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The Influence of Topography on the Global Terrestrial Water Cycle

Sebastian Gnann[1,2], Jane W. Baldwin[3,4], Mark O. Cuthbert[5], Tom Gleeson[6], Wolfgang Schwanghart[1], and Thorsten Wagener[1]

[1]Institute of Environmental Science and Geography, University of Potsdam, Potsdam, Germany, [2]Chair of Hydrology, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany, [3]Department of Earth System Science, University of California Irvine, Irvine, CA, USA, [4]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA, [5]School of Earth and Environmental Sciences, Cardiff University, Cardiff, UK, [6]Department of Civil Engineering, School of Earth and Ocean Science, University of Victoria, Victoria, BC, Canada

Key Points:

- Topography influences water and energy provided by the atmosphere, and the fate of water at and below the land surface
- Topography is associated with gradients and contrasts, whose interactions explain many of the patterns observed in nature
- Topographic gradients and contrasts help posing research questions, designing measurement networks, and building and evaluating models

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

S. Gnann,
sebastian.gnann@hydrology.uni-freiburg.de

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Author Contributions:

Conceptualization: Sebastian Gnann, Mark O. Cuthbert, Tom Gleeson, Thorsten Wagener
Formal analysis: Sebastian Gnann
Visualization: Sebastian Gnann
Writing – original draft: Sebastian Gnann, Jane W. Baldwin, Mark O. Cuthbert, Tom Gleeson, Wolfgang Schwanghart, Thorsten Wagener
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Abstract Topography affects the distribution and movement of water on Earth, yet new insights about topographic controls continue to surprise us and exciting puzzles remain. Here we combine literature review and data synthesis to explore the influence of topography on the global terrestrial water cycle, from the atmosphere down to the groundwater. Above the land surface, topography induces gradients and contrasts in water and energy availability. Long-term precipitation usually increases with elevation in the mid-latitudes, while it peaks at low- to mid-elevations in the tropics. Potential evaporation tends to decrease with elevation in all climate zones. At the land surface, topography is expressed in snow distribution, vegetation zonation, geomorphic landforms, the critical zone, and drainage networks. Evaporation and vegetation activity are often highest at low- to mid-elevations where neither temperature, nor energy availability, nor water availability—often modulated by lateral moisture redistribution—impose strong limitations. Below the land surface, topography drives the movement of groundwater from local to continental scales. In many steep upland regions, groundwater systems are well connected to streams and provide ample baseflow, and streams often start losing water in foothills where bedrock transitions into highly permeable sediment. We conclude by presenting organizing principles, discussing the implications of climate change and human activity, and identifying data needs and knowledge gaps. A defining feature resulting from topography is the presence of gradients and contrasts, whose interactions explain many of the patterns we observe in nature and how they might change in the future.

Plain Language Summary Aristotle already recognized in his Meteorologica (ca. 340 BCE) that mountains often receive more precipitation and provide disproportionately high runoff to the plains that surround them. Since then, countless studies have investigated the influence of topography on the water cycle, but what generalizations can we draw from the existing literature? While hills and mountains influence precipitation patterns everywhere, an increase of precipitation with elevation is mostly observed in temperate regions, while precipitation in the tropics usually peaks at rather low elevations. The highest evaporation rates and most active vegetation zones are often found at mid-elevations, where it is neither too dry nor too cold. And many steep mountains harbor active groundwater systems that are well-connected to rivers, providing water during dry spells. All of this will be affected by climate change: the elevation dependence of rainfall could become weaker, the most productive vegetation zones could move uphill, and especially in plains, rivers could shift from gaining groundwater to losing water to the underlying aquifer. To understand these phenomena and better anticipate the impacts of climate change, we need an interdisciplinary approach that connects atmosphere, land surface, and subsurface, and explores the mechanisms underlying the patterns we observe in nature.

1. Introduction

Topography affects the distribution of water on Earth, often in surprising or extreme ways. Hills not higher than 50 m can already have a distinct orographic effect on precipitation, as Bergeron found in Sweden (Bergeron, 1960; Roe, 2005). Mawsynram in India, often named the wettest place on Earth, receives more than 12,000 mm of rainfall per year on average (Kuttippurath et al., 2021), because the summer monsoon forces extremely moist air through deep canyons surrounded by steep cliffs (Murata et al., 2007). The Atacama desert, which receives less than 1 mm of rainfall per year on average in some places and is often considered the driest place on Earth (Schween et al., 2020), owes its climate in part to topography; one reason for its hyper-aridity are the Andes, which prevent moisture advection from the east (Houston & Hartley, 2003).

The influence of mountains on the water cycle was already appreciated millennia ago by ancient scholars such as Aristotle (4th century BC) and Wang Chong (1st century AD; Needham, 1959), as well as in the Kishkindha sarga of the epic Ramayana (ca. 200 BCE, but uncertain; Singh et al., 2020). In his Meteorologica, written ca. 340 BCE, Aristotle wrote that mountains "act like a thick sponge overhanging the Earth" (cited in Roe, 2005). Mt Fuji—locally known as the water mountain—fits this description very closely; ample rainfall seeps deep into volcanic rock and is slowly released via groundwater and groundwater-fed springs, supplying water to millions of people (Schilling et al., 2023). While mountains are often considered the world's water towers (Immerzeel et al., 2020; Viviroli et al., 2007), groundwater systems in mountains are rarely considered in water tower concepts (Drenkhan et al., 2022). Yet, mountain groundwater systems could become a critical buffer against shrinking snowpacks and glaciers in response to climate change, and may provide a hidden underground reservoir for many of the world's water towers (Somers & McKenzie, 2020; van Tiel et al., 2024).

Since Aristotle, Wang Chong, and the writing of the epic Ramayama, many others have pondered the role of topography in the water cycle. This has resulted in a variety of reviews focusing, for example, on orographic effects on atmospheric circulation and precipitation (Houze, 2012; Kirshbaum et al., 2018; Molnar et al., 2010; Roe, 2005), climate changes and their elevational patterns (Pepin et al., 2022), digital terrain modeling (Moore et al., 1991), hillslope hydrology (Fan et al., 2019), mountain water resources (Viviroli et al., 2011), mountain groundwater systems (Hayashi, 2020; Somers & McKenzie, 2020), or mountain system recharge (Markovich et al., 2019; Wilson & Guan, 2004). There is, however, no review that summarizes current knowledge about the large-scale influence of topography on the terrestrial water cycle, all the way from the atmosphere down to the groundwater.

Here we aim to close this gap by reviewing how topography influences the terrestrial water cycle above, at, and below Earth's surface. Our review is motivated by (a) recent insights that show there is still much to learn about this influence, (b) the potential of topography as a powerful predictor for transferring site-specific knowledge to other regions, and (c) the recognition that topographic gradients are often aligned and interact with other environmental gradients or contrasts (e.g., climate and geology), making them a well-suited playing field for the study of hydrological systems.

Our review focuses on large-scale influences of topography, defined here as anything from the catchment scale to the global scale (approximately 10 km and larger), roughly equal to Dooge's macroscale (Dooge, 1997; Gleeson & Paszkowski, 2014). In some cases, we include smaller scale features that are relevant at large scales, such as headwaters, which are estimated to account for 70%–80% of global stream length and are therefore relevant globally (Downing et al., 2012; Wohl, 2017). For readers interested in the influence of hillslope topography on water and energy fluxes in the Earth system, we refer to the review by Fan et al. (2019).

We organize our review as a vertical cross-section: above the surface (from the vegetation canopy upwards), at the surface (from the canopy to the saturated zone), and below the surface (the saturated zone). These categories should be seen as a useful way of organization rather than a strict separation, as water naturally connects all of them. We conclude our review by presenting organizing principles, discussing the implications of climate change and human activity, and identifying data needs and knowledge gaps.

The influence of topography on the water cycle and the land surface can be very visible. Some examples are shown in Figure 1, including cloud formation due to the orographic lift of moist air, elevational zonation of vegetation, different landforms such as mountains and plains, and large-scale redistribution of water from mountain regions to lowlands. The influence of topography on the subsurface is more difficult to detect, but as we will see below, can reach far and deep.

2. Above the Surface

2.1. Atmospheric Water Availability: Precipitation

On planetary scales, large plateaus and mountain ranges cause considerable changes in atmospheric circulation that can strongly influence precipitation patterns. In the mid-latitudes, major orographic features—such as the Tibetan Plateau, the Rocky Mountains, or the Southern Andes—influence large-scale patterns of circulation by forcing

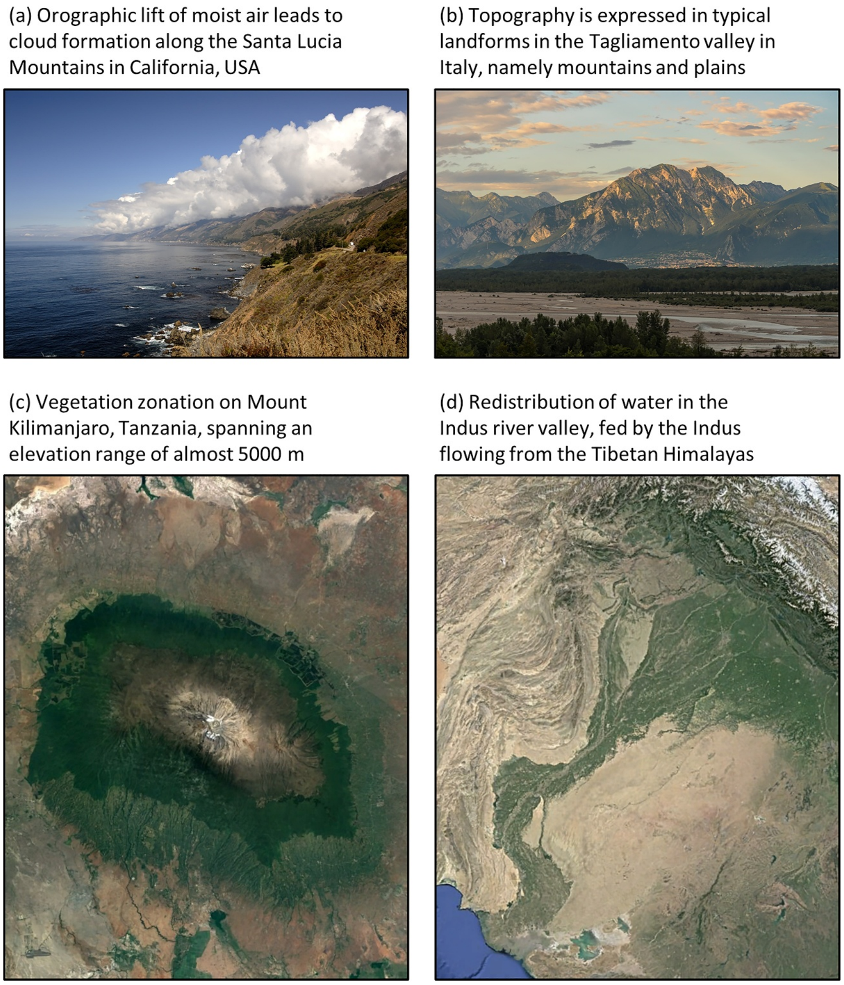


Figure 1. Example photos and satellite images illustrating how topography influences the terrestrial water cycle and the land surface. (a) Orographic lift of moist air leads to cloud formation along the Santa Lucia Mountains south of Monterey, California (photo by Robert Schwemmer; https://commons.wikimedia.org/wiki/File:Wea03310_-_Flickr_-_NOAA_Photo_Library.jpg), (b) topography is expressed in typical landforms in the Tagliamento valley in Italy, namely mountains (Julian Alps) and plains (with Gemona del Friuli; photo by Mirco Peschiutta; https://imaggeo.egu.eu/view/5046/), (c) vegetation zonation on Mount Kilimanjaro, Tanzania, spanning an elevation range of almost 5,000 m, resulting in strong climatic gradients (image taken from Google Earth; Image Landsat/Copernicus), and (d) large-scale redistribution of water in the Indus river valley, fed by the Indus flowing from the Tibetan Himalayas (image taken from Google Earth; Data SIO, NOAA, U.S. Navy, NGA, GEBCO; Image Landsat/Copernicus).

stationary atmospheric waves which can span the globe (Hoskins & Karoly, 1981). These waves are forced both mechanically, through blocking of air flow, and thermally, through elevated sensible heating of the atmosphere, producing vorticity anomalies which result in longitudinally propagating waves (Molnar et al., 2010). Mechanical forcing is typically more influential for tall, thin mountain ranges such as the Andes, whereas thermal forcing is more influential for large areas of high elevation, such as the Tibetan Plateau (Baldwin et al., 2021; Boos & Kuang, 2010). Orographically forced stationary waves alter both patterns of atmospheric ascent and descent and horizontal moisture convergence, shaping large-scale differences in precipitation across the planet (Cohen & Boos, 2017). Global and regional climate modeling studies have elucidated the impacts of some orographic features. The Tibetan Plateau and the Himalayas strengthen the South Asian monsoon circulation and extend the associated intense precipitation further poleward (Boos & Kuang, 2013; Hahn & Manabe, 1975; Wu et al., 2012). Mechanical forcing of the Tibetan Plateau also plays a critical role in driving the East Asian Summer Monsoon by diverting the flow of the westerly jet stream (Baldwin & Vecchi, 2016; Chiang et al., 2015). Some additional nonlocal influences of topography on hydroclimate include formation of mid-latitude deserts in Central to East

Asia by Asian and Middle Eastern orographic features (Broccoli & Manabe, 1992; Rodwell & Hoskins, 1996; Simpson et al., 2015), enhancement of Northwest Pacific tropical cyclone density by Asian orographic features (Baldwin et al., 2019), and enhancement of the North American monsoon by Mexico's Sierra Madre mountains (Boos & Pascale, 2021).

