impacted site's (right) includes endemic shrubs and bryophytes. The map of Colombia (top centre) was produced by the GinkgoMaps project (http://www.ginkgomaps.com)

& Smith, 2014). Chingaza's water has been collected for urban consumption since 1977 and Guerrero's water since the early 1950s. Combined, both páramos supply ~85% of the water demand of Bogotá and neighbouring communities, where ~8 million people live.

2.2 | Field measurements

2.2.1 | Synoptic observations

We collected 34 spatially distributed grab samples of stream water along the main channel of both non-impacted and impacted watersheds; 15 samples were collected along a 2.1-km reach of the Chucua Creek in the non-impacted watershed over the course of 4 days, and 19 samples were collected along a 4.2-km reach of the Guandoque Creek in the impacted watershed. Our goal was to characterize major differences in water chemistry within the study watersheds using a single snapshot-in-time approach. Grab samples were collected during the dry season (March 10–13, 2014) with the goal of characterizing baseflow conditions at both sites. Samples were filtered with 0.45-μm polyvinylidene difluoride (PDVF) filters and refrigerated immediately upon collection. Samples were transported to the United States and analysed for basic ion chromatography and quantitative multielemental composition of over 60 elements using inductively coupled plasma mass spectrometry at the Laboratory for Environmental Analysis at the University of Georgia. We report on the most distinct concentrations of these analyses for representative purposes.

2.2.2 | High-frequency observations

We installed two submersible, lightweight partial pressure CO_2 (pCO_2) sensors (C-sense, Turner Designs, Sunnyvale, CA) along a 250-m stream reach downstream of a stream–wetland transition in the non-impacted watershed to assess pCO_2 diel production and transport dynamics (cf. Heffernan & Cohen, 2010). Our goal was to characterize the diel pCO_2 dynamics between a stream channel and an adjacent wetland using continuous observations. These stream–wetland–stream transitions are prominent in páramo systems and may be important to regulating aquatic biogeochemistry and metabolism due to their high organic C content (Hribljan, Suárez, Heckman, Lilleskov, & Chimner, 2016). These transitions are also currently threatened by agricultural expansion and conversion to grazing lands (Buytaert et al., 2006).

2.2.3 | Injection of a "smart" bioreactive tracer

Using the same wetland–stream transition in the non-impacted site, we performed two injections of the "smart," bioreactive tracer resazurin (Raz), which is irreversibly reduced to resorufin (Rru) through aerobic cellular respiration (González-Pinzón, Haggerty, & Myrold, 2012; Haggerty, Argerich, & Martí, 2008; González-Pinzón, Haggerty, & Argerich, 2014), and the conservative tracer chloride, to investigate differences in stream respiration and relate them with pCO_2 diel patterns. The first injection was at the outlet of the wetland, with tracer recovery at 250 and 500 m downstream. The second injection was at the inlet of the wetland, with tracer recovery at the wetland outlet (which was 110 m downstream) and 250 m downstream from it. In both instances, we used the longitudinal transformation of Raz to Rru as a proxy to estimate water residence times and microbial heterotrophic metabolism. In both cases, we report the cumulative distribution function of each recovered compound (Raz or Rru), scaled to the maximum measured Raz at the first point of recovery downstream of each injection point. This fractional recovery is computed relative to the first sampling point because we are injecting a bioreactive tracer (Raz) and thus no product (Rru) is available at the injection point.

3 | RESULTS

3.1 | Land-use change effects on water quality

Our synoptic survey data revealed contrasting patterns in water chemistry between watersheds. We consistently found greater nutrient (nitrate, NO_3–N; and phosphate, PO_4–P) and dissolved organic carbon (DOC) concentrations in the non-impacted watershed (Figure 3). Conversely, we consistently found greater concentrations of base cations (K, Al, Cd, Mg, and Fe) in the impacted site (Figure 3). Although, in general, these differences were not statistically

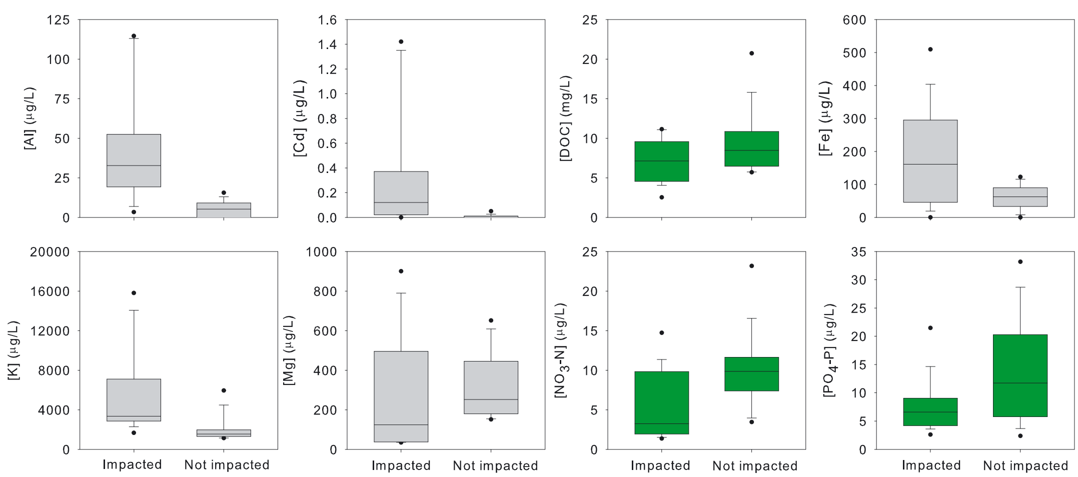

FIGURE 3 Boxplot comparison of various water quality parameters measured in non-impacted (Chingaza) and impacted (Guerrero) watersheds. Boxplots show the median and interquartile range of measurements using synoptic sampling that included 19 and 15 samples at each site, respectively. Carbon and nutrients are shown in green, whereas cations and metals are shown in grey

significant when binned by site, almost in every instance, with the exception of PO_4, the range in concentrations was greater at the impacted site. Given the similarity of the hydrologic regimes in both watersheds during our synoptic sampling, the smaller range in concentrations observed across the non-impacted watershed is indicative of greater biological, chemical, and physical stability.

