

# The hydrology of the humid tropics

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**Hydrological processes in the humid tropics differ from other regions in having greater energy inputs and faster rates of change, including human-induced change. Human influences on population growth, land use and climate change will profoundly influence tropical hydrology, yet understanding of key hydrological interactions is limited. We propose that efforts to collect tropical data should explicitly emphasize characterizing moisture and energy fluxes from below the ground surface into the atmosphere. Research needs to chiefly involve field-based characterizations and modelling of moisture cycling and catchment processes, as well as long-term data acquisition and organization.**

Fresh water is under pressure in the humid tropics from population growth, land use and climate change, all of which are influenced by humans. These pressures are likely to have profound consequences. Here we present a research vision for the humid tropics as an outcome of a community workshop held in Hawaii in March 2011. This report includes various perspectives from the international scientific community and examines the key role that hydrology plays in the functioning of the humid tropics in this age of human impact on all facets of the natural environment. Processes that operate within the hydrological cycle are expected to accelerate as temperatures rise and the capacity of the air to carry moisture increases. Understanding of key interactions is limited geographically and relies heavily on model-based scenarios rather than observations. Better understanding of interactions within the hydrological cycle is needed for the hydrological community to actively address adaptation and mitigation strategies for anthropogenic and climate changes. Of particular concern are interactions among atmospheric moisture fluxes and vegetation, soil water and energy balances, near-surface and subsurface processes (including groundwater resources), and stream flow and the transport of solutes and sediments (Fig. 1).

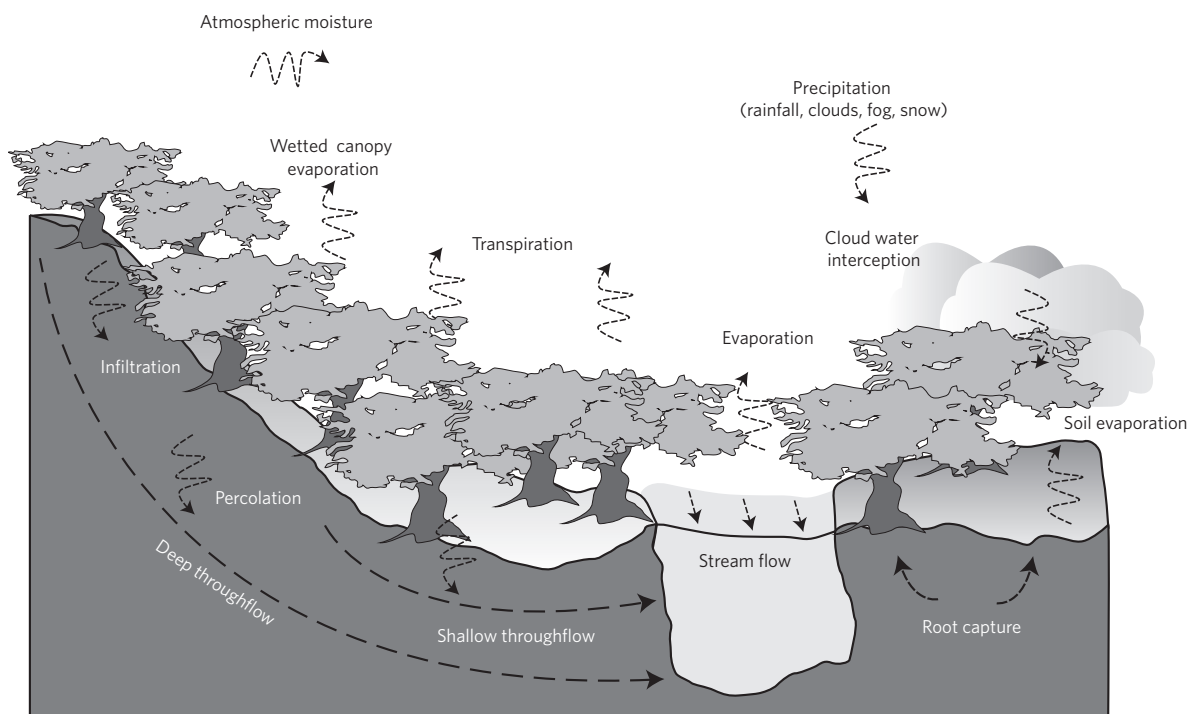
Here we outline the state of knowledge, highlight critical research needs and suggest research strategies that would aid understanding of hydrology in the humid tropics in the context of rapidly changing environmental conditions. We identify three main research needs related to: (1) moisture cycling — we call for more explicit attention to integrated measuring, modelling and understanding of water fluxes across the land–atmosphere continuum; (2) catchment processes — we highlight the need for a clear understanding of how human landscape alterations affect evapotranspiration and runoff ratio in diverse environments, as well as the need for more information on biogeochemical cycling; and (3) long-term data acquisition and organization — we call for integrative field campaigns that

simultaneously capture moisture dynamics from the deep subsurface through the troposphere, including long-term monitoring.