Topography also influences the source and sink regions of atmospheric moisture, in particular whether precipitation is sourced from the oceans or from evaporation over land, which is known as "moisture recycling" (Brubaker et al., 1993; van der Ent et al., 2010). Knowing where a region sources its precipitation from is important to anticipate where changes in land-atmosphere fluxes, for instance due to land use changes, affect a region's moisture supply (Eagleson, 1986; Keys et al., 2012). Mountain ranges can either block moisture from entering the continent or capture moisture from the atmosphere (Gimeno et al., 2012; van der Ent et al., 2010). For example, in the Amazon basin, the Andes block easterly winds from leaving the continent, and about a fourth of all precipitation that falls in the Amazon basin is contributed by evaporation from within the basin (Eltahir & Bras, 1994).

For individual mountains and hills, a commonly stated rule of thumb is that precipitation increases with elevation. In many regions, especially in the mid-latitudes where precipitation (P) is mostly frontal, long-term average precipitation indeed often increases with elevation (Barry, 2008; Roe, 2005; Smith, 1979, 2006); see Figure 2a. Forced mechanical lifting cools the air on the windward side of an orographic barrier, leading to condensation and precipitation (see Figure 1a). On the leeward side, subsidence and resultant warming suppresses precipitation, resulting in the so-called rain shadow (Roe, 2005), which makes the leeward side or inner parts of a mountain range much drier (Frei & Schär, 1998); see Figure 2b. Precipitation at lower latitudes like the tropics is mostly convective, and is thus associated with different dominant orographic processes (Kirshbaum et al., 2018). Here, besides higher precipitation totals overall, we often find precipitation maxima at low- to mid-elevations, which can lead to a humped profile with peak precipitation between 1,000 and 2,000 m (Anders & Nesbitt, 2015; Barry, 2008; Lauer, 1986); see Figure 2a.

While these long-term patterns provide a useful overview (Barry, 2008; Lauer, 1986), profiles and gradients can vary within and between regions and are generally controlled by a range of factors, including microphysical processes and mountain geometry (Roe & Baker, 2006; Smith, 2019). Some of this variability is due to local conditions and thus difficult to generalize, but there are commonalities; rainout rates tend to be higher for steeper slopes (Johansson & Chen, 2003; Smith, 1979); over high mountains, depletion of atmospheric moisture often leads to peak precipitation below the crest (Daly et al., 1994); and in tropical climates, the zone of maximum precipitation tends to rise uphill with decreasing rainfall totals (Barry, 2008). For more detailed regional examples, we refer to Barry (2008). Since precipitation gradients and associated processes are dynamic, different types of precipitation (e.g., convective in summer and frontal in winter) or different weather conditions can lead to variable and complex precipitation-elevation relationships even along the same slope (Houze, 2012; Smith, 1979). At the event scale, precipitation gradients might be enhanced due to stronger westerly winds (Lundquist et al., 2010). At longer time scales, precipitation gradients might be amplified in response to modes of climate variability like the North Atlantic Oscillation (Burt & Howden, 2013).

Short duration (hourly or less) extreme precipitation, usually related to high-intensity convective storms, was found to show a reverse orographic effect in Italy and the southeastern Mediterranean, with peak rainfall at low elevations (Avanzi et al., 2015; Marra et al., 2021, 2022). This is in stark contrast to orographic enhancement found at longer time scales in these regions and shows that orographic effects can differ between time scales. In current simulation models, orographic effects on short duration extreme precipitation are poorly explored (O'Gorman, 2015), and likely not well-captured at the resolution used by most global climate models (approximately 100–200 km; Akinsanola et al., 2020). Even high resolution regional models can be substantially biased in their simulations (Dallan et al., 2023), potentially limiting our ability to anticipate hazards triggered by extreme precipitation such as flash floods or landslides.

2.2. Atmospheric Energy Availability: Potential Evaporation

The evaporation of water requires both energy, which is mainly provided by (net) radiation, and the uptake of water vapor into the atmosphere, which depends on atmospheric conditions such as temperature, vapor pressure deficit, and wind speed. Together, these drivers largely determine potential evaporation (E_{pot}), a proxy for atmospheric water demand (McMahon et al., 2013; McVicar et al., 2007). We here refer to the integrated land

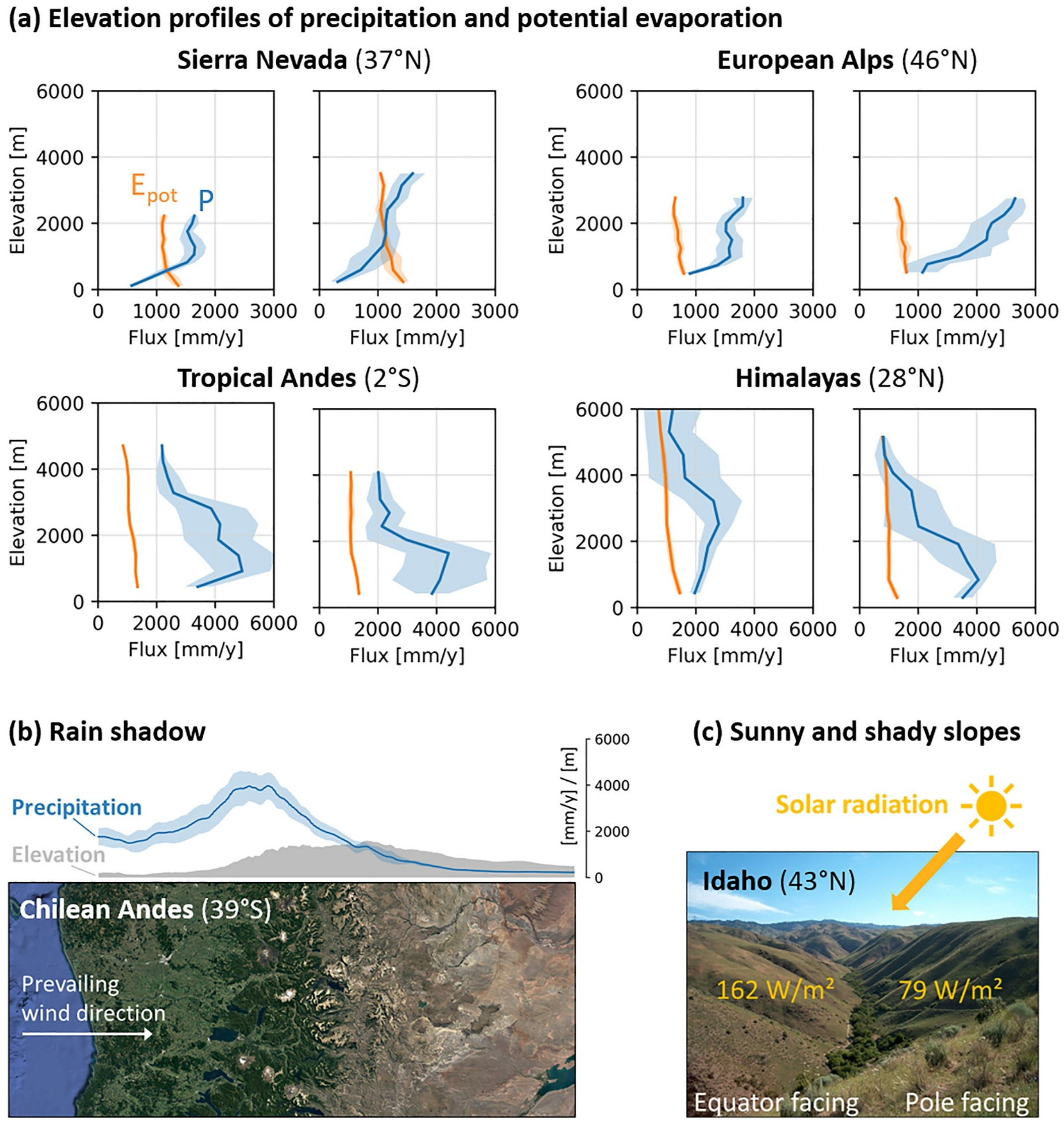


Figure 2. Topography influences the amount of precipitation and potential evaporation at the land surface, which can be combined into the climatic water balance ($P - E_{pot}$). (a) Examples of elevation profiles for precipitation and potential evaporation for different mountain ranges (with average latitudes shown in parentheses). Note the different *x*-axes for the panels. Each of the two panels corresponds to a $0.5 \times 2°$ rectangular swath located on one side of and perpendicular to the mountain ridge; exact locations can be found in Figure S1 in Supporting Information S1. (b) Rain shadow due to orographic barrier, mirrored in vegetation patterns; the longitude ranges from ca. 74°W to 69°W. Image is taken from Google Earth (Data SIO, NOAA, U.S. Navy, NGA, GEBCO; Image Landsat/Copernicus). In panels (a) and (b), solid lines indicate the mean and shaded areas indicate the standard deviation; climate data are extracted from CHELSA climatologies (Brun et al., 2022b; Karger et al., 2017) and topographic data from Geomorpho90m (Amatulli et al., 2020). (c) Aspect-induced contrast between sunny and shady slopes and denser tree cover in the valley where water converges; the original image was provided by Jim McNamara and the data are taken from McNamara et al. (2018).

surface latent heat flux as evaporation, which thus includes transpiration, interception and evaporation from soil and surface water bodies (Miralles et al., 2020). Consequently, potential evaporation also includes energy available for transpiration. In addition, sublimation may return considerable fractions of precipitation back to the atmosphere, especially in cold and windy environments such as many mountain regions (Sexstone et al., 2018; Stigter et al., 2018; Strasser et al., 2008).

Clear sky radiation increases with elevation, but net radiation may change little or even decrease due to increasing cloud cover (especially in humid regions) and increasing albedo (especially at high elevations; Barry, 2008; Hu &

Boos, 2017; Körner, 2021). Temperature generally decreases with elevation (see also Section 3.1), reducing saturation vapor pressure and thus vapor pressure deficit, even if relative humidity is low. Wind speed tends to increase with elevation in the mid-latitudes, but often decreases in the tropics (Körner, 2021). Overall, potential evaporation usually decreases with elevation, mostly attributed to decreasing temperatures, as found in Nepal (Lambert & Chitrakar, 1989), Nevada (Shevenell, 1999), the Swiss Alps (van den Bergh et al., 2013), the Spanish Sierra Nevada (Jódar et al., 2017), or the Tibetan Plateau (Chang et al., 2023); see Figure 2a. There are exceptions, however, such as high tropical mountains where potential evaporation increases with elevation above the cloud forest level, typically at around 1,000–1,500 m (Bean et al., 1994; Leuschner, 2000). A systematic global review is so far lacking, and while most studies agree that potential evaporation decreases with elevation, magnitudes differ between regions and due to uncertainties in how E_{pot} is estimated.

Aspect, the slope exposure, has a marked influence on the incoming radiation, resulting in sunny (equator-facing) and shady (pole-facing) slopes, as well as shadowing in valleys; see Figure 2c. As a consequence, potential evaporation and temperature are higher on sunny than on shady slopes (Fan et al., 2019; Schaetzl & Anderson, 2005), an effect that becomes stronger with increasing slope steepness and increasing latitude (Barry, 2008; Fan et al., 2019). Often, equator-west facing slopes are the warmest and driest, because they receive peak radiation in the afternoon when temperatures are highest (Pelletier & Swetnam, 2017).

Elevational gradients in potential evaporation are typically smaller (on the order of −100 mm/km) than elevational precipitation gradients (which can exceed 1,000 mm/km), so that the climatic water balance ($P - E_{pot}$) in mountains is more strongly determined by changes in precipitation (see Figure 2a). In many mid-latitude mountain ranges, aridity (E_{pot}/P) decreases with elevation, and evaporation often switches from being water-limited ($E_{pot} > P$) at low elevations to being energy-limited ($E_{pot} < P$) at high elevations (e.g., in the Sierra Nevada, see Figure 2a). In tropical regions, evaporation is often most strongly energy-limited at low- to mid-elevations (e.g., around the cloud forest level at about 1,000–1,500 m in the Tropical Andes; see Figure 2a).

3. At the Surface

3.1. Temperature, Snow, and Energy Balances

The average environmental lapse rate of approximately 6°C/km in the free atmosphere regularly translates into a similar decrease of temperature with elevation (Barry, 2008; Körner, 2021). Surface temperature lapse rates are variable, though, and may vary regionally (e.g., between climate regions or between two sides of a mountain), seasonally, and diurnally (Körner, 2021; Minder et al., 2010). Especially in regions of complex topography, the atmospheric boundary layer is often less tightly coupled to the free atmosphere, which sometimes even results in inverse temperature gradients (Karki et al., 2020; Mutiibwa et al., 2015; Pepin & Seidel, 2005).

Temperature inversions—an increase of temperature with elevation—may develop along a sloped surface, usually at night. Air parcels at the same altitude but further downhill cool more slowly because they are further away from the surface, leading to movement of cold air downslope toward the valley floor. Temperature inversions may also develop due to sheltering of valley bottoms, decoupling cold air pools in valleys from air flow aloft. This can happen both locally and regionally, for example, if advection of warm air aloft increases temperatures at higher altitudes (Rupp et al., 2020). Inversions frequently occur during winter in mid-latitude mountain ranges such as the northwestern United States (Rupp et al., 2020; Whiteman et al., 2001) or the European Alps (Vitasse et al., 2017). In the La Brevine valley, for example, cold air pools are responsible for the coldest temperatures ever measured in Switzerland (−41.8°C in January 1987), with the most extreme recorded inversion showing a change of 28°C along just 260 m of elevation difference (Vitasse et al., 2017). Temperature inversions can also occur in tropical regions like the southwestern Yunnan Province in China, where they are so consistent that they are even expressed in inverse vegetation zonation (Ai-liang, 1981).