3.2 | Dynamics of dissolved CO_2 and potential for CO_2 evasion

Figure 4 summarizes the dynamics of pCO_2 in stream water, measured simultaneously at the wetland outlet (i.e., upstream) and downstream locations of a reach at 5-min intervals. At both locations, the water was supersaturated with CO_2 with respect to the atmosphere, although at the wetland outlet pCO_2 showed a greater diel range and pCO_2 maximum values reached three times atmospheric concentrations. In addition, diel fluctuations of pCO_2 were asynchronous with respect to one another (i.e., decoupled in time, even after accounting for the <0.5-hr average transport time between the two locations separated 250 m; cf. Figure 5a). Maximum pCO_2 at the wetland outlet occurred right before sunrise, whereas maximum pCO_2 at the downstream site occurred right before sunset. These asynchronous dynamics result in the observed hysteresis when pCO_2 measurements from both sites are compared against one another (Figure 4).

3.3 | Stream metabolism

Using injections of the bioreactive tracer Raz, we found that the transport along the stream channel was much more advective relative to the wetland, as evidenced by steeper rising limbs in the tracer breakthrough curves presented in Figure 5a (showing results from injection and sampling in the stream channel), with respect to those in Figure 5b (injection at the wetland inlet and sampling at its outlet—110 m downstream—and 250 m further downstream along the channel). Also, using the times to reach 50% Raz plateau concentrations as indicative of mean travel times between sites, the average longitudinal velocity

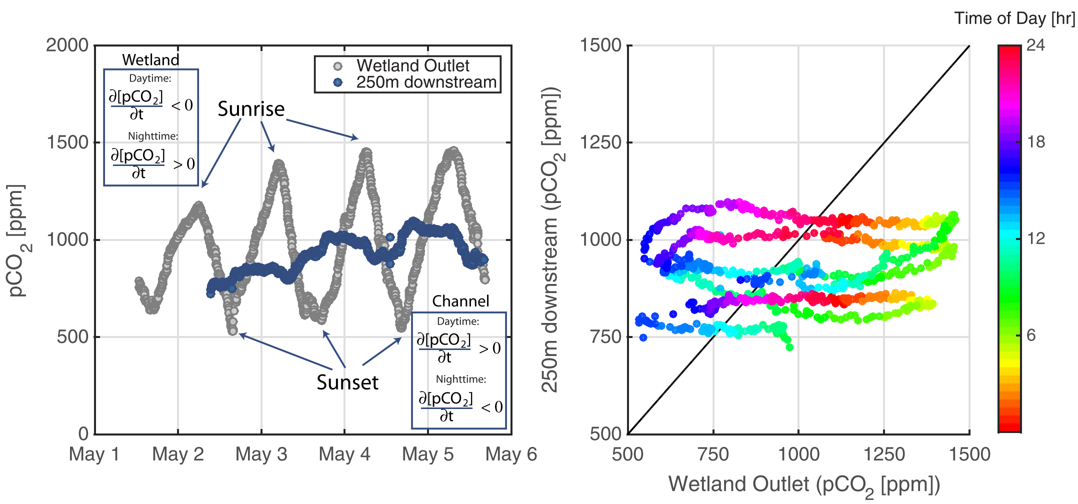

FIGURE 4 Five-minute measurements of dissolved CO_2 (pCO_2) collected simultaneously at the outlet of a natural wetland and 250 m downstream of it along a páramo stream

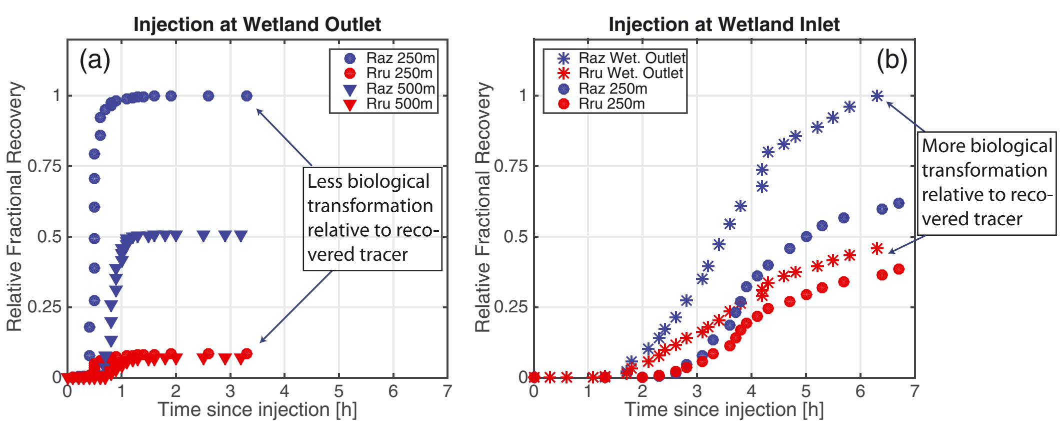

FIGURE 5 Tracer injections using the bioreactive tracer resazurin (Raz), which is irreversibly reduced to resorufin (Rru) through aerobic metabolism. Injections took place at the wetland outlet (left) with samples collected 250 and 500 m downstream from the outlet and at the wetland inlet (right) with samples collected at the wetland outlet (i.e., 110 m downstream from the injection) and 250 m downstream from the outlet. This figure shows greater biological transformation of Raz (blue) to Rru (red) in the wetland (right) than in the stream channel (left) as a result of increased metabolic activity and travel times

($u = L_{up-down}/t_{up-down}$, where u, L, and t are velocity, distance, and time, respectively) was greater along the stream channel (i.e., u_{reach}= 250 m/0.16 hr = 0.43 m/s) than along the wetland (i.e., $u_{wetland}$= 110 m/3.3 hr = 1×10^{-3} m/s), that is, water moving along the stream channel flowed ~46× faster than it did along the wetland. Those differences in transport velocities resulted in differences in metabolism, that is, <15% of the Raz was transformed to Rru by aerobic respiration in the stream channel, compared with ~50% in the wetland.