## The dynamic environment of the humid tropics

The humid tropics lie between the Equator and 25° in both the Northern and Southern Hemispheres, and include areas in which precipitation exceeds evaporation for at least 270 days per year. Convergence of surface trade-wind easterlies and equatorial westerlies within the humid tropics creates deep convection, as well as cyclonic vorticity conducive to tropical cyclogenesis. The humid tropics cover one-fifth of the global land surface, produce the greatest amount of runoff<sup>1</sup> and are subject to the greatest intensity of land-cover disturbance through forest cutting<sup>2</sup>. The atmospheric component of the hydrological cycle in the humid tropics involves processes spanning a wide range of spatial and temporal scales<sup>3</sup>. These include (1) features of the global circulation such as the Hadley cell, multi-decadal oscillations (for example, the Pacific Decadal Oscillation), multi-annual regional circulations (for example, the El Niño/Southern Oscillation), regional monsoon dynamics, and mesoscale circulations such as land–sea breezes, orographic flows and precipitation; (2) local land–atmosphere cycling of mass and energy, which are influenced by surface roughness, albedo and emissivity, soil moisture dynamics, and thus energy balance partitioning; and (3) microscale phenomena such as the microphysics of interactions between aerosols and clouds, and evaporation from soil pores and plant stomata. Over land, intense convection above rainforests (Amazon, Congo, the maritime subcontinent of the Indo-Malayan archipelago and northern Australia) and atmospheric latent heating along mountain ranges large and small (Andes, Himalayas, Annam Highlands) are on a par with the Intertropical Convergence Zone in terms of forcing, and show large interannual variability<sup>4</sup>. Tropical mountains play an important part in modulating and harvesting atmospheric moisture. Nearly 1.4 billion people

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**Figure 1 | Schematic view of the tropical hydrological cycle with water fluxes represented by dashed lines.** Shallow throughflow is typically activated during storm events and can occur through a variety of means, including pipe flow. Surface runoff and periodic lowland flooding are not pictured. The fluxes illustrated here are present in temperate environments, but the magnitude and rate of these fluxes are typically greater in humid tropical environments. The variety of fluxes shown here reinforces the need for integrated measurement and modelling efforts, as well as the complexity and interconnectedness of potential responses to climate and land-cover changes.

rely on water supplied by the main rivers of southeast Asia, for example, much of which comes directly from orographic precipitation<sup>5</sup>. Atmospheric moisture cycling in the humid tropics is distinguished from that in the midlatitudes by its much warmer and uniform temperatures, large interannual and subseasonal variability and the intensity and pronounced spatial gradients of precipitation, and its impact on water and terrestrial material fluxes, especially river flows and sediment transport<sup>6</sup>. For example, annual precipitation in the West Maui Mountains of Hawaii has been observed to vary by up to 1,000 mm per 1 km horizontally and more than 500 mm per 100 m change in elevation<sup>7</sup>.

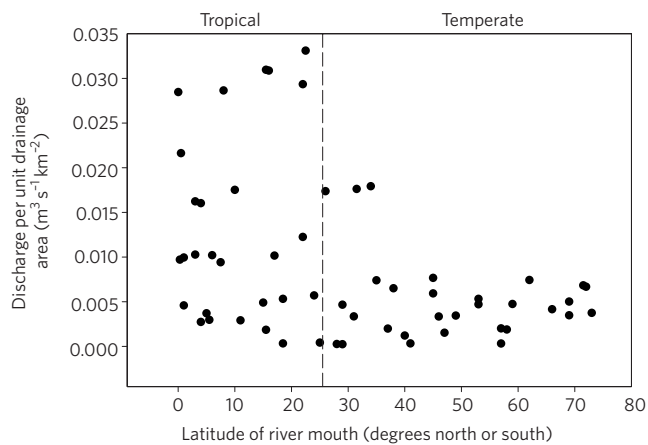
Flows of water and related exchanges of energy and carbon over land areas are tightly bound to the amount, functional type, age and density of vegetation. Tropical land cover is highly dynamic owing to rapidly shifting patterns of land use<sup>8</sup>. Although tropical land cover produces important feedbacks to climate and water fluxes at local to global scales<sup>9</sup>, increases in carbon dioxide and resulting global climate change also influence tropical vegetation<sup>10</sup>. General circulation model scenarios of future climate changes suggest contrasting responses across the tropics, such as drying in the Amazon Basin and increases in precipitation intensity in East Africa<sup>11</sup>. The latter could have profound geomorphic and hydrological implications (for example, soil erosion), which might undercut any gain in agricultural productivity associated with increases in precipitation amounts.