Due to its close relationship with temperature, topography is also closely linked to the distribution of snow and glaciers. The fraction of precipitation falling as snow generally increases with elevation, but this is strongly conditioned by latitude. Globally, the snow line decreases relatively consistently with latitude, from elevations close to 5,000 m in the tropics down to sea level in polar regions (between 2001 and 2016; J. C. Hammond et al., 2018). Glaciers follow a similar pattern and start to occur, on average, at slightly higher elevations (around 5,500 m in the tropics; between 1999 and 2010). Variability can be large, though, with lower average elevations in maritime than in continental climates (Pfeffer et al., 2014). The total amount of snow that accumulates on the land surface results from the interplay of temperature, precipitation totals, snow redistribution, sublimation, and melt. For instance, in the European Alps and Pyrenees, snow depth (near the time of maximum seasonal snow accumulation) first increases with elevation due to decreasing temperatures and increasing precipitation, but then decreases due to redistribution downslope by wind, sloughing, and avalanching (Grünewald et al., 2014).

Atmosphere and land surface are closely linked through energy and water balances. In many mountain regions, this connection is particularly visible in patterns of snowmelt. For example, in the western USA where most snow accumulates at temperatures around −3 to 0°C, a 3°C warming could drastically reduce winter snowpack and related summer streamflow (Bales et al., 2006; Barnett et al., 2005). Once snow accumulates on the surface, radiative and turbulent heat fluxes govern the timing and magnitude of snowmelt. Other energy balance components like ground heat fluxes may be important in specific situations, but are typically small (e.g., smaller than 10% of net radiation; Bilish et al., 2018; Turnipseed et al., 2002). Snowmelt timing overall follows the seasonal cycle, but is modified by topography in several ways. Temperature lapse rates lead to an elevation-dependent delay in the timing of maximum snow accumulation and the start of the snowmelt season. In the Californian Sierra Nevada, for instance, the start of the snowmelt season is estimated to be delayed by 4 days for each 100 m increase in elevation (Lundquist et al., 2003; Reece & Aguado, 1992). Details of different energy fluxes shape local patterns of snowmelt. Above the treeline, shortwave radiation, affected by patterns of albedo, dominates temporal and spatial variations in snowmelt (Marks & Dozier, 1992). In contrast, below the treeline, exchange of longwave radiation plays a crucial role in snowmelt in forests (Link & Marks, 1999). The relative importance of different energy balance components also varies seasonally, related to seasonal changes in radiation inputs, temperature, snow cover, water availability, and vegetation activity (Baldocchi et al., 1997; Turnipseed et al., 2002).

Several challenges limit our understanding of energy balances in mountainous terrain, as well as our ability to close such balances (Foken, 2008; Stoy et al., 2013). The first challenge is observational: given the heterogeneity inherent in mountainous terrain, specialized station-based measurements are necessary to capture the relevant processes, but are seldom set up with sufficient density in these often difficult to reach locations (Bales et al., 2006; Lundquist et al., 2003). The second challenge is theoretical, though aggravated by observational limitations: there is still no widely accepted, viable theory for the exchange of energy, mass, and momentum in the boundary layers of hills and mountain regions. Monin-Obukhov similarity theory is frequently used to parameterize turbulent fluxes in numerical weather and climate models (Foken, 2008). However, this theory was developed and tested for flat terrain (Businger et al., 1971), and many of its assumptions break down in hilly and mountainous terrain, which exhibits a greater range of spatial scales of variability and meso- or large-scale motions such as slope and valley winds (Rotach et al., 2015). Solutions have been suggested to accurately represent exchange over specific alpine locations under certain conditions (Moraes et al., 2005; Nadeau et al., 2013), but further work is needed to develop broadly applicable theories for parameterizing surface exchange over complex topography (Serafin et al., 2018).

3.2. Vegetation, Soil Moisture, and Land-Atmosphere Fluxes

The relationship between topography and vegetation is one of the most visible features at the land surface and was already described by Alexander von Humboldt over two centuries ago (Rahbek et al., 2019); see Figure 1c. The reasons for the elevational zonation of vegetation are primarily (atmospheric) differences in energy and water availability, and especially temperature (Holdridge, 1967). One example for this is the tree line, which decreases from 4,000 to 5,000 m in the tropics to sea level in (near-)polar regions, largely because the decrease of temperature with elevation limits tree physiology (an approximate limit is a growing season mean temperature of about 6°C; Paulsen & Körner, 2014). Yet even within the same vegetation zone, vegetation characteristics like biomass and leaf area index may reduce with elevation (van den Bergh et al., 2013).

Another visible expression of topography in vegetation patterns are contrasts between sunny and shady slopes (Fan et al., 2019; Pelletier et al., 2018). In steppe ecotones, for example, aspect and its effects on incoming radiation and water supply strongly determine the occurrence of forests (H. Liu et al., 2012). Generally, in water-limited environments ($E_{pot} > P$), cooler pole-facing slopes support lusher vegetation (Figure 2c), while in energy-limited environments ($E_{pot} < P$), warmer equator-facing slopes allow for higher plant productivity and longer growing seasons, as indicated by higher tree lines.

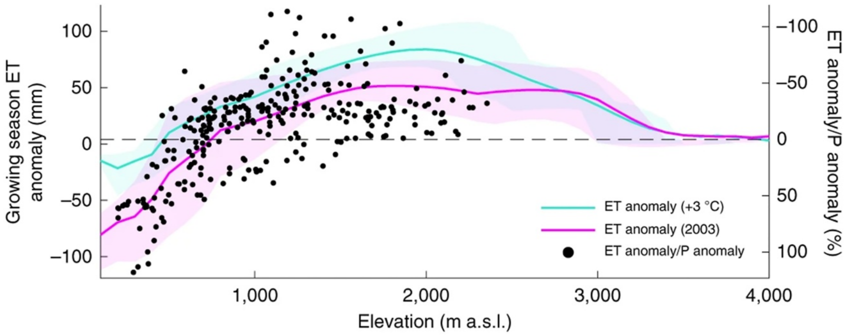


Figure 3. Drought paradox in the European Alps. During the 2003 heatwave or with a warming climate, actual evaporation will respond differently with elevation. At low elevations, water is limited and evaporation is reduced, while at high elevations greater evaporative demand and longer growing seasons enhance evaporation. The solid lines (left axis) show evaporation anomalies, computed based on the 2001–2003 mean and averaged over 100 m elevation bins, for the 2003 heatwave (magenta) and for a +3°C climate change scenario (cyan); the shaded areas show interquartiles ranges. The solid points (right axis) show the ratio of evaporation anomalies to precipitation anomalies for 334 catchments, indicating how strongly evaporation anomalies contributed to the streamflow deficits during the 2003 growing season. From Mastrotheodoros et al. (2020) with permission from Springer Nature.

These vegetation patterns are often closely related to soil moisture, the large-scale distribution of which is strongly controlled by climate, especially precipitation (McColl et al., 2017). Consequently, at the scale of whole mountain ranges, soil moisture will tend to follow patterns in the climatic water balance (e.g., Stark & Fridley, 2023). Especially in mid-latitude mountains, soil moisture will first increase with elevation but may decrease again when temperatures become so low that freezing becomes important. For instance, soil moisture was found to peak at around 2,000 m in the Swiss Alps due to seasonal freezing (Pellet & Hauck, 2017). This threshold elevation will depend on the climate zone, but it is likely that similar patterns of soil moisture exist across many mid-latitude mountain ranges. At catchment and hillslope scales, surface and subsurface lateral redistribution of water along topographic gradients becomes more important (Fan et al., 2019). Especially under wet conditions, topography strongly influences the spatial organization of soil moisture through gravity-driven flow, while under dry conditions, differences in evaporation can have a stronger effect (Grayson et al., 1997; Western et al., 1999). Sunny slopes generally exhibit lower soil moisture than shady slopes (H. Liu et al., 2012; Fan et al., 2019), unless cold temperatures result in freezing (Seyfried et al., 2021). These processes, despite occurring at rather small scales, can have a considerable effect on larger scale land-atmosphere fluxes and water balances (Fan et al., 2019; Stieglitz et al., 1997).

Evaporation (E_{act}) fluxes along elevational gradients—closely linked to vegetation activity as transpiration is the dominant evaporative flux globally (Jasechko et al., 2013; Wei et al., 2017)—are strongly controlled by interactions in atmospheric water availability and demand. In regions where precipitation increases and potential evaporation decreases with elevation, such as the Californian Sierra Nevada (Goulden et al., 2012) or the European Alps (Mastrotheodoros et al., 2020), vegetation becomes increasingly energy-limited with elevation (see Figure 2a), often resulting in peak evaporation (primarily transpiration) at mid-elevations. This elevational change in aridity (E_{pot}/P) is key to understanding the "drought paradox," in which evaporation in large parts of a mountain range can be higher than average in warm and dry years despite low precipitation (Jolly et al., 2005; Mastrotheodoros et al., 2020; Teuling et al., 2013). At low elevations, water supply from precipitation is already limited and dry conditions further reduce evaporation. At mid- to high-elevations, however, water is not limited, so greater evaporative demand and longer growing seasons enhance evaporation, resulting in overall higher evaporation rates (see Figure 3). In addition to these elevational patterns, sunny slopes generally support larger amounts of evaporation, particularly in absence of water limitations.

Low temperatures impose physiological limits on vegetation activity, often seasonally, that is outside the growing season (Cooper et al., 2020; Goulden et al., 2012; Hunsaker et al., 2012; Körner, 2021). For instance, in the Boulder Creek catchment in the Colorado Front Range, growing season length was found to be shortened by 50 d/km uphill (Barnard et al., 2017). Similarly, reductions in plant biomass with elevation can reduce transpiration by as much as the reduction in atmospheric energy supply (van den Bergh et al., 2013). The decrease in temperature with elevation (or on pole-facing slopes) can thus limit transpiration independent of atmospheric demand, constituting a temperature limitation that is (related to) but distinct from an energy (E_{pot}) limitation (Bowling et al., 2018; Churkina & Running, 1998).

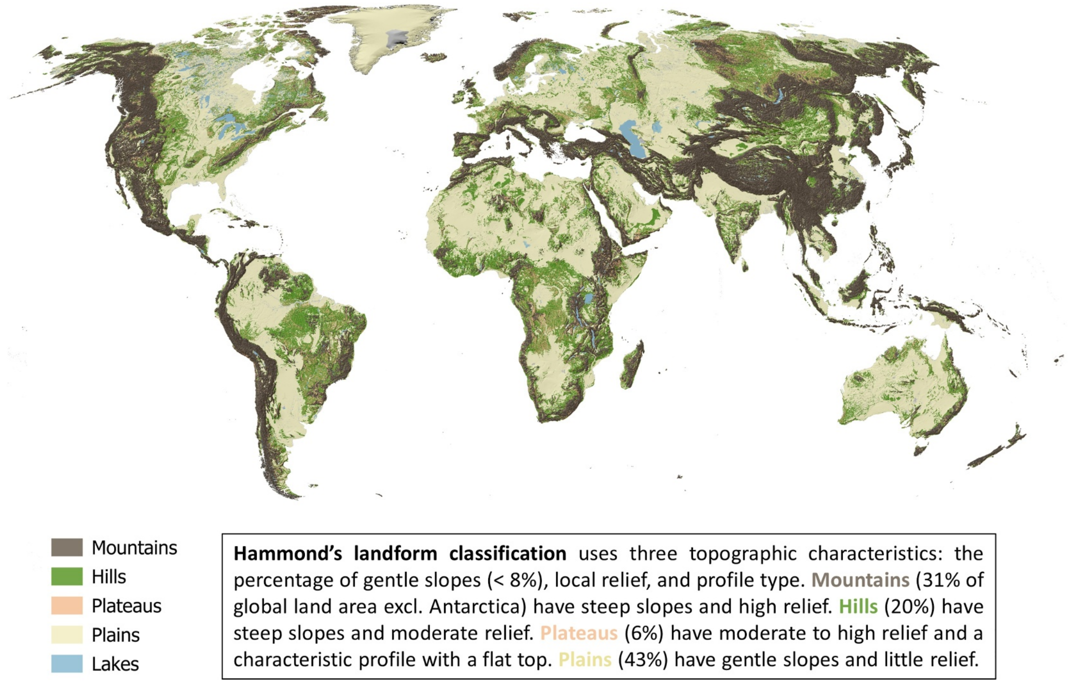
Lower temperatures at higher elevations also increase the fraction of precipitation falling as snow, which was found to be associated with a decrease in evaporative fraction (E_{act}/P) for the same climatic aridity (E_{pot}/P; Berghuijs et al., 2014). Several explanations have been put forward to explain how variable snow fractions might affect evaporation and streamflow, related to differences in timing and intensity of snowmelt and to changes in the energy balance (see e.g. Gordon, Brooks, et al., 2022). In particular, reduced snow cover decreases the albedo, increasing net radiation and temperature and hence evaporation (Meira Neto et al., 2020; Milly & Dunne, 2020). This effect is not always taken into account, even though potential evaporation might be overestimated by up to 50% if increases in albedo due to partial snow cover are neglected (Meira Neto et al., 2020).