4 | DISCUSSION

4.1 | Land-use change effects on water quality

Through a synoptic sampling rapid assessment, we found clear water quality differences between the impacted and non-impacted watersheds for several elements, including those shown in Figure 3. Our results showed greater concentrations of Al, Cd, Fe, and K in the impacted watershed, whereas DOC, NO_3, and PO_4 were greater in the non-impacted watershed. Although, in most instances, these differences were not statistically significant at the landscape scale, it is important to note that the range in the concentrations was almost always greater in the impacted watershed, an indication of the degree of variability within the stream network and likely a result of the variability in land uses within the watershed. Land uses at the impacted site differed from the lower to the upper part of the watershed and included potato crops and pasture for grazing at lower elevations and shrubland and dense grassland at higher elevations (Peña-Quemba et al., 2016). In particular, concentrations of DOC, NO_3, and PO_4 were lower near and around the wetland complexes of the impacted site (i.e., the headwater of Guandoque Creek), but the complexity of the land fragmentation at the impacted site prevented us from singling out the connection between land cover and stream water quality. Our findings, however, highlight the need to understand the role of land fragmentation in mediating water quality, particularly in landscapes as disturbed—and as unexplored—as páramos. The widespread land cover fragmentation of impacted páramos is known to drive multiple environmental effects, ranging from niche and habitat loss to biodiversity reduction to soil acidification to interruption of connectivity across the terrestrial–aquatic interface (Otero, Figueroa, Muñoz, & Peña, 2011). The inverse pattern of Fe and PO_4 suggests that higher Fe at the impacted site might lead to the binding of phosphorus with less available PO_4 in solution, whereas the opposite seems to occur at the not-impacted site. This phenomenon has been well documented in forested environments (e.g., Dillon & Molot, 1997), but to the best of our knowledge, it remains unexplored in páramos. We note that these patterns are shown at the watershed level, because our one-time sampling methodology does not allow us to assertively determine the effects of each individual land use on water quality, not only across space but also across time (e.g., wet vs. dry periods). Targeted experiments via rapid assessments could be developed to examine these relationships further either at the watershed scale or across individual reaches.

The role of agriculture on water quality has been long studied in temperate regions (Karr & Dudley, 1981), but it remains poorly addressed in intertropical regions (Scanlon, Jolly, Sophocleous, & Zhang, 2007). Research in temperate regions has linked agriculture with disruptions in water quality of lentic (e.g., wetlands and groundwater) and lotic (e.g., streams) systems through nutrients, pesticides, and eutrophication (Carpenter, Ludwig, & Brock, 1999). Other studies in temperate regions have characterized the dynamics of nutrient cycling taking place downstream of wastewater effluents and the reduction of oxygen content of the water (known as the "dissolved oxygen sag"; Cox, 2003; O'Connor, 1967); these dynamics remain poorly examined in tropical environments. Information on the effects of other forms of disturbance on water quality, including hydraulic fracturing (e.g., Jackson et al., 2014) or mining (e.g., Ross, McGlynn, & Bernhardt, 2016), is virtually non-existent in the tropics. It is very likely that the processing rates and even the mechanisms known to affect aquatic ecosystems in temperate regions via agricultural runoff, point-source pollution, or mining are not directly transferable to tropical environments in Latin America due to the increased and relatively constant solar radiation, the lack of a marked winter season, the relative higher temperature and rainfall, and the differences in seasonality (dry vs. rainy seasons). In a sharp contrast with the highly regulated water reclamation systems employed in developed countries, wastewater is poorly managed in tropical Latin America and more than 85% of human waste is dumped in rivers, lakes, or groundwater without any form of treatment (United Nations Development Programme, 2006). This represents a challenge not only for the communities living downstream but also for our understanding of biochemical processes as mass balances are far less constrained due to the unregulated inputs and outputs (e.g., Miserendino, Brand, & Di Prinzio, 2008).

Synoptic studies and chemical comparisons are commonly reported in the literature of mountainous regions in temperate systems (e.g., Inyan & Williams, 2001; Mast, Murphy, Clow, Penn, & Sexstone, 2016; Royall & Kennedy, 2016), but they have been rarely reported for mountainous streams in tropical regions. Although monitoring data are considered the base of management decisions in the tropics (Castello et al., 2013), the lack of consistent monitoring programmes often forces researchers and decision makers to use surrogates for water quality in high-elevation regions (including satellite imagery as a measure of erosion and soil loss [Wantzen & Mol, 2013] and percent ground cover as a proxy for water quality states [Oyague Passuni & Maldonado Fonkén, 2014]). Few journal-published studies have examined chemical effects of land-use change in páramos (Farley, Kelly, & Hofstede, 2004; Peña-Quemba et al., 2016), and their observations have mostly focused on soil quality and soil C losses, but not water quality. We suggest that synoptic water sampling and targeted experimental work (as described below) can provide a useful path towards understanding system dynamics in locations where rapid assessments are necessary and long-term data are either limited or simply non-existent.

4.2 | Dynamics of dissolved CO_2 and potential for CO_2 evasion

The observed pCO_2 dynamics are likely dominated by (a) primary production and metabolism in the wetland and (b) turbulent mixing in the stream channel (Figure 4). Wetland photosynthesis appears to drive the rapid daytime decrease in pCO_2, whereas night-time respiration is likely responsible for the diel increase of pCO_2. The relatively low temperatures of páramos (Hofstede, 1995) combined with the high organic content of soils (Hribljan et al., 2017) facilitate that wetland pCO_2 concentrations at this site reach three times the concentrations of atmospheric CO_2. Turbulent mixing in the stream channel appears to drive the rapid degassing that results in considerably lower pCO_2 concentrations just 250 m downstream of the wetland outlet (Figure 4a; recall that we estimated that water along the stream channel flows ~46× faster than along the wetland) and hampers the diel build-up of pCO_2 observed in the wetland.