Compared with humid temperate zones, the humid tropics are characterized by greater energy inputs in the form of fluxes of water vapour from the midlatitudes, more intense precipitation, rapid weathering of inorganic and organic material, and rapid introduction of large volumes of water and sediment<sup>12–19</sup>. Soil-forming factors in the tropics do not differ from the temperate zones, but tropical soils can develop distinct characteristics due to differences in climate, flora and fauna<sup>20</sup>. Downstream and channel-floodplain

fluxes of water, solids, dissolved solutes and organic carbon also show proportionally greater rates and magnitudes than comparable streams in the temperate zones<sup>13,14,21–23</sup> (Fig. 2).

### Anthropogenic modifications in the humid tropics

Population pressure in developing countries has led to increasing fragmentation of land cover, with consequent effects on hydrological fluxes<sup>24,25</sup>. Humans continue to alter mass and energy cycling across all spatial and temporal scales, but the intensity of these modifications increases with decreasing spatial scale, becoming most pronounced at the level of local land use and point source emissions. Figure 3 shows the relatively high evapotranspiration rates in forests next to lower rates in deforested agricultural lands in the Panama Canal region at the end of the dry season<sup>26</sup>. Despite work on the effects of conversion of tropical forest to pasture<sup>27</sup>, more work is required on other important replacement land covers, such as secondary vegetation and selective logging<sup>28</sup>. Although shifting cultivation, as in southeast Asia<sup>29</sup>, and smallholder expansion, as in Brazil, have been important drivers of land-cover change in the past, various internal and external forces<sup>30</sup> have made large-scale industrial agricultural conversion to pasture, permanent crops and tree plantations<sup>31</sup> the dominant factors in much of the humid tropics. These land-cover conversions have significant impacts on local and regional hydrology<sup>32</sup>, as does the disturbance of rainforests by selective felling<sup>33,34</sup>. Indeed, in many parts of the humid tropics, disturbed rainforests are more extensive than areas of undisturbed rainforest. For example, deforestation in central Brazil during the past four decades has been associated with measurable decreases in the evapotranspiration rate (Fig. 4), shifts in the location, intensity and timing of rainfall events, a lengthening of the dry season and increased streamflow<sup>32,35–42</sup>. Pressure to preserve and expand forested area, promoted for example by REDD (the United Nations programme Reducing Emissions from Deforestation and Forest

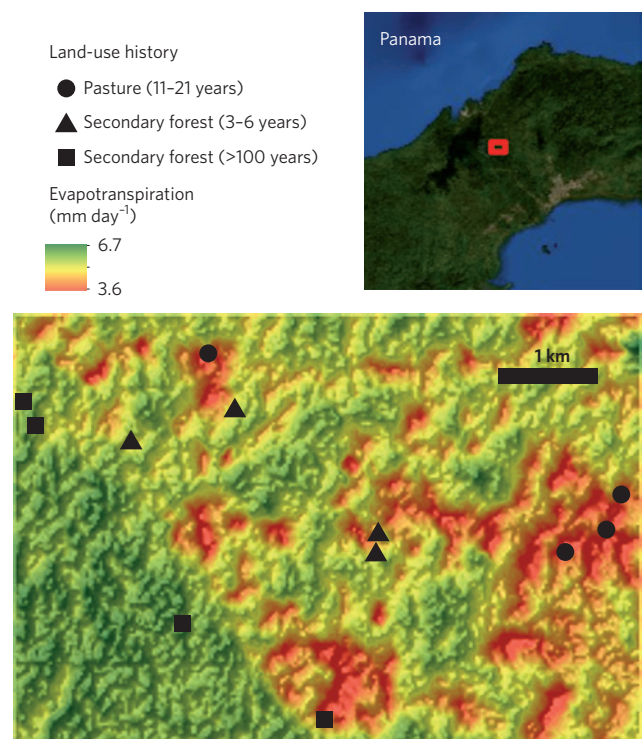


**Figure 2 | Average discharge per unit drainage area as a function of latitude at the river mouth, showing differences between tropical and temperate latitudes.** The range of discharges from tropical latitudes is much greater and includes some of the largest riverine fluxes of water on the Earth. Data on drainage area, latitude and discharge taken from ref. 95.