Lateral redistribution of water along topographic gradients, either via unsaturated flow or groundwater flow, can decouple local water availability and thus evaporation from climatic water supply, both at hillslope (Fan et al., 2019) and larger scales (Maxwell & Condon, 2016; Maxwell & Kollet, 2008; Miguez-Macho & Fan, 2021). Water redistribution is particularly important in areas with considerable relief and can be both positive and negative, by removing water upslope and providing it downslope (Fan et al., 2019; Stieglitz et al., 1997). In the lower elevation zones of the Upper Merced River catchment in Yosemite Valley, for example, transpiration shows little sensitivity to year-to-year climate variability due to topographically controlled high soil moisture (Christensen et al., 2008). And in the Monte Desert in Argentina, vegetation is sustained by Andean snowmelt delivered from hundreds of kilometers away (Jobbágy et al., 2011). Globally, 10% of vegetation is estimated to rely on water sourced from upslope areas, a dependence that increases in riparian forests and desert oases to up to 47% (Miguez-Macho & Fan, 2021).

3.3. Earth's Major Landforms and the Critical Zone

Tectonic and isostatic uplift and subsidence, as well as weathering and erosion, drive landscape evolution and give rise to Earth's major landforms, such as mountains, plains, and plateaus (see Figure 1b). These landforms can be classified using topographic data (E. H. Hammond, 1954; Meybeck et al., 2001) and are relevant for hydrology as a first-order guide to the main water stores in different landscapes. Uplands (mountains, hills, and plateaus) undergo net erosion and make up slightly more than half of Earth's land area (approximately 57% excluding Antarctica; Karagulle et al., 2017); as show in Figure 4. Here, water is mostly stored in soils and unconsolidated rock (regolith), or fractured bedrock. Lowlands (plains) undergo net deposition and make up the remainder of Earth's land area (approximately 43%). Here, water is stored in soils and thick layers of sediments, which often harbor large aquifers. In addition to these below ground stores, water can also be stored in surface waters and as snow or ice, the latter being more important in typically colder mountain regions (see Section 3.1). Within (some of) these landforms, the critical zone—ranging from the canopy to fresh bedrock (Grant & Dietrich, 2017)—is further influenced by topography-induced differences in climate, the gravity-driven movement of water and material, and by the interaction of topography with regional tectonic stress fields (see Figures 5b–5d).

Weathering processes are strongly conditioned by water availability and temperature. Cold and dry climates favor physical weathering, whereas warm and wet climates favor chemical and biological weathering (Riebe et al., 2015; Schaetzl & Anderson, 2005); see Figure 5a. As a consequence, physical weathering processes become more dominant at higher elevations (e.g., due to freeze-thaw processes), resulting in the production of coarse sediments (Dahlgren et al., 1997; Riebe et al., 2015), including those constituting typical alpine landforms such as talus, moraines, and rock glaciers (Hayashi, 2020). As we move downhill, higher temperatures enhance chemical weathering rates, at least until water becomes limiting. Soil organic content often increases with elevation (up to non-vegetated elevations) due to slower breakdown of organic material and wetter conditions (Dieleman et al., 2013; Egli et al., 2008). Similarly, we find more organic-rich soils on cooler and wetter shady slopes, especially in water-limited environments (Pelletier et al., 2018). On steep slopes, landsliding and a high mobility of sediments limit the time available for weathering, so that sediment is coarser when it enters the stream (Riebe et al., 2015; Shobe et al., 2021). At larger scales, preferential transport of fine materials may further lead to a shift toward finer sediment downstream (Schaetzl & Anderson, 2005). Exceptions might arise if sediments have a different origin, such as glacial deposits, which cover about 10% of the global land area (Börker et al., 2018). Former glaciations might have "reset" the equilibrium that might otherwise be expressed in land surface processes (Church & Slaymaker, 1989), and may lead to large swaths of coarse sediments also in lowlands (e.g., in



Hammond's landform classification uses three topographic characteristics: the percentage of gentle slopes (< 8%), local relief, and profile type. **Mountains** (31% of global land area excl. Antarctica) have steep slopes and high relief. **Hills** (20%) have steep slopes and moderate relief. **Plateaus** (6%) have moderate to high relief and a characteristic profile with a flat top. **Plains** (43%) have gentle slopes and little relief.

Figure 4. Global distribution of landforms based on Karagulle et al. (2017), excluding Antarctica. Lakes are from the Global Lakes and Wetlands Database (Lehner & Döll, 2004). According to this classification, uplands (mountains 31%, hills 20%, plateaus 6%) comprise 57% of the land area, and lowlands (plains) comprise 43%. This compares well with Pelletier et al. (2016b) who estimate 54% uplands and 44% lowlands globally (the remainder are water and ice).

northeastern Europe). The relationship between topography and soil structure is less explored, but since soil structure is promoted by vegetation and biological activity (Bonetti et al., 2021), it will likely show some relationship with elevation and slope aspect (see Section 3.2). The interplay between soil properties, such as soil texture, soil organic content, and soil structure, determines soil hydrological properties (e.g., water holding capacity and hydraulic conductivity), in turn influencing water availability, infiltration, and runoff (Vereecken et al., 2022).

Topography-induced differences in potential energy drive the movement of water and sediment, making topography the dominant control on erosion rates globally (Harel et al., 2016; Hergarten & Kenkmann, 2019; Montgomery & Brandon, 2002). In uplands with steep slopes (≈0.1 m/m on average; see Supporting Information S1), soils are usually a few decimeters to a few meters deep, though they may also be completely absent in some regions (Pelletier et al., 2016b). There is ample empirical evidence that soil depth is inversely related to topographic slope (Brosens et al., 2020; McKenzie & Ryan, 1999) and curvature (Heimsath et al., 1997; Patton et al., 2018; Tesfa et al., 2009), and process-based models confirm this relationship theoretically (Dietrich et al., 2003; Pelletier & Rasmussen, 2009; Pelletier et al., 2016b); see Figure 5b. In valley bottoms, the accumulation of alluvium and colluvium can lead to sedimentary deposits tens of meters thick, even in uplands (Pelletier et al., 2016b). In lowlands with gentle slopes (≈0.01 m/m on average), sedimentary deposits can be tens to hundreds of meters thick. Here, sediment depth is less strongly controlled by surface topography, but has been shown to be inversely related to topographic roughness, likely because rugged terrain limits the deposition of sediments by, for instance, glaciers (Pelletier et al., 2016b).

In uplands, regolith thickness can range from a few meters to tens of meters, and there is increasing evidence that the influence of topography extends deep into the subsurface (see e.g., review by Riebe et al. (2017)). Rempe and Dietrich (2014) hypothesized that drainage of fresh bedrock controls regolith depth from the bottom up, leading to thicker regolith profile upslope where water tables are deeper and the subsurface is flushed more regularly by infiltrating water (Figure 5c). On the other hand, climatic differences such as an increase of precipitation with elevation might control regolith depth from the top down, particularly in water-limited regions. For example, in the Californian Sierra Nevada regolith depth increases markedly with elevation, at least up to elevations where the

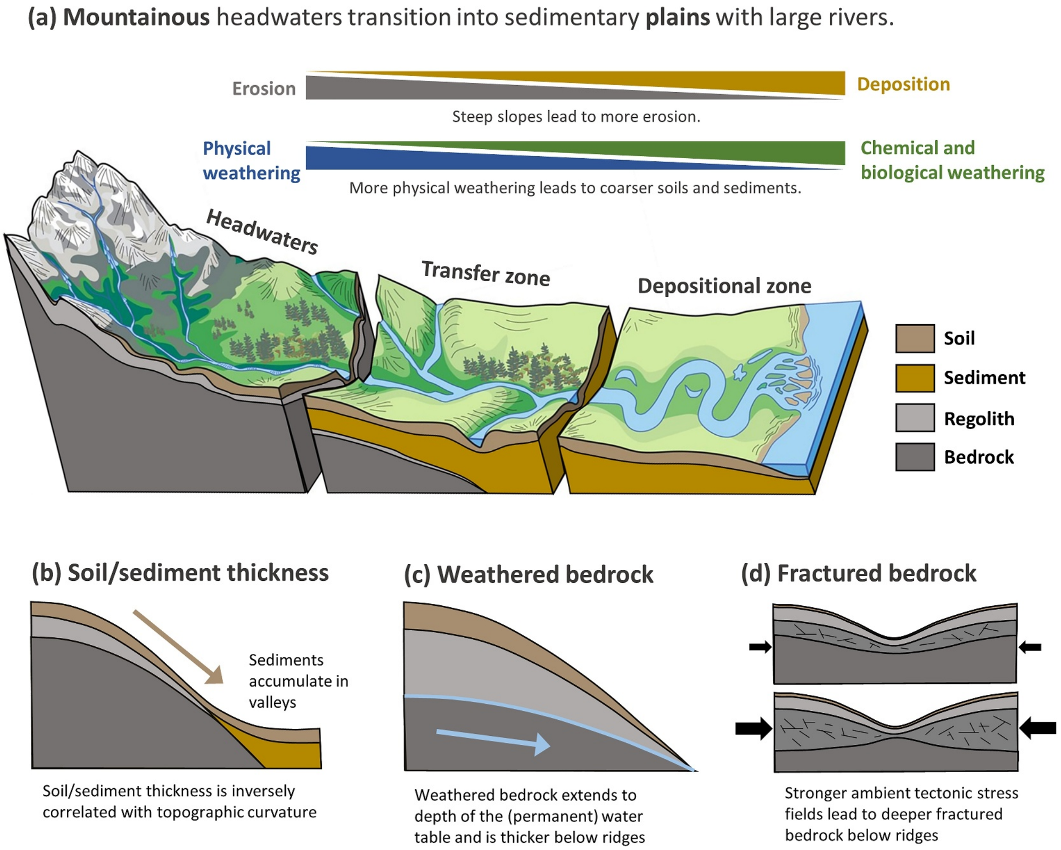


Figure 5. (a) Along topographic gradients, we find typical geomorphic and fluvial landforms, ranging from mountainous headwaters to large rivers traversing sedimentary plains. Mountains are dominated by erosion, while plains are dominated by deposition. Weathering at high elevations is mostly physical due to lower temperatures, leading to coarse soils and sediments, including alpine sediments like talus and moraines. At smaller scales, topography organizes the critical zone by controlling (b) soil and sediment depth, (c) the thickness of the weathered zone, and (d) the distribution of bedrock fractures. Figure in (a) is based on https://www.nps.gov/subjects/geology/fluvial-landforms.htm (originally by Trista L. Thornberry-Ehrlich, Colorado State University, after Miller, 1990), (b) and (c) are based on Riebe et al. (2017), and (d) is based on Pelletier et al. (2016b).

effects of former glaciation become relevant (Klos et al., 2018). Similarly, pole-facing slopes tend to develop deeper regolith as they are wetter (Churchill, 1982; Pelletier et al., 2018), and as they experience deeper rock damage due to frost cracking (Riebe et al., 2017). While these examples highlight how weathering can control regolith production, the removal (transport) of regolith via erosion, generally more efficient in steeper environments, can also limit regolith depth. In Uganda, for example, tectonically active regions traversed by well incised stream channels have thinner regolith, whereas tectonically quiet, flat areas can retain a deeply weathered mantle of crystalline rock (Taylor & Howard, 2000). Most rocks are already fractured when they are uplifted to the near-surface (Molnar et al., 2007), providing hotspots for infiltration and weathering. The interaction of topography with regional tectonic stress fields might further open, grow, or compress rock fractures and thereby affect regolith depth (St. Clair et al., 2015); see Figure 5d. Generally, weathered and fractured rock layers can constitute large fractions of root zone storage, and in some regions rock moisture can provide more than 300 mm of water annually (McCormick et al., 2021).

3.4. River Networks and Surface Waters

River networks follow topographic gradients (see Figure 5a). In mountain landscapes, rivers commonly incise uplifting landscapes and in this way determine the pace of denudation by setting the base level of hillslopes (Burbank et al., 1996). When entering mountain forelands with gentler slopes, rivers start to deposit their sediments and form larger alluvial systems, ranging from stable meandering channels to highly dynamic braided channels (Charlton, 2007). Rivers often migrate gradually through floodplains, but can also relocate rapidly during so-called avulsions. Avulsions can cause rivers to migrate laterally, sometimes in conjunction with devastating floods, and to split into multiple channels, forming alluvial fans and deltas (Brooke et al., 2022). Lakes and wetlands also follow topography and tend to occur in local topographic lows, particularly in humid regions or previously glaciated areas without extensive drainage networks, and in continental topographic lows along the coast (Bertassello et al., 2018; Fan & Miguez-Macho, 2011; Hu et al., 2017).

Especially when viewed from above, many river networks exhibit a deep sense of regularity that is accompanied by scale-invariant properties. At least since the work of Horton (1945) and Strahler (1957), stream ordering systems have been used to derive, relate, and ultimately explain various, often fractal properties of network structure (i.e., topology). A theory that reproduces the fractal properties of river networks well is the concept of optimal channel networks, which assumes that river networks, when they are in equilibrium between uplift and erosion, self-organize toward a state that minimizes energy dissipation through the network (Hergarten & Pietrek, 2023; Rinaldo et al., 1992; Rodriguez-Iturbe & Rinaldo, 1997). More recently, linking river network structure, hydrological dynamics, and ecology has enabled new ways to describe and understand how rivers provide important ecological corridors and pathways for species, populations, and pathogens (Rinaldo et al., 2020; Rodriguez-Iturbe et al., 2009).