The hysteretic relationship observed between paired, upstream–downstream pCO_2 measurements suggests non-linear hydrologic controls on the reactivity of the system. It is likely that if travel times were shorter—such as during wetter times of the year—hysteresis would disappear because the system becomes more connected and reaction and transport timescales become much more similar. Analogous hysteresis analysis in soil CO_2 demonstrated that the magnitude of hysteresis loops is indicative of the wetness status of the system, given that water content is correlated with the CO_2 diffusivity and this is a mechanism by which CO_2 is removed from the soil (Riveros-Iregui et al., 2007; Riveros-Iregui, McGlynn, Epstein, & Welsch, 2008). The same studies suggest that analysis of hysteresis in CO_2 at various times of the year may yield insight into the relative magnitudes of *production* and *transport* of CO_2 at diel and seasonal time scales. Thus, we suggest that examining paired upstream–downstream dynamics of variables such as pCO_2 can allow for deeper examination of production/uptake and transport of tropical streams, and the role of these streams in the transformation of dissolved nutrients.

Finally, recent studies have highlighted the contribution of headwater streams to the carbon cycle via outgassing from rivers, lakes, reservoirs, and stream sediments (Marx et al., 2017). Given their large proportion among all rivers in a network, headwater streams are known to contribute large amounts of CO_2 (Crawford, Stanley, Dornblaser, & Striegl, 2017) and CH_4 (Crawford et al., 2017) to the atmosphere. These fluxes remain virtually unknown in páramos, where soils are known to have carbon contents even >40% (Comas et al., 2017; Hribljan et al., 2017; Peña-Quemba et al., 2016). Carbon cycling dynamics in these high-elevation landscapes are likely to be important to both regional and global carbon cycles and represent a knowledge gap in Latin American science. Our data suggest that most of the outgassing in wetland systems occurs near the stream–wetland interface, where the pCO_2-enriched water coming out of the wetland undergoes turbulent mixing.

4.3 | Stream metabolism and nutrient retention potential

As shown in Figure 1, studies on stream metabolism and nutrient transformation in Latin America are severely lacking and are essentially non-existing in high-elevation regions. Our tracer injections of the bioreactive tracer Raz sheds light on stream metabolism dynamics of the unexplored páramo and provides additional information to help explain the differences in wetland versus stream CO_2 dynamics. Figure 5a shows that the transformation rate of the tracer (a proxy for aerobic respiration) is low in the stream channel, likely due to environmental conditions at the site (elevation at point of injection was 3,540 m.a.s.l., mean annual temperature = 2 °C) and short residence times. Travel times and dispersion increase significantly across the wetland (cf. slower, less steep, tracer rising limb), favouring the interaction between the metabolic tracer and bacteria in the presence of abundant particulate and dissolved organic matter. Our analysis has the potential to represent a range of metabolism dynamics in alpine tropical ecosystems of Latin America, where hydrologic buffering is high due to thick soils, high soil organic content, and short vegetative cover (e.g., shrubs and bryophytes). More importantly, the conceptual understanding derived from this analysis—namely, the apparently inverse correlation between travel times dynamics and metabolism rates—could be tested across a number of sites of contrasting land use to improve our understanding of the feedbacks between physical and biological processes in alpine tropical regions of Latin America.

5 | CALL FOR A SYSTEMATIC IMPLEMENTATION OF RAPID ASSESSMENTS IN LATIN AMERICA: CHALLENGES AND OPPORTUNITIES

Water quality monitoring is typically done using two approaches: (a) observations over time at a single site (Eulerian monitoring) and (b) observations across space, representative of a short time window (Lagrangian monitoring). Eulerian monitoring helps us understand the average response of fluvial parameters (e.g., stream discharge and nutrient concentrations) to upstream events (e.g., precipitation, spills, and forest fires), ranging from hours to decades. Eulerian monitoring can be done continuously (or semicontinuously) using dedicated sensors deployed at a site (Figure 6a) or through rapid assessments (Figure 6b). The frequency of the rapid assessment campaigns defines the resolution of the type of events that can be monitored (e.g., short-term response to spills, seasonality and multiyear trends) and how such monitoring compares with continuous monitoring (i.e., higher monitoring frequency results in shorter signal gaps). Whereas both continuous and rapid assessment sampling can be used to characterize the system's response to known disturbances (e.g., tracer injections or anticipated effluent discharge events), continuous monitoring offers intrinsic advantages to learning about unexpected or previously undocumented system responses to environmental disturbances, provided that the signals being tracked by the sensors are properly corrected for false positives (Bergamaschi et al., 2014; Downing, Pellerin, Bergamaschi, Saraceno, & Kraus, 2012; Saraceno, Shanley, Downing, & Pellerin, 2017). Continuous monitoring can provide insight into biogeochemical dynamics at the scale of single events, but it remains cost-prohibitive for many research programmes throughout the world. A single NO_3 sensor could be used to monitor only one dedicated site in an Eulerian monitoring framework. Paradoxically, such sensor alone would likely only provide incomplete information at an almost continuous frequency, making it harder to interpret data and develop new mechanistic understanding.

Several types of observations could be performed during rapid assessments, and the techniques chosen should match the questions

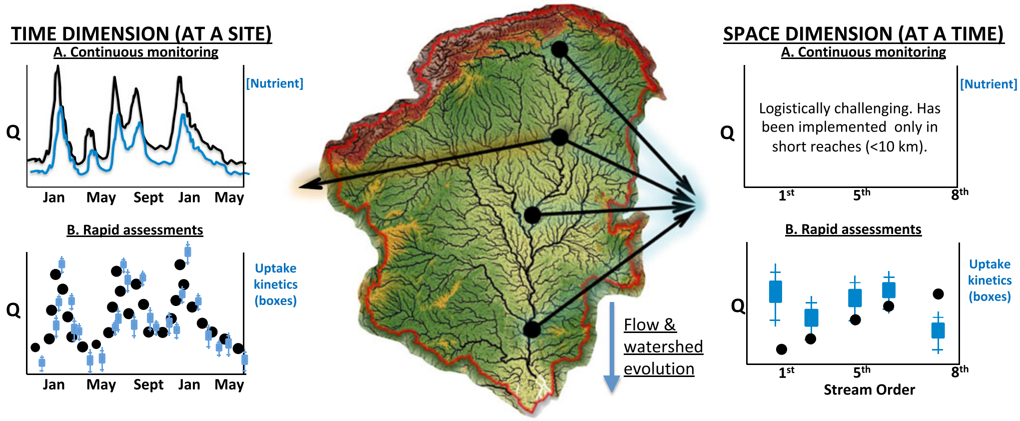

FIGURE 6 Conceptual diagram of continuous monitoring compared with rapid assessments in the time dimension (at a site; Eulerian monitoring) and space dimension (in a short time scale; Lagrangian monitoring)