Degradation), may have unexpected consequences for regional water resources.

Human activities have already altered stream form and function in many locations throughout the tropics<sup>43</sup>. Extensive unaltered areas remain, but many of those areas are under high development pressure. This presents an opportunity to study environmental changes and stream responses. Several recent studies in the southeastern Amazon show that deforestation has probably increased discharge of the 750,000-km<sup>2</sup> Tocantins/Araguaia River system by nearly 20% in the past 40 years (ref. 39). Exceptions to this general response are environment-specific and include some mountain cloud-forest streams, which can decrease in flow with deforestation where moisture harvesting by trees was significant<sup>44</sup>. Although the effects of anthropogenic activities on sediment delivery rates have been addressed on a regional scale<sup>45</sup>, few studies have been made of actual delivery mechanisms at the local level<sup>46</sup>. Anthropogenic effects on sediment dynamics include increased sediment yield with commercial forestry<sup>47</sup>, road construction and open-cast mining<sup>14</sup>, all of which have accelerated in the humid tropics during recent decades.

Future anthropogenic modification of the tropical hydrosphere is likely to be driven by freshwater supply, food production and energy development needs<sup>48</sup>. Each of these is interrelated, and modifications of the local land surface will propagate from deep groundwater to the troposphere<sup>49</sup>. The potential impact will, however, be highly variable and dependent on the regional setting. For example, deforestation in Brazil may have altered moisture convergence into the South American continent<sup>50</sup>. If this alteration of the land surface gradient from the Atlantic to the Andes increases convective development closer to the ocean, this will have profound impacts for wide swathes of the continent and potentially alter the Intertropical Convergence Zone. Similarly, the alteration of irrigation practices in India could alter moisture convergence in the Himalayas, thus affecting the availability of water resources across the Indian subcontinent<sup>51</sup>. Emerging evidence linking the modification of regional cloudiness and precipitation to air pollution, dust production and transport, and large-scale circulation further illustrates the potential for direct and indirect feedbacks on the water cycle<sup>52</sup>. Large portions of the humid tropics, including Indonesia and the Amazon Basin, are among the global hotspots for atmospheric brown clouds, where organic carbon and sulphate mass reach very high levels as a result of pollution accumulating during the dry season<sup>53</sup>. The brown clouds decrease the annual mean value of solar radiation and thus