In addition to dimensionless properties of network structure, there are river network properties that relate to physical size and thus tie these topological structures back to the topographic dimensions of real landscapes. One such property is drainage density, usually defined as the ratio of total channel length to catchment area, which is strongly dependent on the minimum upstream area needed for a channel to initiate (Horton, 1932; Tarboton et al., 1992). While field and theoretical studies have shown that climate, vegetation, relief, and lithology influence drainage networks (Collins & Bras, 2010; Melton, 1957; Moglen et al., 1998), increasingly available large-scale data sets now allow to investigate the controls on drainage densities at unprecedented scales. For example, by analyzing 101 catchments in the USA, Sangireddy et al. (2016) found that drainage density increases with increasing precipitation and greater relief in humid regions. By contrast, drainage density decreases with precipitation in semi-arid to arid regions, related to denser vegetation cover, and shows little relationship with relief. Lastly, time plays a crucial role in creating the layout of river networks. For instance, many landscapes sculpted by recent glaciations are in a transient state and still require thousands of years to attain their equilibrium dendritic form (Wickert, 2016).

Within their channel networks, rivers store less than 0.01% of all freshwater, yet they transport approximately one third of precipitation falling over land back to the oceans (Dorigo et al., 2021; Oki & Kanae, 2006). Some water is also discharged to the oceans underground through groundwater systems, but this flux is comparatively small (smaller than 1%; Luijendijk et al., 2020). About one fifth of the land area does not drain to the oceans (J. Wang et al., 2018). The water trapped in these endorheic basins leaves as evaporation (including transpiration), which together with evaporation from all other land areas, makes up the other two thirds of precipitation falling over land (Dorigo et al., 2021; Oki & Kanae, 2006). Rivers also redistribute large amounts of water over the land surface, somewhat offsetting the uneven distribution of precipitation (see Figure 1d). Mountains often receive more precipitation than other landscapes, which they store temporarily as snow or ice, and then deliver it to their downstream regions. Since over 50% of mountain areas play an essential or supportive role for water supply in their downstream regions, mountains are often considered the water towers of the world (Viviroli et al., 2007). The role of mountains as water supply systems is especially important if their storage is large, their provision is stable, and if the demand downstream is high (Immerzeel et al., 2020). In South America, for example, mountains play an increasingly important role as we move from the tropics to the mid-latitudes, since low elevations become more water-limited and the amount of snow storage increases with latitude.

How effective river systems are in routing water, and how they produce flood water levels and floodplain inundation areas, strongly depends on topographic features such as channel slope, channel geometry, and floodplain morphology (Bates & De Roo, 2000; Devitt et al., 2023; Yamazaki et al., 2011), as well as network structure and drainage density (Basso et al., 2023; Pallard et al., 2009; Rodriguez-Iturbe & Rinaldo, 1997). Steep valleys with efficient drainage networks are particularly prone to flash floods (Gaál et al., 2012), with potential for heavy damage due to faster flow velocities and the additional risk of erosion, debris transport, and landslides (Bronstert et al., 2018; Dietze et al., 2022). Extensive, flat areas like sedimentary plains are less at risk from flash floods, at least in humid regions, but continued heavy rainfall or snowmelt upstream can lead to overbank floods of long duration (Gaál et al., 2012). Since these floods usually occur further downstream in the depositional zones of large streams (see Figure 5a), they have low flow velocities and lack the capacity to carry much coarse material.

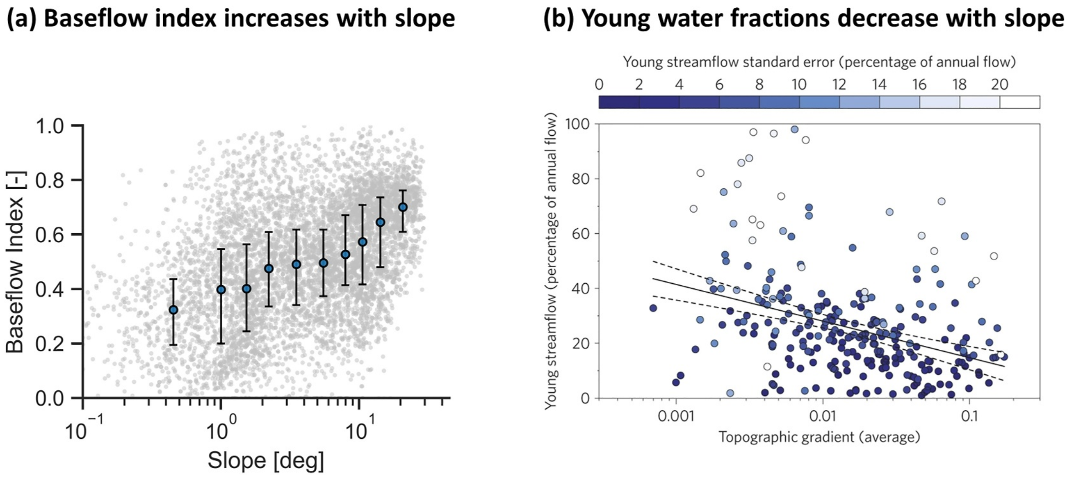


Figure 6. Steeper catchments release more baseflow and older water, as indicated by large samples of catchment data. (a) Baseflow index (BFI; the ratio of baseflow to total streamflow) against topographic slope (Spearman rank correlation $\rho_s = 0.44$) for 6,830 catchments from the Caravan data set (Kratzert et al., 2023a). Note that accounting for aridity (partial $\rho_s = 0.44$) and snow fraction (partial $\rho_s = 0.42$) via partial correlations does not alter the correlation substantially. (b) Young water fractions against topographic slope ($\rho_s = -0.36$), taken from Jasechko et al. (2016) with permission from Springer Nature.

4. Below the Surface

4.1. Local Redistribution of Water

Topography influences how water moves through the landscape, thereby affecting both catchment response and transit times, which in turn determine the dynamics of a stream and the quality of its water. Although these processes mostly operate at the headwater scale, they are critical for global water and nutrient cycling, as headwater streams are estimated to account for 70%–80% of global stream length (Downing et al., 2012; Wohl, 2017).

The influence of topography on runoff processes has been studied extensively (M. G. Anderson & Burt, 1978; Beven & Kirkby, 1979; Dunne, 1983). Topography strongly influences stormflow generation through its control on saturated areas, which tend to occur where it is flat and where upstream areas are large (Beven & Kirkby, 1979). Profile curvature (along the topographic gradient) is important because decreasing slopes—associated with concave geometry—slow down flow and thus promote saturation (Troch et al., 2002). Plan curvature (perpendicular to the topographic gradient) is important because it influences convergence or divergence of flow, with convergent areas delivering more water and being more saturated (M. G. Anderson & Burt, 1978; Beven & Kirkby, 1979). This affects both the dominant stormflow generation mechanisms and the spatial distribution of saturated areas and saturated flow. Subsurface stormflow is most common in steep humid regions with convex slopes, while saturation excess flow becomes more important in flat regions with concave slopes, especially if soils are thin (Dunne, 1978, 1983). Within catchments, regions that are flat and have large upstream areas, typically close to the stream network, are most often saturated and generate most runoff. These areas expand with increasing saturation (e.g., after storms), as do stream networks themselves. In contrast to the geomorphic channel network that evolves over geological time scales, the actively flowing network can be highly dynamic and varies on seasonal and event time scales (Godsey & Kirchner, 2014), with dynamics that are strongly shaped by topography (Prancevic & Kirchner, 2019).

It is increasingly recognized that groundwater systems play a key role in the hydrology of mountain regions (e.g., Andermann et al., 2012; Cochand et al., 2019; Illien et al., 2021). There is consequently a clear need to understand the relationship between topography and groundwater-fed baseflow, which is an important source of water in mountains and downstream regions, both for ecosystems and humans (Somers & McKenzie, 2020; van Tiel et al., 2024). Overall, empirical and theoretical evidence suggests that steeper catchments tend to release more baseflow and older water (Beck et al., 2013; Carlier et al., 2019; Jasechko et al., 2016; Santhi et al., 2008; Sayama et al., 2011; Tetzlaff et al., 2009), as shown in Figure 6. This highlights the active role of groundwater in uplands, buffering streamflow seasonally and into dry periods (Hayashi, 2020; Somers & McKenzie, 2020), while

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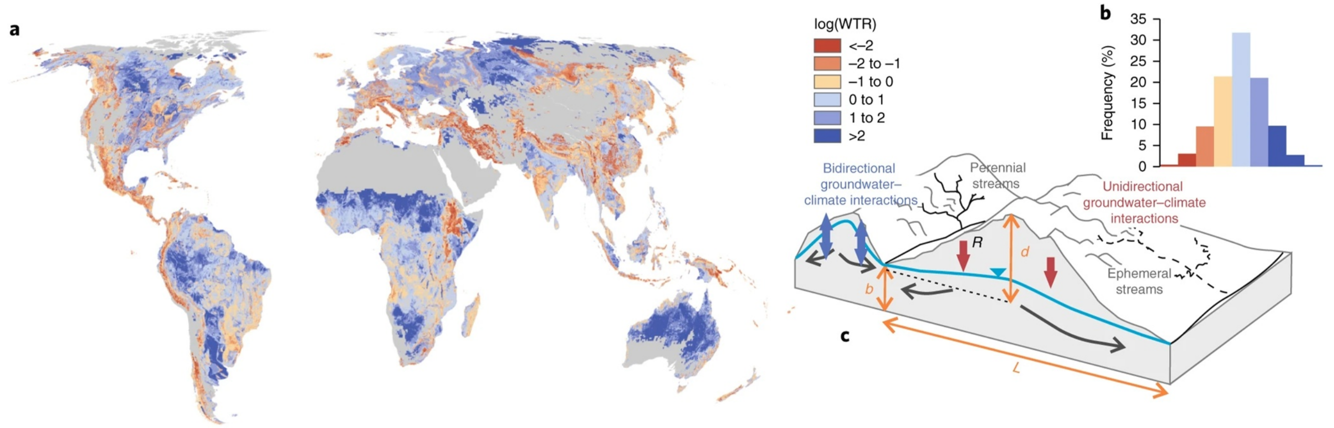

Figure 7. Water table ratio (WTR; Haitjema & Mitchell-Bruker, 2005) is a measure of the relative fullness of the subsurface, indicating whether water tables are topography-controlled (rather shallow) and thus coupled to the atmosphere, or recharge-controlled (rather deep) and thus largely decoupled from the atmosphere. (a) Global map of $\log_{10}$(WTR) with hyper-arid regions of recharge < 5 mm yr^{-1} shaded in gray. (b) Frequency distribution of global values of $\log_{10}$(WTR). (c) Conceptual model of WTR; WTR depends on recharge *R*, terrain rise *d*, distance between perennial streams *L*, saturated thickness of the aquifer *b*, and hydraulic conductivity *K* (not shown here). From Cuthbert et al. (2019) with permission from Springer Nature.

stabilizing stream temperatures and water quality (Hare et al., 2021; Kelleher et al., 2012; Singha & Navarre-Sitchler, 2022).

To better understand the topographic drivers of groundwater-fed baseflow, we may conceptualize baseflow to be controlled by three (inter-related) factors. First, the amount of water that is partitioned into the subsurface; second, the connectivity between groundwater and streams; and third, the dynamics of groundwater flow (i.e., its response time). Steeper slopes are better drained and therefore less likely to be saturated, thus promoting infiltration and deeper flowpaths. This might enhance deep weathering, which in turn increases the storage capacity of the subsurface. In addition, in mountain regions, alpine sediments often constitute highly permeable aquifers with considerable storage capacity (Hayashi, 2020). Groundwater systems in uplands also tend to be better connected to streams, especially in deeply incised valleys that tap into local aquifers (Floriancic et al., 2022; Gleeson & Manning, 2008). While steeper slopes partition more water into (deeper and slower) subsurface flow paths (see Figure 6a), steeper topographic gradients also make baseflow more dynamic (i.e., baseflow variability increases; see Figure S6 in Supporting Information S1). In steep hillslopes, the nature of groundwater flow becomes less diffusive and more kinematic (Brutsaert, 2005; Lyon & Troch, 2007), which can result in fast response times (on the order of days) that may be quick enough to be considered stormflow (Beven, 1982). In summary, topographic controls on groundwater processes are still only partly understood, but there is ample evidence of active groundwater systems in uplands, including many mountainous areas.

4.2. Interactions Between Groundwater and the Land Surface

Distributions of water table depth often mirror surface topography. High up in the landscape, water tables tend to be deep, while at low elevations where water converges, water tables tend to be shallow. Global observations (Fan et al., 2013) confirm this tendency by showing a weak correlation between slope and water table depth ($\rho_s = 0.21$; see Figure S7 in Supporting Information S1). Water table depth is therefore often conceptualized as being controlled (to first order) by topography, as well as climate and geology. These controls can be combined into the water table ratio (WTR; Haitjema & Mitchell-Bruker, 2005). WTR is defined as $WTR = RL^2/mKHd$, where R [m/d] is groundwater recharge, L [m] is the distance between groundwater-fed streams, K [m/d] is hydraulic conductivity, H [m] is the average aquifer thickness, d [m] is the maximum terrain rise, and m [−] is either 8 or 16, depending on the geometry of groundwater flow (1-D linear or radial).