being addressed. Here, we suggest a few assessments that hold exceptional promise to yield new insights in this data-scarce region and could represent cost-effective investments in hydrologic research across climatic and geomorphological gradients of Latin America. First, due to the intense and fast transformation of watersheds via agriculture and mining in Latin America, understanding the spatiotemporal variability of aquatic N and P and associated reaction rates in the stream network (e.g., Cheng & Basu, 2017), and the transport and fate of heavy dissolved metals (e.g., Kalbitz & Wennrich, 1998), is of paramount importance especially within highly connected water bodies (e.g., wetland–stream transitions). Similarly, assessing changes of CO_2 and CH_4 fluxes across the terrestrial–aquatic interface, including their vertical (i.e., to the atmosphere) and lateral (i.e., downstream) components, has been recently highlighted in the literature as a grand challenge and opportunity to understand the role of land use and climate changes in sensitive ecosystems (Tank, Fellman, Hood, & Kritzberg, in press). These experiments should be performed across contrasting sites with various flows, geology, and land uses (e.g., Hinckley, Ebel, Barnes, Murphy, & Anderson, 2017). In the absence of semicontinuous monitoring networks or programmes, repetitive (over time) short-term tracer experiments can become a powerful tool to assess travel time distributions or flushing times (e.g., Rinaldo et al., 2011), or the processing rates and self-purification capacities in tropical environments. All these observations could be achieved using automated sensors that are readily deployable or via synoptic and discrete sample collection, thereby maximizing data collection capacity of single or multiple research teams.

Throughout this paper, we have highlighted the benefits of rapid assessments to advance hydrologic research in Latin America and in other regions where monitoring networks are not available. We present three case studies using rapid assessments conducted in the high-elevation mountains of Colombia. Our results represent an initial examination of the effects of land-use change on stream nutrient dynamics in one of the most biodiverse and threatened ecosystems on Earth (Madriñán, Cortés, & Richardson, 2013), considered the leading edge of climate change in the tropics (Williams, Jackson, & Kutzbacht, 2007). Our experience in the region demonstrates that rapid assessments not only are necessary but also represent a cost-effective, practical step towards developing long-term research in Latin America and may represent a path towards establishing research networks in the region. Rapid assessments may be a way to develop and nurture a relationship with local communities that can benefit from long-term environmental monitoring (e.g., Arias et al., 2015; Zamudio-Rodriguez, 2012) while providing evidence to help communities address their own challenges in the management of water resources.

ACKNOWLEDGMENTS

We thank the Alméciga Family for site access; and Rebecca Chaisson, Adam Gold, and Jacob Mortensen for lab and field support. This work was partially supported by the Administrative Department of Science, Technology, and Innovation of Colombia (COLCIENCIAS) under the Diaspora Program. We thank the members of the Carbonshed Lab at UNC for suggestions on an earlier version of this manuscript. Three reviewers and the HP editor provided valuable suggestions for the improvement of this manuscript.

AUTHOR CONTRIBUTIONS

All authors contributed equally to the conception, design, data acquisition, analysis, and writing of this manuscript.

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REFERENCES

Abbott, B. W., Gruau, G., Zarnetske, J. P., Moatar, F., Barbe, L., Thomas, Z., … Pinay, G. (2018). Unexpected spatial stability of water chemistry in headwater stream networks. *Ecology Letters*, *21*(2), 296–308. https://doi.org/10.1111/ele.12897

Arias, P. A., Villegas, J. C., Machado, J., Serna, A. M., Vidal, L. M., Vieira, C., … Mejía, Ó. A. (2015). Reducing social vulnerability to environmental change: Building trust through social collaboration on environmental monitoring. *Weather, Climate, and Society*, *8*(1), 57–66. https://doi.org/10.1175/WCAS-D-15-0049.1

Asbjornsen, H., Goldsmith, G. R., Alvarado-Barrientos, M. S., Rebel, K., Van Osch, F. P., Rietkerk, M., … Dawson, T. E. (2011). Ecohydrological advances and applications in plant-water relations research: A review. *Journal of Plant Ecology*, *4*(1–2), 3–22.

Asbjornsen, H., Mason, R. H., Scullion, J. J., Holwerda, F., Muñoz-Villers, L. E., Dawson, T. E., … Bruijnzeel, L. A. (2017). Interactions between payments for hydrologic services, landowner decisions, and ecohydrological consequences: Synergies and disconnection in the cloud forest zone of central Veracruz, Mexico. *Ecology and Society*, *22*(2), 25. https://doi.org/10.5751/ES-09144-220225

Bergamaschi, B., Downing, B., Pellerin, B., Saraceno, J. F., Fleck, J., Kraus, T., … Fujii, R. (2014). Use of optical measurements for understanding and quantifying biogeochemical processes. *Abstracts of Papers of the American Chemical Society*, *248*, 1.

Bernhardt, E. S., Heffernan, J. B., Grimm, N. B., Stanley, E. H., Harvey, J. W., Arroita, M., … Yackulic, C. B. (2018). The metabolic regimes of flowing waters. *Limnology and Oceanography*, *63*(S1), S99–S118. https://doi.org/10.1002/lno.10726

Boulton, A. J., Boyero, L., Covich, A. P., Dobson, M., Lake, S., & Pearson, R. (2008). Are tropical streams ecologically different from temperate streams. In D. Dudgeon (Ed.), *Tropical stream ecology* (pp. 257–284). Burlington, MA: Academic Press.

Bruijnzeel, L. A., Mulligan, M., & Scatena, F. N. (2011). Hydrometeorology of tropical montane cloud forests: Emerging patterns. *Hydrological Processes*, *25*(3), 465–498.