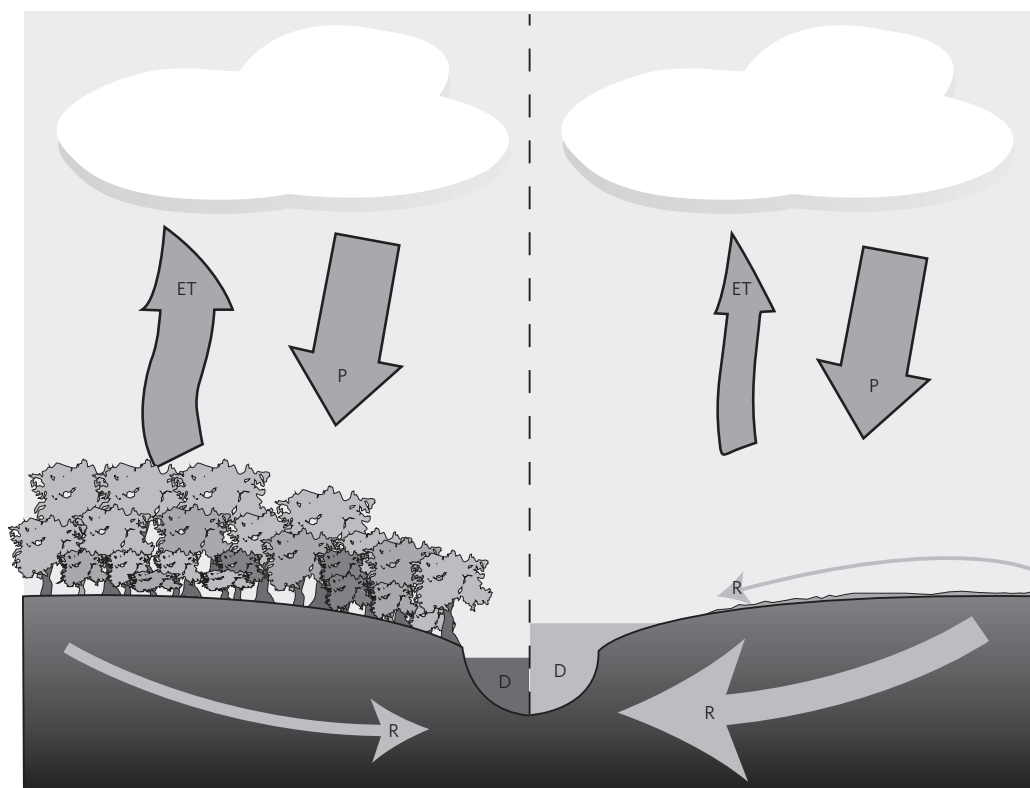
**Figure 3 | Example of how evapotranspiration rates in disturbed rainforests in the dry season are related to land-use history.** This example demonstrates the potential of optical/thermal remote sensing in the humid tropics where clouds are an important constraint<sup>90</sup>. We combined data from two independent studies covering the Agua Salud Project in Panama<sup>96</sup>: one study used the Surface Energy Balance Algorithm for Land<sup>26,97,99</sup> to map evapotranspiration on 27 March 2000 (Fig. 1 in ref. 26), and the other randomly selected different land-use types on the same soil and topography (Fig. 1 in ref. 98). The average evapotranspiration rates of the sites with pasture and with secondary forests of 3–6 years and over 100 years of age are, respectively, 4.4, 5.3 and 5.8 mm per day. In ungauged tropical watersheds, even one Landsat-derived evapotranspiration map will be of great value for the improvement of model unit delineation, because evapotranspiration is not only the largest component of the water balance during the dry season but also a good indicator of the spatial distribution of root-zone soil moisture<sup>77</sup>.

affect radiative forcing and/or melt rates in the humid tropics in manners not yet well understood.

Such feedbacks bring to the forefront the importance of understanding the dynamics of coupled human–natural systems that will determine the future of the hydrological cycle in the humid tropics<sup>48</sup>. This must also extend to understanding the underlying social and economic motivations governing land-use change, and at what spatial and temporal scales these alterations will be conducted. Enhancing our understanding of future changes will require an explicit emphasis on multiscale interactions, from deep groundwater through to the atmosphere, and their geographical variation.

### Research vision for the changing humid tropics

All aspects of tropical hydrology — from fluxes of energy and water within the atmosphere, to those within vegetation, land surface and subsurface systems, to stream outputs of water, sediment and solutes — are distinguished from other regions of the globe by substantially greater spatial and temporal variability, higher magnitudes, pronounced spatial gradients, and consequently the potential for rapid and significant change in response to anthropogenic alterations and associated water fluxes. One critical difference between



**Figure 4 | Schematic of local and regional hydrological response to deforestation.** Deforestation reduces local evapotranspiration (ET) through decreased plant water demand from vegetation or fallow fields compared with native vegetation. Even though precipitation (P) patterns may be affected at regional scales, at relatively small scales they are unlikely to be proportional to the local decrease in evapotranspiration. As a result, total water yield (R) and river discharge (D) are increased. The water yield increases with increasing area of a watershed deforested and tends to be concentrated as a baseflow increase, unless subsequent land uses substantially decrease the rate of rainfall infiltration. The size of the effect depends on the precipitation rate and land-cover changes that occur, but observations from small watersheds show a 10–25% increase for water yield<sup>42</sup> and a threefold increase in discharge<sup>43</sup>.

the tropics and subtropics and other regions is that climate change impacts will directly alter the precipitation regime and other aspects of the hydrological cycle, as opposed to impacts associated with increasing temperature that indirectly affect the hydrological cycle (for example, heatwaves or thawing of permafrost)<sup>11</sup>. To address the challenge of sustainable development and informed adaptation in the ‘Anthropocene’, a concerted effort towards characterizing the ‘accelerated’ tropical water cycle is necessary and urgent. This requires a holistic framework for observing and monitoring moisture cycling over land. We argue that tropical data collection efforts should explicitly emphasize characterization of the subsurface to troposphere interactions across strong physiographic and ecological gradients to close the water budget. Three main research needs are identified below.