WTR is a measure of the relative fullness of the subsurface, which distinguishes between topography-controlled (rather shallow) and recharge-controlled (rather deep) water tables (Cuthbert et al., 2019; Haitjema & Mitchell-Bruker, 2005). The global distribution of WTR shown in Figure 7 broadly correlates with the global distribution of groundwater levels, which tend to be deep in steep, dry, and highly permeable regions (Fan et al., 2013). In wet

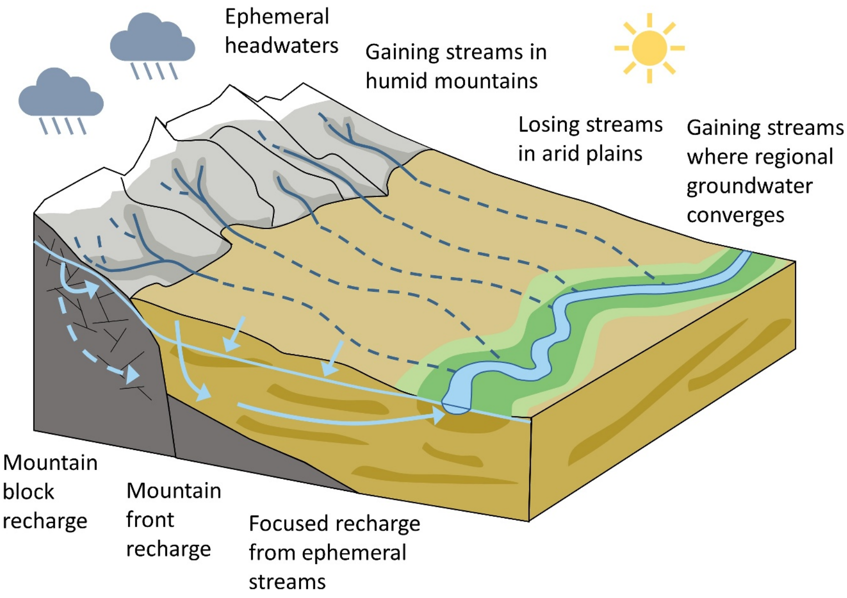

Figure 8. Example of a mountain-plain transition in a dry region (such as the southwestern USA) and associated groundwater-stream interactions and recharge processes. Aligned gradients in climate (wetter in the mountains), geology (more permeable in the plains), and topography (driving water from the mountains to the plains) result in different groundwater-stream interactions. Image based on Thiros (1999).

regions with low permeability, water tables closely resemble local topography. In dry regions with high permeability, water tables follow regional topography. However, despite general agreement on the main drivers, global estimates of water table depth remain highly uncertain. Global hydrological models show a large spread in estimated water table depths and they tend to overestimate topographic controls compared to available observations, introducing large uncertainties into assessments of groundwater accessibility by vegetation, surface waters, and humans (Reinecke et al., 2024).

Water table depth regulates how groundwater interacts with the surface, such as with vegetation and the atmosphere (Cuthbert et al., 2019; Fan et al., 2017; Maxwell & Condon, 2016) and with streams (Winter, 1998). From topography alone, we might expect losing streams in mountainous headwaters with small upstream areas and gaining streams further down in the plains (Fan, 2019); and indeed, many headwater streams with small drainage areas are intermittent or ephemeral, suggesting limited supply of groundwater flow to these streams (Brinkerhoff et al., 2024; Messager et al., 2021). However, as we move from mountains to plains, the climate often becomes drier and bedrock aquifers transition into deep, highly permeable sedimentary aquifers, sometimes depleted due to water withdrawals for irrigation (de Graaf et al., 2019; Jasechko et al., 2021). As a result, we often find gaining streams in mountains, losing streams in mountain foothills, and eventually gaining streams again where regional groundwater systems converge (Jasechko et al., 2021; Jobbágy et al., 2011; Larned et al., 2011; Winter, 2007); see Figure 8. A similar pattern can also be found at smaller scales, where permeability contrasts (from low to high) often lead to water losses into the underlying aquifer (Konrad, 2006). This shows how important it is to consider topographic, climatic, and geological factors in combination, for example, using interactive indices such as the WTR (Figure 7). The tendency for losing streams in flat regions is also reflected in reduced amounts of baseflow (Figure 6a), supporting the idea of limited bi-directional groundwater-stream interactions in the absence of strong relief, especially in drylands (Quichimbo et al., 2020).

If the water table (or the capillary fringe) is shallow enough, plants can access groundwater, and the atmosphere and groundwater systems interact bi-directionally. Globally, an estimated 46% of the land surface is connected to vegetation, mostly in regions with subdued topography (Cuthbert et al., 2019); see Figure 7. Within all climate zones, landscape position alters forest growth patterns, both positively (e.g., in oases) and negatively (e.g., in swamps; Roebroek et al., 2020). Along smaller-scale topographic gradients, vegetation-groundwater interactions are expressed in varying rooting depths (Fan et al., 2017). In uplands with deep water tables, roots tend to be shallow and rely on precipitation as their water source. In lowlands with shallow water tables, roots tend to be shallow to avoid oxygen stress. In between, roots can grow deep and tap (at least temporarily) into aquifers, coupling groundwater to the atmosphere (Fan et al., 2017) and leading to high ratios of transpiration to soil evaporation because only roots can access this deeper water (Maxwell et al., 2014). The topographically-driven connection between vegetation and groundwater also alters how vegetation responds to changes in climatic conditions, with shallow groundwater tables in topographic lows providing a crucial buffer against plant water stress (Condon, Atchley, & Maxwell, 2020; Emanuel et al., 2014).

4.3. Regional Redistribution of Water

Regional groundwater systems can deliver water to areas far away from the original atmospheric supply of groundwater recharge and can be an important element of water and solute balances (Ameli et al., 2018; Condon, Markovich, et al., 2020; Fan, 2019). For instance, deep groundwaters might emerge 1,000 m downhill as mountain block recharge, sometimes suggested to be decades or even centuries old (Alvarez-Campos et al., 2022). The evaporation of this remotely sourced groundwater might even lead to enhanced precipitation through local moisture recycling, especially in dry regions (Bierkens & van den Hurk, 2007; Anyah et al., 2008). Regional groundwater flow systems are usually similar in scale and direction to their topographic driver (Gleeson & Manning, 2008; Tóth, 1963). However, the (relative) importance of regional groundwater flow is also greatly influenced by climate and geology, and is greatest in dry regions with deep, permeable substrate, that is in regions with recharge-controlled water tables (Condon & Maxwell, 2015; Fan & Schaller, 2009; Gleeson et al., 2011). Overall, estimating actual groundwater fluxes at large scales is still challenging due to uncertainties in both data sets and model representations, making global scale estimates of groundwater fluxes—similar to water table depths (Reinecke et al., 2024)—very uncertain (Condon et al., 2021; Gleeson et al., 2021).

Groundwater flow between surface catchments is common and can make up a considerable fraction of a catchment's water balance, particularly for small catchments. In some cases, groundwater exports can be up to an order of magnitude larger than streamflow exports (Neu et al., 2011). A global study with thousands of catchments concluded that 36% of catchments showed substantial deviations between topographically-delineated surface catchment areas and effective catchment areas (Y. Liu et al., 2020). Flatter catchments showed larger variability in their water balances, possibly because lowlands with highly permeable sediments (e.g., glacial landscapes, alluvial plains) and/or drier climates have a lot of inter-catchment groundwater flow even in the absence of strong relief (Devito et al., 2005). This interplay between topographic, climatic, and geologic factors is captured by the WTR (Gleeson et al., 2011), which, however, cannot directly predict groundwater exports and imports. While catchments at the upper end of a regional topographic gradient are more likely to be groundwater exporters and catchments at the lower end more likely to be groundwater importers (Fan, 2019; Gordon, Crow, et al., 2022), these linkages and the magnitude of these fluxes remain poorly constrained at the global scale.

Mountain system recharge refers to all water that originates in the mountain block and recharges basin-fill aquifers (Bresciani et al., 2018; Markovich et al., 2019; Wilson & Guan, 2004). It can be divided into (surface) mountain front recharge, which is water lost by mountain streams at the mountain front, and diffuse and focused mountain block recharge, which is water that enters basin-fill aquifers via different subsurface paths (Bresciani et al., 2018; Markovich et al., 2019); see Figure 8. Mountain block recharge is estimated to make up 5%–50% of basin-fill recharge and can therefore be a crucial water source, especially in dry regions (Markovich et al., 2019). In theory, the potential for mountain block recharge is highest in regions with important regional groundwater systems, characterized by high permeability, thick aquifers, deep water tables, little stream incision and high elevation above the adjacent basin (Markovich et al., 2019). In practice, knowledge about mountain block recharge is mostly limited to a few well-studied sites and transferability is often complicated due to geological heterogeneity. Also, while more and more studies quantify the amount of mountain block recharge, less is known about travel and response times of these groundwater systems, which may range from a few decades to several millennia (Gardner & Heilweil, 2014). Globally, 25% of all land area is estimated to have groundwater response times of less than 100 years, including large parts of humid mountain ranges like the Oregon Cascades or the European Alps (Cuthbert et al., 2019). While these estimates are very uncertain, they provide a starting point for anticipating the effects of climate change, such as the time scales after which streams may shift from gaining to losing conditions (Duffy, 2004).

5. Discussion and Conclusion

The following section is divided into six parts. We first present organizing principles (Section 5.1), then discuss potential climate change impacts (Section 5.2) and the relationship between topography and human activity (Section 5.3). We subsequently identify data needs (Section 5.4) as well as open questions (Section 5.5), and finally draw some conclusions from our review (Section 5.6).

5.1. Organizing Principles

We organize this discussion around two types of general features, which are often associated with and sometimes caused by topography: gradients and contrasts. Gradients are defined as systematic (typically smooth) changes of a variable through (geographical) space, such as lapse rates or precipitation-elevation relationships. Contrasts are defined as step changes, such as differences between sunny and shady slopes, sharp changes in geology, or threshold-like features such as the snow line.

Important topography-related gradients and contrasts as well as other effects are summarized in Table 1. Of course, no gradient or contrast is perfectly defined and without noise, as natural heterogeneity and interacting processes always result in scatter that may blur the underlying patterns. Whether certain gradients or contrasts dominate will further depend on the scale of analysis. For instance, we may find thicker regolith on sunny instead of shady slopes due to confounding geological conditions, such as foliation parallel or perpendicular to the land surface (Leone et al., 2020). In this case, the dominant local contrast is geology, yet across many sites, the climatic contrast will emerge as the dominant driver of regolith thickness (Yetemen et al., 2015). The conceptual focus on gradients and contrasts may not be equally useful for all environmental processes. However, gradients and contrasts can help us (a) synthesize and organize our conceptual understanding, (b) analyze data and design observational networks, and (c) advance predictive modeling across a wide range of processes.

1. Gradients and contrasts are potential building blocks for system conceptualizations (or so-called perceptual models; Enemark et al., 2019; Wagener et al., 2021) aimed at explaining the dominant characteristics and processes of environmental systems. For example, Roebroek et al. (2020) combined gradients in climate and topography (landscape position) to explain hydrological controls on forest growth globally. And Pelletier et al. (2018) combined contrasts in slope aspect with multiple gradients (e.g., elevational and latitudinal gradients in climate) to explain why sunny and shady slopes differ systematically in their slope steepness. Such simplifications help us to break down even highly complex systems into their dominant constituents, and provide a basis for posing hypotheses on how changing controls might impact overall system behavior.
2. Gradients and contrasts can be used to design experiments or observational networks. This has been done for decades in (small-scale) field hydrology (e.g., Goulden et al., 2012; Robins et al., 1965; Zacharias et al., 2011) and in environmental research more generally (e.g., Rosero et al., 2010; Sanders & Rahbek, 2012), but it is less common for large-scale hydrology. Large sample, multi-site data sets are often put together retrospectively, but they were not conceived as networks a priori (Wlostowski et al., 2021). Practical reasons such as limited funding and organizational challenges notwithstanding, this can limit the scientific insights gained in comparative studies.
3. Gradients and contrasts provide information for model building and evaluation. First, they may be used as constraints on a priori parameter ranges and relative behavioral differences in models. For instance, Hartmann et al. (2015) used four contrasting karst landscapes—delineated by climate and relief—to define hydrologically similar landscapes, which made it possible to reduce parameter uncertainty for ungauged locations. Second, relationships that emerge along gradients and contrasts can be used to evaluate spatially distributed models, which should realistically reproduce patterns found in observations (Dallan et al., 2023; Gnann et al., 2023). These strategies are rarely used in large-scale hydrological modeling to date, but offer a great opportunity to improve our predictive modeling capabilities and to establish perceptual models that can be compared with different simulation models (Gleeson et al., 2021; Wagener et al., 2021).