Buytaert, W., Celleri, R., De Bievre, B., Cisneros, F., Wyseure, G., Deckers, J., & Hofstede, R. (2006). Human impact on the hydrology of the Andean paramos. *Earth-Science Reviews*, *79*(1–2), 53–72.

Buytaert, W., & De Bièvre, B. (2012). Water for cities: The impact of climate change and demographic growth in the tropical Andes. *Water Resources Research*, *48*(8). n/a-n/a. https://doi.org/10.1029/2011WR011755

Carpenter, S. R., Ludwig, D., & Brock, W. A. (1999). Management of eutrophication for lakes subject to potentially irreversible change. *Ecological Applications*, *9*(3), 751–771.

Castello, L., McGrath, D. G., Hess, L. L., Coe, M. T., Lefebvre, P. A., Petry, P., … Arantes, C. C. (2013). The vulnerability of Amazon freshwater ecosystems. *Conservation Letters*, *6*(4), 217–229. https://doi.org/10.1111/conl.12008

Célleri, R., & Feyen, J. (2009). The hydrology of tropical Andean ecosystems: Importance, knowledge status, and perspectives. *Mountain Research and Development*, *29*(4), 350–355. https://doi.org/10.1659/mrd.00007

Cheng, F. Y., & Basu, N. B. (2017). Biogeochemical hotspots: Role of small water bodies in landscape nutrient processing. *Water Resources Research*, *53*(6), 5038–5056. https://doi.org/10.1002/2016WR020102

Chessman, B. C. (1995). Rapid assessment of rivers using macroinvertebrates: A procedure based on habitat-specific sampling, family level identification and a biotic index. *Australian Journal of Ecology*, *20*(1), 122–129. https://doi.org/10.1111/j.1442-9993.1995.tb00526.x

Comas, X., Terry, N., Hribljan, J. A., Lilleskov, E. A., Suarez, E., Chimner, R. A., & Kolka, R. K. (2017). Estimating belowground carbon stocks in peatlands of the Ecuadorian páramo using ground-penetrating radar (GPR). *Journal of Geophysical Research: Biogeosciences*, *122*(2), 370–386. https://doi.org/10.1002/2016JG003550

Cox, B. A. (2003). A review of dissolved oxygen modelling techniques for lowland rivers. *Science of the Total Environment*, *314-316*, 303–334. https://doi.org/10.1016/S0048-9697(03)00062-7

Crawford, J. T., Loken, L. C., West, W. E., Crary, B., Spawn, S. A., Gubbins, N., … Stanley, E. H. (2017). Spatial heterogeneity of within-stream methane concentrations. *Journal of Geophysical Research: Biogeosciences*, *122*(5), 1036–1048. https://doi.org/10.1002/2016JG003698

Crawford, J. T., Stanley, E. H., Dornblaser, M. M., & Striegl, R. G. (2017). CO2 time series patterns in contrasting headwater streams of North America. *Aquatic Sciences*, *79*(3), 473–486. https://doi.org/10.1007/s00027-016-0511-2

Dillon, P. J., & Molot, L. A. (1997). Effect of landscape form on export of dissolved organic carbon, iron, and phosphorus from forested stream catchments. *Water Resources Research*, *33*(11), 2591–2600. https://doi.org/10.1029/97WR01921

Downing, B. D., Pellerin, B. A., Bergamaschi, B. A., Saraceno, J. F., & Kraus, T. E. C. (2012). Seeing the light: The effects of particles, dissolved materials, and temperature on in situ measurements of DOM fluorescence in rivers and streams. *Limnology and Oceanography-Methods*, *10*, 767–775. https://doi.org/10.4319/lom.2012.10.767

FAO (2003), Review of the world water resources by country. Food and Agriculture Organization of the United Nations Rep., FAO Technical Paper, vol. 23., Rome.

Farley, K. A., Kelly, E. F., & Hofstede, R. G. M. (2004). Soil organic carbon and water retention following conversion of grasslands to pine plantations in the Ecuadoran Andes. *Ecosystems*, *7*(7), 729–739.

Fennessy, M. S., Jacobs, A. D., & Kentula, M. E. (2007). An evaluation of rapid methods for assessing the ecological condition of wetlands. *Wetlands*, *27*(3), 543–560. https://doi.org/10.1672/0277-5212(2007)27%5B543:AEORMF%5D2.0.CO;2

González-Pinzón, R., Haggerty, R., & Myrold, D. D. (2012). Measuring aerobic respiration in stream ecosystems using the resazurin-resorufin system. *Journal of Geophysical Research: Biogeosciences*, *117*(G3). G00N06. https://doi.org/10.1029/2012JG001965

González-Pinzón, R., Haggerty, R., & Argerich, A. (2014). Quantifying spatial differences in metabolism in headwater streams. *Freshwater Science*, *33*(3), 798–811. https://doi.org/10.1086/677555

Gotsch, S. G., Asbjornsen, H., Holwerda, F., Goldsmith, G. R., Weintraub, A. E., & Dawson, T. E. (2014). Foggy days and dry nights determine crown-level water balance in a seasonal tropical montane cloud forest. *Plant Cell and Environment*, *37*(1), 261–272.

Grau, H. R., & Aide, M. (2008). Globalization and land-use transitions in Latin America. *Ecology and Society*, *13*(2). art 16

Haggerty, R., Argerich, A., & Martí, E. (2008). Development of a "smart" tracer for the assessment of microbiological activity and sediment-water interaction in natural waters: The resazurin-resorufin system. *Water Resources Research*, *44*, 1–10.

Hamel, P., Riveros-Iregui, D., Ballari, D., Browning, T., Célleri, R., Chandler, D., … Rocha, H. (2017). Watershed services in the humid tropics: Opportunities from recent advances in ecohydrology. *Ecohydrology*, e1921. https://doi.org/10.1002/eco.1921

Heffernan, J. B., & Cohen, M. J. (2010). Direct and indirect coupling of primary production and diel nitrate dynamics in a subtropical spring-fed river. *Limnology and Oceanography*, *55*(2), 677–688. https://doi.org/10.4319/lo.2010.55.2.0677

Hewlett, J. D., & Hibbert, A. R. (1967). Factors affecting the response of small watersheds to precipitation in humid areas. In W. E. Sopper, & H. W. Lull (Eds.), *Forest hydrology* (pp. 275–291). New York: Pergamon Press.