**Moisture cycling.** Because of a more vigorous hydrological cycle closely tied to the variability of precipitation, the rates of geomorphic and ecological response will be very strong. This in turn makes it particularly difficult, in contrast to the midlatitudes, to project nonlinear feedbacks between atmospheric humidity and associated water fluxes in the tropics, and consequently the implications for adaptation (for example, vegetation productivity versus soil loss). Notwithstanding our limited understanding of multiscale, multiphase hydrological processes and land–atmosphere interactions, the representation of extreme gradients in atmospheric models is an important research challenge for the coarse resolution generally necessary for climate modelling. The arbitrary distinction of the atmosphere as beginning with the evapotranspiration input and ending with the precipitation on the surface has led to the land surface being treated as a lower boundary condition in the quest to

understand atmospheric moisture cycling<sup>54</sup>. Precipitation patterns and hydrogeology determine groundwater recharge patterns, however, and in turn groundwater dynamics can markedly alter regional freshwater availability and vertical moisture profiles in the vadose zone, thus affecting the available water for bare soil evaporation and plant transpiration<sup>55</sup>. Because the ground surface is treated as a lower boundary condition in atmospheric models, the models do not treat actual surface and subsurface pathways well, if at all. The dominant timescales for these different moisture cycling regimes vary from multidecadal, for global circulation and groundwater, to millisecond, for aerosol processes and turbulent transport in the atmosphere. Therefore, a more explicit emphasis on integrated measuring, modelling and understanding water fluxes across the land–atmosphere continuum is warranted.

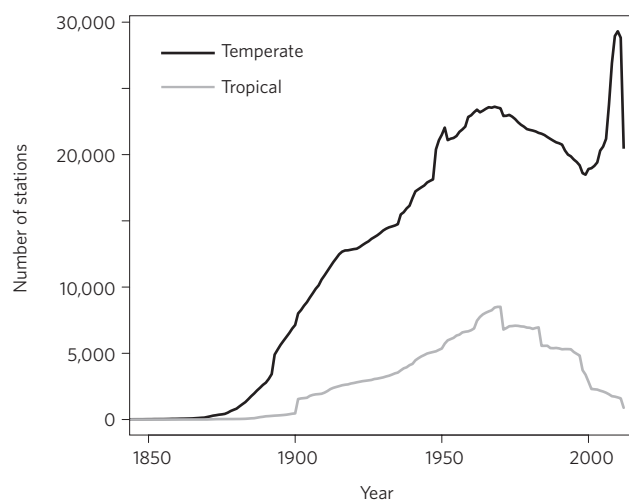
Specifically, we recommend increased attention to efforts to quantify the relative magnitude of interactions between the various moisture reservoirs<sup>56</sup>. This would allow researchers to address questions such as “At what spatial and temporal scales will agricultural production alter both groundwater recharge and regional precipitation dynamics?” More importantly, we must be able to assess how these temporal interactions vary spatially across tropical regimes<sup>57</sup> such as monsoon-dominated systems, complex orography, island systems and tropical lowlands. Once the relevant cross-scale interactions have been quantified spatially, assessment of the impacts of future anthropogenic alterations both locally and through regional and global teleconnections can proceed<sup>58</sup>.

Throughout the tropics, intentionally and inadvertently introduced plants, some of which aggressively invade native forests, can alter water fluxes<sup>59</sup>. There is an urgent need to recognize these emerging patterns and drivers of land-cover change and to

respond with observations targeted at underrepresented ecosystems (disturbed rainforests, tree plantations) and regions (Asia and Africa). Understanding and predicting the influences of land-cover change must be achieved with attention to concurrent regional climate changes resulting from global warming. In many moist tropical regions, trends and projections suggest a drier future<sup>60</sup>. Therefore, work is needed to better understand the biological and hydrological responses of tropical ecosystems to increasing drought, extending studies on the roles of deep roots, hydraulic lift, stomatal regulation, leaf-area changes and xylem cavitation.