Environmental gradients both exist along locations that are spatially connected and along locations that vary systematically with respect to one or more environmental variables. For instance, we often look at individual places that span a range of climate regimes but are not directly connected in space. This approach is useful but treats places (or catchments) like isolated entities, even though they are often organized in networks (Phillips et al., 2015) and connected to their wider environment, with water moving downwind in the atmosphere, downstream in rivers, and downgradient in groundwater systems (Sivapalan, 2017). For example, to understand

Table 1
Summary Table Organizing the Main Findings of the Review

Theme	Key points
I. Above the surface	1. **Planetary scale stationary waves** induced by large orographic features can influence precipitation thousands of km away 2. **Frontal precipitation** (typical for the mid-latitudes) usually increases with elevation until atmospheric moisture is depleted (e.g. in very high mountains); rainfall gradients can sometimes exceed 1,000 mm/km (G) 3. **Convective precipitation** (typical for the tropics) usually leads to low- or mid-elevation precipitation maxima (G) 4. **Extreme precipitation intensities**, associated with convective storms, often decrease with elevation in mid-latitudes (G) 5. **Rain shadow** effects result in windward sides receiving more precipitation than leeward sides, sometimes up to a factor of 10 (C) 6. **Clear sky radiation** increases with elevation, but **net radiation** often stays constant or decreases due to increasing cloud cover and increasing albedo; exceptions are arid and cloud-free mountains, for example, in the tropics (G) 7. **Potential evaporation** (the energy available for all evaporative fluxes including transpiration) mostly decreases with elevation; gradients are often on the order of −100 mm/km or more (G) 8. **Equator-facing slopes** receive more radiation, and are thus warmer and drier, than **pole-facing slopes**; this contrast gets stronger with increasing slope steepness and with increasing latitude (C)
II. At the surface	1. **Surface temperature** decreases with elevation (G) (a) The average lapse rate is often similar to the environmental lapse rate of the free atmosphere (≈6°C/km) (b) Lapse rates are spatially and temporally variable, though, and may even reverse (e.g. during temperature inversions) 2. **Snow accumulation and melt** are especially important at high elevations (a) The elevation at which snow occurs regularly (“snow line”) decreases from about 5,000 m in the tropics down to sea level in polar regions (G/C) (b) The timing of maximum snow accumulation and the start of the snowmelt season are delayed with increasing elevation (G) 3. **Vegetation** and topography are visibly linked, often expressed in elevational zonation of vegetation (a) The tree line decreases from 4,000 to 5,000 m in the tropics down to sea level in (near-) polar regions (G/C) (b) Pole-facing slopes support higher vegetation productivity in water-limited regions, and equator-facing slopes support longer growing seasons in temperature-limited regions (C) 4. **Soil moisture** is controlled by topography through the climatic water balance and moisture redistribution (a) At large scales, soil moisture often increases with elevation due to increasing precipitation, but decreases once low temperatures result in freezing (G/C) (b) At small scales, gravity-driven redistribution of water leads to high soil moisture in areas of topographic convergence, especially under wet conditions (G) 5. **Evaporation** (the integrated land surface latent heat flux) is influenced by topography beyond the climatic water balance in several ways (a) The presence of snow at higher elevations can limit evaporation due to snow hydrological processes and increased albedo (G/C) (b) The decrease of temperature with elevation shortens growing season length and affects vegetation characteristics, which can reduce evaporation independent of atmospheric water and energy supply (G) (c) Water redistribution along topographic gradients enhances water availability downslope; globally, 10% of vegetation relies on water sourced uphill, and in riparian forests and desert oases this can be close to 47% (G) 6. **Earth's major landforms** are closely linked to topography, which has evolved through the interaction of tectonics and climate (C) (a) Uplands (mountains, hills, and plateaus; 57% of land area) have rather steep slopes (≈ 0.1 m/m on average), undergo net erosion and are characterized by bedrock near the surface

Table 1
Continued

Theme	Key points
	(b) Lowlands (plains; 43% of land area) are flat (≈ 0.01 m/m on average), undergo net deposition and are characterized by thick sedimentary deposits (up to several 100 m) 7. **Critical zone characteristics** carry the imprint of topography (a) Cold temperatures at high elevations favor physical weathering, leading to coarser sediments, including alpine sediments such as talus and moraines (G/C) (b) Soil depth is inversely correlated with topographic curvature; soil can be absent in very steep regions and up to a few meters thick in flat regions (G) (c) Drainage of fresh bedrock causes weathering, leading to a thicker weathered zone (regolith) in regions with deeper water tables (e.g. below hilltops) (G) (d) Interactions of topographic and tectonic stress fields control the distribution of open bedrock fractures (G/C) 8. **River networks** follow topography and redistribute water over the land surface (a) Drainage densities increase with greater relief in humid regions but show a weak relationship to relief in semi-arid to arid regions (G/C) (b) Over 50% of mountain areas play an essential or supportive role for their downstream regions, making them the water towers of the world (c) Steep valleys are particularly prone to flash floods, while extensive, flat plains are more prone to overbank floods of long duration (C)
III. Below the surface	1. **Stormflow generation and saturated areas** are controlled by topography (a) Saturation tends to occur where it is flat and upstream areas are large (i.e. in areas of landscape convergence) (G) (b) Subsurface stormflow is common in steep humid regions with convex slopes, while saturation excess flow is common in flat regions with concave slopes (C) 2. **Baseflow** volume and dynamics are influenced by topography (a) Regions with steeper slopes are associated with more baseflow and older water, as they tend to be less saturated, allow for deeper infiltration, and have better groundwater-stream connectivity (G/C) (b) Baseflow in steep regions is more dynamic, that is, it has faster response times and is more variable (G/C) 3. **Water table depth** emerges from the interplay of topography, climate, and geology (a) Water tables tend to be shallower in flat areas and where water converges (e.g. downhill, in valleys) (G) (b) Water table depth is also modulated by climate and geology; in wet regions with low permeability, water tables are shallow and closely resemble local topography, in dry regions with high permeability, water tables are deep and follow regional topography (G/C) 4. **Regional groundwater systems** are most relevant in (dry and highly permeable) regions with little local relief and strong regional relief, indicating where mountain block recharge and inter-catchment groundwater flow are important (G/C) (a) About one in three catchments is estimated to have an effective catchment area that differs substantially from their topographic catchment area; these catchments are mostly located in flat regions (b) Mountain block recharge is estimated to make up 5%–50% of basin-fill recharge

Note. References are left out for readability but are all cited in the text. The letters in parentheses indicate whether the point primarily reflects a gradient (G) or a contrast (C); where there is no letter in parenthesis, the point is not related to a gradient or contrast, and where there are both (G/C), the point might be regarded as either gradient or contrast.

whether a place receives regional groundwater flow or mountain block recharge, we need to know if and how it is embedded into the regional groundwater system (Fan, 2019). Topography is one of the most important organizers of large-scale spatial connectivity, especially at and below the land surface. Using frameworks that consider spatial connectivity along topographic gradients, for example, from summit to sea, will therefore be crucial for a better understanding of large-scale hydrology and should be included in conceptualizations of hydrological systems.

A key challenge for understanding the role of topography in the water cycle is the fact that topography is related to, and often co-evolves with, many other system features (Troch et al., 2015). Many hydrological patterns, such as elevational changes in land-surface fluxes (Figure 3), or groundwater-stream connectivity (Figure 8), are the result of interacting gradients and contrasts. These interactions pose serious challenges if we want to gain mechanistic (or causal) understanding that allows for reliable extrapolation in space and time. Purely statistical analyses might be a good starting point but have limitations, as there is a high chance of spurious correlations in such highly interconnected systems. A prime example is elevation, which is rarely a causal driver but regularly used as a predictor (Körner, 2007). We might address this issue by carefully controlling for certain variables, for instance by using partial correlations, by directly addressing interactions using interactive indices (e.g., WTR; Haitjema & Mitchell-Bruker, 2005), or by using frameworks that combine different variables (e.g., climate and topography; Roebroek et al., 2020). Another strategy is the use of causal inference methods (e.g., causal graphs; Blum et al., 2020; Massmann et al., 2021) or models that encode the (assumed) functioning of a system. This is akin to framing our system understanding as a hypothesis (or multiple competing hypotheses) that can then be tested with empirical data (Clark et al., 2011; Kirchner, 2006; Schumm, 1998).

5.2. Climate Change

The consequences of climate change, such as rising temperatures and changes in other atmospheric variables, can exhibit elevation dependence. Faster warming at higher elevations has been attributed to several possible mechanisms (Pepin et al., 2015), though a recent global analysis showed only a weak tendency with strong variations between regions (Pepin et al., 2022). Empirical studies have further found a tendency for reduced elevation dependence of precipitation in mid-latitudes, possibly related to a weakened jet stream (Luce et al., 2013; Pepin et al., 2022). Model simulations suggest some systematic changes, too, such as weakened rain shadow effects and greater leeward changes in extreme precipitation (Diffenbaugh et al., 2005; Shi & Durran, 2015), but also increases in convective rainfall at high elevations in summer (Giorgi et al., 2016). Overall, however, knowledge of how climate change will alter orographic effects on precipitation and particularly its extremes remains limited (O'Gorman, 2015; Pepin et al., 2022). Changes in potential evaporation will likely follow changes in temperature, but will be modulated by changes in net radiation, relative humidity, and wind speed (Chang et al., 2023; Scheff & Frierson, 2014; J. Sun et al., 2020). There are examples of elevation dependent changes in potential evaporation (Chang et al., 2023; J. Sun et al., 2020), but concurrent changes in other drivers limit our understanding of this effect. For example, wind speed has shown elevation-dependent reductions in some places, which might reduce evaporative demand especially at higher elevations (McVicar et al., 2010). Particularly strong changes are expected at snow-rain transitions, where reduced albedo increases net radiation and temperature disproportionally (Meira Neto et al., 2020; Pepin et al., 2015).

Changes in atmospheric water and energy availability will lead to changes in evaporation and vegetation activity. As shown in Figures 3 and 9, an increase in temperature and thus evaporative demand will have divergent effects on different elevation zones. In many mid-latitude mountain ranges where precipitation increases with elevation, increasing temperatures will likely lead to more water-stressed vegetation at low elevations, while increased evaporative demand and longer growing seasons will enhance evaporation at higher elevations (Jolly et al., 2005; Mastrotheodoros et al., 2020; Teuling et al., 2013); see Figure 9. However, if precipitation gradients change and foothills become wetter (Pepin et al., 2022), we might expect enhanced evaporation also at low elevations (see Figure 9), and in some cases possibly even shifts of plant species downhill (Crimmins et al., 2011). Increases in evaporation, especially at higher elevations, may lead to substantial reductions in streamflow and thus water availability for lowland populations, projected to become more reliant on mountain water resources in the future (Viviroli et al., 2020). Tropical mountains with different precipitation gradients will likely show different patterns, with increased evaporation at lower (energy-limited) elevations and increased water stress at higher elevations, which are sometimes already rather arid environments (Leuschner, 2000). In addition, vegetation itself will modulate how atmospheric changes translate into changes at the land surface. For instance, reductions in stomatal conductance due to increased CO_2 levels will likely lead to lower transpiration rates than the increase in atmospheric evaporative demand would suggest (Milly & Dunne, 2016), though it is not yet clear how elevation dependent changes in plant physiology and partial CO_2 pressure will modulate this effect.

At the land surface, the position along a topographic gradient modulates how atmospheric changes will translate into hydrological changes, with potentially strong implications for ecosystems. Since lateral redistribution of water leads to wetter valleys and drier hilltops, an increase in evaporative demand will lead to a greater evaporation increase in valleys (Condon, Atchley, & Maxwell, 2020; Maxwell & Kollet, 2008); see Figure 9. Similarly, shallow water tables in valleys might reduce tree mortality by providing a buffer against droughts (Esteban et al., 2021; Hawthorne & Miniat, 2018; Hoylman et al., 2019), which are likely to set in quicker and

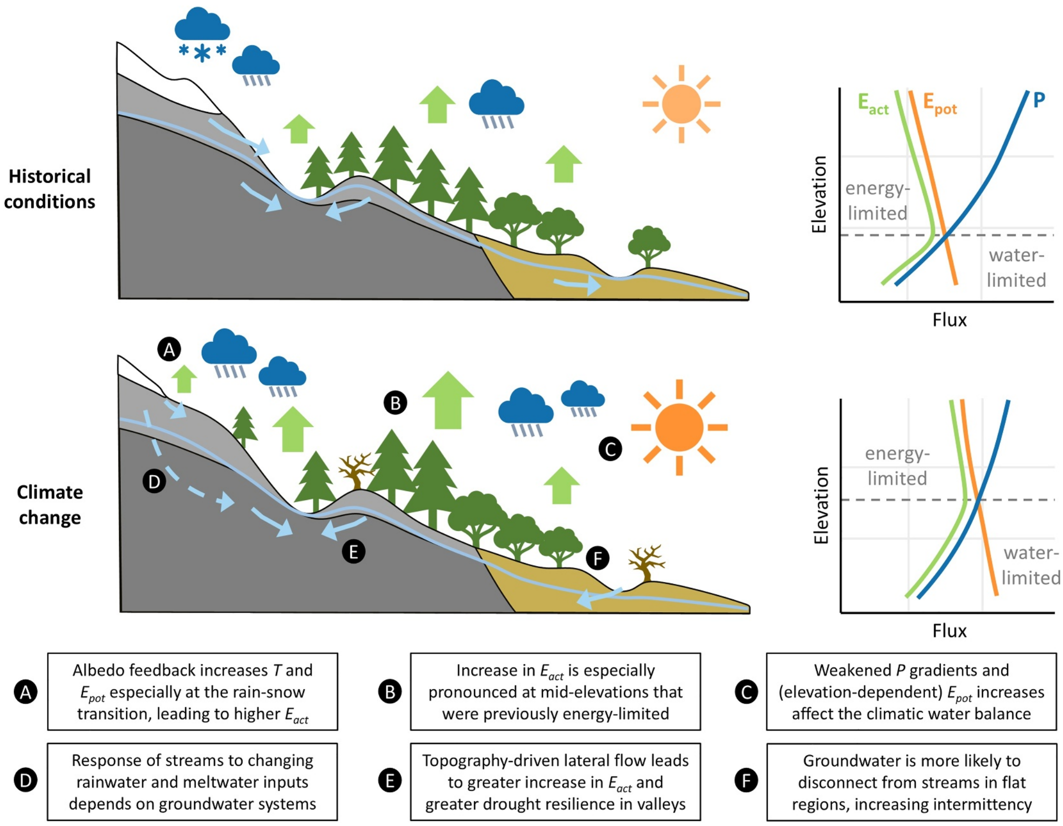

Figure 9. Climate change effects on the water cycle will likely show a strong relationship with topography, especially elevation and slope. This infographic conceptually compares historical conditions to hypothesized future conditions with climate change. The infographic shows a mountain cross-section, highlighting several processes above, at and below the surface (left), and elevation profiles of precipitation, potential evaporation and actual evaporation (right). A uniform increase in E_{pot} will likely lead to more E_{act} at formerly energy-limited elevations, shifting the E_{act} peak upwards, though this effect may be modulated by changes in precipitation gradients, plant physiological responses, and gravity-driven moisture redistribution.

become more intense with climate change (Trenberth et al., 2014). Lateral flow can also modulate the response of soil moisture and water table depth to changes in recharge, with faster declines below hilltops and slower decline in valleys (Maxwell & Kollet, 2008). This can be seen, for instance, in northeastern Germany (Germer et al., 2011), where water tables in local highs (recharge zones) have fallen much faster than water tables in local lows (discharge zones). Groundwater-stream interactions are likely more sensitive to changes in water table depth in flat regions (e.g., plains), where streams already switch from gaining to losing conditions between seasons, rather than in steep regions (e.g., hills), where groundwater levels tend to stay above stream water levels all year round (Miguez-Macho & Fan, 2012).