Hinckley, E.-L. S., Ebel, B. A., Barnes, R. T., Murphy, S. F., & Anderson, S. P. (2017). Critical zone properties control the fate of nitrogen during experimental rainfall in montane forests of the Colorado Front Range. *Biogeochemistry*, *132*(1), 213–231. https://doi.org/10.1007/s10533-017-0299-8

Hofstede, R. G. M. (1995). The effects of grazing and burning on soil and plant nutrient concentrations in Colombian páramo grasslands. *Plant and Soil*, *173*, 111–132.

Horton, R. E. (1933). The role of infiltration in the hydrologic cycle. *Transactions of the American Geophysical Union*, *14*, 446–460.

Hribljan, J. A., Suarez, E., Bourgeau-Chavez, L., Endres, S., Lilleskov, E. A., Chimbolema, S., … Chimner, R. A. (2017). Multidate, multisensor remote sensing reveals high density of carbon-rich mountain peatlands in the páramo of Ecuador. *Global Change Biology*, *23*(12), 5412–5425. https://doi.org/10.1111/gcb.13807

Hribljan, J. A., Suárez, E., Heckman, K. A., Lilleskov, E. A., & Chimner, R. A. (2016). Peatland carbon stocks and accumulation rates in the Ecuadorian páramo. *Wetlands Ecology and Management*, *24*(2), 113–127. https://doi.org/10.1007/s11273-016-9482-2

Hu, J., & Riveros-Iregui, D. A. (2016). Life in the clouds: Are tropical montane cloud forests responding to changes in climate? *Oecologia*, *180*(4), 1061–1073. https://doi.org/10.1007/s00442-015-3533-x

IAvH (2012), Proyecto: Actualización del Atlas de Páramos de Colombia. Convenio Interadministrativo de Asociación 11–103, Instituto de investigación de recursos biológicos Alexander von Humbold y Ministerio de Ambiente y Desarrollo Sostenible. Esc 1:100.000. Bogotá D.C. Colombia.

Inyan, B. J., & Williams, M. W. (2001). Protection of headwater catchments from future degradation: San Miguel River Basin, Colorado. *Mountain Research and Development*, *21*(1), 54–60. https://doi.org/10.1659/0276-4741%20(2001)021%5B0054:POHCFF%5D2.0.CO;2

Jackson, R. B., Vengosh, A., Carey, J. W., Davies, R. J., Darrah, T. H., O'Sullivan, F., & Pétron, G. (2014). The environmental costs and benefits of fracking. *Annual Review of Environment and Resources*, *39*(1), 327–362. https://doi.org/10.1146/annurev-environ-031113-144051

Kalbitz, K., & Wennrich, R. (1998). Mobilization of heavy metals and arsenic in polluted wetland soils and its dependence on dissolved organic matter. *Science of the Total Environment*, *209*(1), 27–39. https://doi.org/10.1016/S0048-9697(97)00302-1

Karr, J. R., & Dudley, D. R. (1981). Ecological perspective on water quality goals. *Environmental Management*, *5*(1), 55–68. https://doi.org/10.1007/BF01866609

Lovett, G. M., Burns, D. A., Driscoll, C. T., Jenkins, J. C., Mitchell, M. J., Rustad, L., … Haeuber, R. (2007). Who needs environmental monitoring? *Frontiers in Ecology and the Environment*, *5*(5), 253–260. https://doi.org/10.1890/1540-9295(2007)5%5B253:WNEM%5D2.0.CO;2

Madriñán, S., Cortés, A. J., & Richardson, J. E. (2013). Páramo is the world's fastest evolving and coolest biodiversity hotspot. *Frontiers in Genetics*, *4*, 192. https://doi.org/10.3389/fgene.2013.00192

Marx, A., Dusek, J., Jankovec, J., Sanda, M., Vogel, T., van Geldern, R., … Barth, J. A. C. (2017). A review of CO2 and associated carbon dynamics in headwater streams: A global perspective. *Reviews of Geophysics*, *55*(2), 560–585. https://doi.org/10.1002/2016RG000547

Mast, M. A., Murphy, S. F., Clow, D. W., Penn, C. A., & Sexstone, G. A. (2016). Water-quality response to a high-elevation wildfire in the Colorado Front Range. *Hydrological Processes*, *30*(12), 1811–1823. https://doi.org/10.1002/hyp.10755

Miserendino, M. L., Brand, C., & Di Prinzio, C. Y. (2008). Assessing urban impacts on water quality, benthic communities and fish in streams of the Andes Mountains, Patagonia (Argentina). *Water, Air, and Soil Pollution*, *194*(1), 91–110. https://doi.org/10.1007/s11270-008-9701-4

Moore, G. W., Orozco, G., Aparecido, L. M. T., & Miller, G. R. (in press). Upscaling transpiration in diverse forests: Insights from a tropical premontane site. *Ecohydrology*, e1920. n/a. https://doi.org/10.1002/eco.1920

Moreno-Torres, R. R., & Ruiz-Rodriguez, A. J. (2016). Recopilación Documental del Estado Actual del Ecosistema Altoandino Páramo de Guerrero (Zipaquirá–Cundinamarca), 113 pp, Universidad Distrital Francisco José De Caldas, Bogota, D.C.

O'Connor, D. J. (1967). The temporal and spatial distribution of dissolved oxygen in streams. *Water Resources Research*, *3*(1), 65–79. https://doi.org/10.1029/WR003i001p00065

Ogden, F. L., & Stallard, R. F. (2013). Land use effects on ecosystem service provisioning in tropical watersheds, still an important unsolved problem. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(52), E5037–E5037.