**Catchment processes.** Large gaps in our knowledge of streams in the humid tropics need to be addressed before we can effectively understand ongoing catchment change. Because of limited field research on catchment inputs to streams, and on stream form and function across diverse sites, we cannot synthesize data and develop conceptual or quantitative models analogous to those developed for temperate sites. Among the primary gaps with respect to hydrological inputs to streams are a clear understanding of the complex ways in which human landscape alterations (for example, deforestation and land management) affect evapotranspiration and the subsequent runoff ratio, and how that response differs as a function of environment (for example, soil type, climate, topography or land cover). In the Andes and in Central America, a close association between landforms and precipitation has been detected by mapping precipitation features from Tropical Rainfall Measurement Mission satellite data<sup>61,62</sup>. Specifically, the spatial distribution and the diurnal cycle of shallow and deep embedded convective systems linked to high rainfall amounts follow river valleys and adjacent ridges very closely. This suggests that topography strongly drives the spatial distribution of precipitation, a pattern that probably continues into runoff and sediment transport.

Little is known about the magnitudes of different flow paths of water, residence times and timing of delivery for fluxes to streams in the tropics<sup>63,64</sup>. The recently established Critical Zone Observatories — four in Europe, six in the United States — are designed to study integratively the chemical, physical and biological processes that shape the Earth's surface. The observatories include research initiatives focused on the origination of solutes in the soil profile, but only the Luquillo (Puerto Rico) observatory lies within the tropics. Data gaps regarding delivery of material to tropical streams highlight our inability to address how anthropogenic disturbances, which limit the development of deeply weathered soil profiles, can alter local and regional flow regimes. With respect to biogeochemical cycling, we need more information on: (1) magnitudes and rates of different flow pathways, transport and cycling of carbon and other nutrients; (2) chemical inputs from precipitation, including changes during the year and during an event; (3) the role of dust inputs; and (4) anthropogenic alteration to the systems themselves. The ability of streams to retain and microbially process organic matter strongly influences global carbon cycles<sup>65</sup>, yet we know little of hyporheic exchange, in-stream wood dynamics or bedload dynamics in tropical streams, all of which strongly influence carbon retention and processing. Furthermore, changes in stream temperature from deforestation, stream modification and/or changing climate will affect microbial processing rates and the in-stream carbon cycle and food web, but the full scope of the temperature changes that may occur, and the carbon cycle and food web responses, are largely unknown. Rivers draining basins where tracks of tropical cyclones cross tectonically active terrains tend to be strongly controlled by large floods<sup>66</sup>, and floods can dominate channel morphology and sediment dynamics, yet the scarcity of field studies that detail behaviour during extreme events<sup>47</sup> continues to hamper our ability to understand the geomorphic role of floods of varying magnitude and recurrence interval across various settings.



**Figure 5 | Number of precipitation stations in the Global Historical Climatology Network data set for each year.** The plot shows the much smaller and decreasing number of stations in tropical latitudes relative to those in temperate latitudes. Tropical stations are between the Equator and 25° latitude, and temperate stations are between 25° and 60° latitude in both the Northern and the Southern Hemispheres. The two lines in the plot are separate data sets, rather than cumulative numbers (that is, there are now more than 25,000 precipitation stations in the temperate zones alone).

Fundamentally, we need many more field-based studies in diverse river basins before we can effectively understand how changing climate and resource use affect stream form and function. Limited field research on catchment processes in the humid tropics suggests that extrapolating knowledge of rates and magnitudes of processes in temperate catchments to the tropics is inappropriate and misleading<sup>15,16,67</sup>.

**Long-term data acquisition and organization.** Hydrological measurements in many tropical countries are waning (Fig. 5). At present, the lack of homogenized data throughout the tropics means that we are left questioning whether the generally poor performance of atmosphere and ecosystem models results from our current lack of understanding, or is simply a matter of not having enough high-quality data to assess model output properly throughout the region<sup>68</sup>. Therefore, it is essential to obtain proper observational data, but what data are necessary? We argue that integrative field campaigns that simultaneously capture moisture dynamics from the deep subsurface through the troposphere are needed, including long-term monitoring to address low-frequency dynamics associated with both deep groundwater and large-scale atmospheric circulations<sup>69</sup>. Although isolated efforts such as the Large Scale Biosphere–Atmosphere Experiment in Amazonia<sup>70</sup> have been fairly successful, systematic coordinated, concurrent experiments across the humid tropics would allow teleconnection studies and generalization of fundamental knowledge about water fluxes and moist atmospheric processes through synthesis. Finally, open-platform databases, such as the Source to Sink Information Center for Global River and Delta Systems ([www.meas.ncsu.edu/sealevel/s2s/](http://www.meas.ncsu.edu/sealevel/s2s/)), should be used to coordinate existing data sets, many of which may already address particular knowledge gaps and/or provide a strategic springboard for additional studies.