Otero, J. D., Figueroa, A., Muñoz, F. A., & Peña, M. R. (2011). Loss of soil and nutrients by surface runoff in two agro-ecosystems within an Andean paramo area. *Ecological Engineering*, *37*(12), 2035–2043. https://doi.org/10.1016/j.ecoleng.2011.08.001

Oyague Passuni, E., & Maldonado Fonkén, M. S. (2014/15). Relationships between aquatic invertebrates, water quality and vegetation in an Andean peatland system. *Mires and Peat*, *Art*, *14*, 1–21.

Peña-Quemba, D. C., Rubiano-Sanabria, Y., & Riveros-Iregui, D. A. (2016). Effects of land use on soil CO2 flux in the Paramo de Guerrero, Colombia. *Agronomia Colombiana*, *34*(3), 364–373. https://doi.org/10.15446/agron.colomb.v34n3.58791

Penman, H. L. (1948). Natural evaporation from open water, hare soil and grass. *Proceedings of the Royal Society of London. Series a, Containing Papers of a Mathematical and Physical Character*, *193*(1032), 120–145. https://doi.org/10.1098/rspa.1948.0037

Rinaldo, A., Beven, K. J., Bertuzzo, E., Nicotina, L., Davies, J., Fiori, A., … Botter, G. (2011). Catchment travel time distributions and water flow in soils. *Water Resources Research*, *47*(7). n/a-n/a, https://doi.org/10.1029/2011WR010478

Riveros-Iregui, D. A., Emanuel, R. E., Muth, D. J., McGlynn, B. L., Epstein, H. E., Welsch, D. L., … Wraith, J. M. (2007). Diurnal hysteresis between soil CO2 and soil temperature is controlled by soil water content. *Geophysical Research Letters*, *34*, L17404. https://doi.org/10.1029/2007GL030938

Riveros-Iregui, D. A., McGlynn, B. L., Epstein, H. E., & Welsch, D. L. (2008). Interpretation and evaluation of combined measurement techniques for soil CO2 efflux: Discrete surface chambers and continuous soil CO2 concentration probes. *Journal of Geophysical Research*, *113*, G04027. https://doi.org/10.1029/2008JG000811

Ross, M. R. V., McGlynn, B. L., & Bernhardt, E. S. (2016). Deep impact: Effects of mountaintop mining on surface topography, bedrock structure, and downstream waters. *Environmental Science & Technology*, *50*(4), 2064–2074. https://doi.org/10.1021/acs.est.5b04532

Royall, D., & Kennedy, L. (2016). Historical erosion and sedimentation in two small watersheds of the southern Blue Ridge Mountains, North Carolina, USA. *Catena*, *143*, 174–186. https://doi.org/10.1016/j.catena.2016.03.020

Sanchez, A., Posada, J. M., & Smith, W. K. (2014). Dynamic cloud regimes, incident sunlight, and leaf temperatures in Espeletia grandiflora and Chusquea tessellata, two representative species of the Andean Páramo, Colombia. *Arctic, Antarctic, and Alpine Research*, *46*, 371–378. https://doi.org/10.1657/1938-4246-46.2.371

Saraceno, J. F., Shanley, J. B., Downing, B. D., & Pellerin, B. A. (2017). Clearing the waters: Evaluating the need for site-specific field fluorescence corrections based on turbidity measurements. *Limnology and Oceanography-Methods*, *15*(4), 408–416. https://doi.org/10.1002/lom3.10175

Scanlon, B. R., Jolly, I., Sophocleous, M., & Zhang, L. (2007). Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. *Water Resources Research*, *43*(3). https://doi.org/10.1029/2006WR005486

Scheren, P. A. G. M., Zanting, H. A., & Lemmens, A. M. C. (2000). Estimation of water pollution sources in Lake Victoria, East Africa: Application and elaboration of the rapid assessment methodology. *Journal of Environmental Management*, *58*(4), 235–248. https://doi.org/10.1006/jema.2000.0322

Scholl, M. A., Eugster, W., & Burkard, R. (2011). Understanding the role of fog in forest hydrology: Stable isotopes as tools for determining input and partitioning of cloud water in montane forests. *Hydrological Processes*, *25*(3), 353–366.

Tank, S. E., Fellman, J. B., Hood, E., & Kritzberg, E. S. (in press). Beyond respiration: Controls on lateral carbon fluxes across the terrestrial-aquatic interface. *Limnology and Oceanography Letters*. n/a-n/a, https://doi.org/10.1002/lol2.10065

Tetzlaff, D., Carey, S. K., McNamara, J. P., Laudon, H., & Soulsby, C. (2017). The essential value of long-term experimental data for hydrology and water management. *Water Resources Research*, *53*(4), 2598–2604. https://doi.org/10.1002/2017WR020838

Toro, J., Requena, I., & Zamorano, M. (2010). Environmental impact assessment in Colombia: Critical analysis and proposals for improvement. *Environmental Impact Assessment Review*, *30*(4), 247–261. https://doi.org/10.1016/j.eiar.2009.09.001

UNDP (2006), United Nations Development Programme (2006). Human development report. Beyond scarcity: Power, poverty, and the global water crisis. ISBN 0-230-50058-7Rep.

Veblen, T. T., Young, K. R., & Orme, A. R. (2007). *The physical geography of South America*. (p. 360)Oxford University Press.

Wantzen, M. K., & Mol, H. J. (2013). Soil erosion from agriculture and mining: A threat to tropical stream ecosystems. *Agriculture*, *3*(4), 660–683. https://doi.org/10.3390/agriculture3040660

Williams, J. W., Jackson, S. T., & Kutzbacht, J. E. (2007). Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(14), 5738–5742. https://doi.org/10.1073/pnas.0606292104

Winter, T. C., Harvey, J. W., Franke, O. L., & Alley, W. M. (1998). *Ground water and surface water a single resource*, USGS Circular 1139 *Rep. 1139*. (p. 79). Denver, CO: United States Geological Survey.

Zamudio-Rodriguez, C. (2012). Governance of water resources in Colombia. *Revista Gestión Y Ambiente*, *3*, 99–112.

How to cite this article: Riveros-Iregui DA, Covino TP, González-Pinzón R. The importance of and need for rapid hydrologic assessments in Latin America. *Hydrological Processes*. 2018;32:2441–2451. https://doi.org/10.1002/hyp.13163