In addition to multidisciplinary efforts, the macroscale perspective captured by the spatial and temporal dynamics of water fluxes and states from many surface stations is also vitally important. These data must be consistently measured and processed. The FLUXNET<sup>71</sup> project, a worldwide network of micrometeorological tower sites,

provides a notable example of this type of effort, collecting a wide range of biophysical data in a high-quality, consistent manner. Yet critical regional gaps exist: there is no FLUXNET tower in the Andes, for example. A deliberate effort to extend high-quality monitoring consistently across various regions would greatly improve our ability to understand boundary-layer hydrology and land–atmosphere interactions in the tropics, especially when coupled with remote sensing for cost-effective extrapolation of hydrological point observations over large areas of inaccessible humid tropical lands<sup>72</sup>. An integrated monitoring system for temporal and spatial changes must include temporally continuous ground measurements at the point scale and spatially continuous remote-sensing observations at discrete time periods that are merged in distributed hydrological models for the retrieval of continuous space–time distributions of the hydrological variables of interest such as latent heat flux, soil moisture and carbon flux.

Frequent cloudiness and dense vegetation in the humid tropics pose a challenge for satellite-based monitoring of dynamic hydrologic variables such as evapotranspiration and root-zone water content because optical/thermal sensors cannot penetrate clouds<sup>73,74</sup> and radar sensors have difficulty breaking through thick canopies<sup>75,76</sup>. But quantitative remote sensing of hydrological parameters in the tropics is now sophisticated enough for the parameterization of water balance models<sup>73,77</sup>. Parameters that can be derived several times per day under all weather conditions are incoming solar radiation every 15–30 min (refs 78–81) and precipitation every 3–6 h (refs 82–85). Given that precipitation represents the main forcing on water balances in the humid tropics, it is encouraging to detect a growing understanding of the factors that affect the quality of operational precipitation products<sup>82,83,86–89</sup>, especially in complex mountainous terrain<sup>16,90</sup> and under convective conditions<sup>85,91</sup>. Precipitation products based solely on satellite observations typically present regional and seasonal biases, but they can be considerably improved by using gauge measurements for bias adjustment of precipitation<sup>82,87–89</sup>.

Other parameters can only be derived when imagery is available at intermittent periods. Daily evapotranspiration<sup>26,92</sup> and the status of root-zone soil moisture<sup>73</sup> can be derived from cloud-free optical/thermal imagery (Fig. 3), and temporal changes of water levels in lakes and rivers can be derived from radar imagery<sup>93,94</sup>. Although each of these remote-sensing products has its limitations, their assimilation in hydrological models is expected to exceed the sum of their individual contributions and to deepen our understanding of the spatial dynamics of tropical water fluxes and states.

## Conclusions

Water pressures in the humid tropics are on the cusp of rapid change. Processes that operate within the hydrological cycle are expected to accelerate as temperatures rise and the capacity of the air to carry moisture increases. Our current understanding of key interactions is limited geographically and relies heavily on modelling rather than empirical data. Specific components of tropical hydrology remain less explored than their counterparts in the temperate regions because fewer resources have been dedicated to studying the humid tropics. We recommend an increased emphasis on efforts to quantify the human influence on all aspects of tropical hydrology and the relative magnitude of interactions between the various moisture reservoirs.

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### Author contributions

All authors contributed to writing the synthesis offered in this Review. Individual subtopics covered by each author are: E.W., lead author and fluvial geomorphology and Fig. 2; A.B. and N.B., atmospheric processes; N.B., Fig. 5; N.A.C., J.M. and F.O., hillslope hydrology; M.C., stream hydrology and Fig. 4; T.G. and J.J., land-atmosphere interactions; S.G. and R.H., biogeochemistry; S.G., Fig. 1; J.M.H.H., soil hydrology and remote sensing and Fig. 3.

### Additional information

The authors declare no competing financial interests. Reprints and permissions information is available online at [www.nature.com/reprints](http://www.nature.com/reprints). Correspondence and requests for materials should be addressed to E.W.