Rising atmospheric temperatures will lead to changes in the accumulation and melt of frozen water, affecting water availability in mountains and downstream areas. For many glaciated basins, streamflow will initially increase due to increased melt, yet snow and ice melt are projected to decline eventually once these frozen water stores have been depleted (Barnett et al., 2005; Huss & Hock, 2018; Siirila-Woodburn et al., 2021). Such snowmelt trends are worsened by albedo feedbacks (less snow accumulation leads to a darker surface, enhancing absorbed shortwave radiation and snowmelt; Kapnick & Hall, 2010; Pepin et al., 2015). Changes in the amount of snowfall and the seasonal distribution of precipitation are projected to lead to more rainfall-dominated streamflow regimes with lower summer flows (Barnett et al., 2005; Beniston, 2012; Siirila-Woodburn et al., 2021). However, different regions have shown divergent changes in seasonal streamflow timing so far; catchments with higher snow fractions experienced a higher and earlier seasonal peak, while less snowy catchments experienced a delayed flow peak, as they are more sensitive to decreasing winter precipitation (Han et al., 2024).

How exactly streams respond to changes in climatic drivers will critically depend on internal catchment dynamics, which in turn are closely linked to characteristics of and connectivity to groundwater systems (Markovich et al., 2016; Somers et al., 2019; Tague et al., 2008). Because groundwater systems can store water for a long time and slowly release it, they may provide some resilience to declining frozen water stores (Somers & McKenzie, 2020). In addition, permafrost thawing may alter recharge rates and activate previously frozen subsurface compartments, affecting groundwater flow and streamflow (Kuang et al., 2024; X. Wang et al., 2019). At the same time, decreasing recharge rates due to increases in vegetation water use might deplete groundwater stores and consequently reduce streamflow (Carroll et al., 2024). To better anticipate the future of mountain water resources thus requires an integrated understanding of cryospheric and hydrological processes, particularly groundwater processes, whose importance in mountain environments is increasingly recognized (Drenkhan et al., 2022; Hayashi, 2020; Somers & McKenzie, 2020; van Tiel et al., 2024).

5.3. Human Activity

Humans are now considered a geological force affecting the water cycle globally through water use, environmental degradation, and climate change (Abbott et al., 2019; Gleeson et al., 2020; Montanari et al., 2013; Sivapalan et al., 2012; Wagener et al., 2010). Humans also have a close relationship with topography; topography connects people and places, shapes how people use the land and its waters, and influences how people move and where they settle.

Millions of dams worldwide now disrupt stream connectivity that naturally exists along topographic gradients, with 63% of the world's very long rivers (>1,000 km) no longer free-flowing (Grill et al., 2019). This human influence not only alters the flow of water, sediments, solutes, and organisms, but is also a potential source of conflict, as can be seen for the Grand Ethiopian Renaissance Dam, damming the Blue Nile River and impacting downstream countries like Sudan and Egypt (Wheeler et al., 2020; Zhang et al., 2015). Since the dependence of lowland populations on mountain water resources is projected to increase, especially in heavily irrigated and water scarce areas, downstream populations might become increasingly vulnerable in the future, and upstream human actions might create considerable potential for conflict (Viviroli et al., 2020).

Through its influence on climate and accessibility, topography also affects land use patterns. In the Andes, agricultural land use shows an elevation zonation not dissimilar to Humboldt's vegetation zones (e.g., from coffee to crops like corn to grazing animals; see Stadel, 1991). Yet changes in temperature and water availability due to climate change may shift the zones in which certain crops can be grown, such as coffee (Moat et al., 2017; Ovalle-Rivera et al., 2015) and wine (Hannah et al., 2013), with potential follow-on implications for irrigation water use. Globally, urbanization and land used for agriculture are increasing faster in higher inland areas than in coastal lowlands, so that more elevated areas might experience disproportionate increases in pressure on land and water resources (Kummu et al., 2016).

Topography influences patterns of human settlement. For example, people tend to settle relatively uniformly in floodplains that are sensitive to frequent low magnitude events, suggesting that they have adapted to this risk. By contrast, in floodplains most sensitive to rare extreme magnitude events, people tend to settle in rarely flooded areas. These areas often have not been flooded in their lifetimes but could become increasingly flood prone with climate change (Devitt et al., 2023). This is somewhat similar to the adaptation effect, the observation that more frequent flooding is often associated with decreasing vulnerability, and the levee effect, the observation that the absence of frequent flooding is often associated with increasing vulnerability (Di Baldassarre et al., 2015). Population growth may also push people to move to previously uninhabited areas that are more exposed to certain hazards. For instance, in many fast growing cities in the tropics, humans increasingly settle on steeper slopes at the city margins, increasing the risk of and exposure to rainfall triggered landslides substantially (Ozturk et al., 2022). Other changing environmental conditions, such as increasing malaria transmission in highlands due to rising temperatures, might further lead populations to change settlement locations (Rodó et al., 2021), in turn affecting land and water use.

While many interactions between humans and their physical environment are local or have been studied locally, there may be more general patterns and feedbacks that explain these interactions across large scales (e.g., Devitt et al., 2023; Di Baldassarre et al., 2018). Topography is a key variable in this respect, as it is closely related to many aspects of the water cycle, the environment more generally, as well as human mobility. An improved understanding of the interplay between physical and social processes will enable us to better anticipate water security risks, social developments, environmental hazards, and potentially even conflicts (Di Baldassarre et al., 2015, 2019; Drenkhan et al., 2022; Sivapalan et al., 2012).

5.4. Data Needs

Despite millions of terabytes of data being generated each day, we still lack high quality observations for many essential variables and parameters, as well as uncertainty estimates and other metadata. In this section, we briefly discuss data availability and quality for a range of variables that play a critical role in the terrestrial water cycle and are, as shown above, related to topography: precipitation, potential evaporation, land surface fluxes and energy balance components, subsurface characteristics (e.g., regolith depth), and hydrological variables measured at and below the surface (e.g., streamflow, groundwater recharge, and water table depth). This is not an exhaustive overview of all the variables that exist, but highlights some important examples that are either biased or particularly uncertain in relation to topography. Uncertainties in digital elevation models (DEMs)—the basis for deriving global topography—are not discussed here in detail given comprehensive existing reviews by Wechsler (2007) and Hawker et al. (2018).

Many hydrological applications require precipitation estimates that cover a large extent (e.g., a continent) and are of relatively high resolution (e.g., 50 km or finer). Several global products are now available at approximately 10 km resolution, such as IMERG (Huffman et al., 2020), ERA5 (Muñoz-Sabater et al., 2021), or MSWEP (Beck et al., 2019). Climatologies (i.e., 30 year averages) are available at 1 km resolution, such as WorldClim (Fick & Hijmans, 2017) or CHELSA (Karger et al., 2017). These products employ various methods to derive gridded precipitation estimates, differing in their spatial and temporal resolution, the data sources they use (e.g., station, satellite, or reanalysis data), and the way they include covariates such as elevation and aspect (Daly et al., 1994, 2002; Karger et al., 2017). In mountain regions, station densities tend to be low and observational uncertainties high (which applies equally to station, satellite and radar data; Derin & Yilmaz, 2014; Germann et al., 2006; Shahgedanova et al., 2021; Q. Sun et al., 2018; Viviroli et al., 2011). Also, precipitation tends to be more spatially variable and orographic effects are not always well understood or well parameterized. As a result, gridded precipitation estimates are usually most uncertain in mountain regions, as illustrated in Figure 10. Especially in regions with low station density (e.g., Chilean Andes, Ethiopian Highlands; see Fick & Hijmans, 2017), variability between data sets is large because station data do not provide a strong constraint. To better account for these uncertainties, we can combine multiple data sources into probabilistic precipitation products (Tang et al., 2022). In the long run, however, we also need strategies to reduce these uncertainties.

There are several ways forward to reduce the uncertainties present in precipitation estimates. First, it is critical to maintain and extend observational networks, particularly in data sparse mountain regions outside Western Europe and North America (Lundquist et al., 2019; Shahgedanova et al., 2021; Thornton et al., 2021; Viviroli et al., 2011). While station observations will remain representative of only a small fraction of the land surface and can be very uncertain (e.g., due to undercatch or snow), they remain fundamental to develop and evaluate gridded data sets and models (Lundquist et al., 2019), and to complement satellite or radar measurements that are themselves limited in mountain regions (Germann et al., 2006; Q. Sun et al., 2018). Second, knowledge of orographic processes should be incorporated into gridded precipitation products and models. Many approaches rely on static interpolation procedures and may be improved by injecting existing knowledge on topography-precipitation relationships, as attempted by CHELSA using a semi-mechanistic downscaling procedure that accounts for variable topography-precipitation relationships (Karger et al., 2017). And third, we should foster an increased dialogue between atmospheric and hydrological scientists (Lundquist et al., 2019; Shuttleworth, 2012). Hydrologists could benefit from developments in atmospheric modeling capabilities in mountain regions and conversely provide independent data (e.g., snow, streamflow, or soil moisture) that can help evaluate and improve atmospheric models and precipitation estimates (e.g., by inverting those variables to derive precipitation rates; Beck et al., 2019; Brocca et al., 2015; Lundquist et al., 2015, 2019).

Extending observational networks is also critical for improved estimation of potential evaporation, radiative and turbulent heat fluxes, soil moisture, and snow depth and distribution (Dozier et al., 2016; Thornton et al., 2021). For instance, global gridded products of potential and actual evaporation—essentially models themselves—are often highly uncertain and it is unclear how well they capture smaller scale patterns along topographic gradients (Elnashar et al., 2021; Pimentel et al., 2023, see also Figure S2 in Supporting Information S1). We require in-situ observations to both ground-truth larger scale estimates and to improve fundamental process understanding.

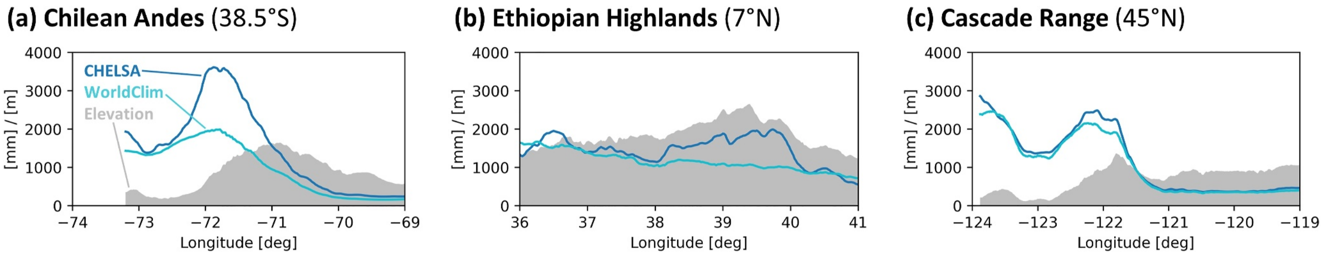

Figure 10. Different data products can lead to substantially different precipitation estimates in mountain regions, especially in regions with a sparse observational database (a) and (b). Here we show average annual precipitation along a west-east transect (averaged over 2° north-south, with average latitudes shown in parentheses) for (a) the Chilean Andes, (b) the Ethiopian Highlands, and (c) the Cascade Range, USA. The data products are CHELSA (Karger et al., 2017) and WorldClim (Fick & Hijmans, 2017), both widely used in research (Web of Science citations are each >1,000 as of 2024). Globally, CHELSA and WorldClim differ most in uplands with averages of 1,019 and 858 mm/y, respectively, and less so in lowlands with averages of 726 and 678 mm/y, respectively. A similar plot for potential evaporation is shown in Figure S2 in Supporting Information S1.

To do so, a fusion of different measurements will be necessary, placed strategically along topographic and other gradients. These could include measurements of potential evaporation using atmometers (van den Bergh et al., 2013), radiative and turbulent heat fluxes using meteorological stations and eddy flux towers (Goulden et al., 2012; Pastorello et al., 2020; Turnipseed et al., 2002), specific evaporation components like transpiration using sap flow measurements (Matyssek et al., 2009), soil moisture using soil resistance probes (Stark & Fridley, 2023), and snow depth using snow pillows or ultrasonic depth sensors (Dozier et al., 2016). Combined with remote sensing data that provide more uniform spatial coverage at a range of scales (Dozier et al., 2016; Goulden et al., 2012; Jung et al., 2019), these measurements will help to provide an increasingly comprehensive picture of land surface processes in topographically complex mountain regions and along elevational gradients.

Various critical zone characteristics as well as deeper geological layers, which influence the movement and storage of water, carry the imprint of topography (see Figure 5). While some influences of topography on the critical zone have been known for a long time (G. K. Gilbert, 1909; Riebe et al., 2017), measurement campaigns continue to provide new insights, in particular deep drilling and geophysical imaging techniques (Parsekian et al., 2015; Riebe et al., 2017). Extending these measurements systematically along climatic, topographic, and geological gradients will be invaluable to create a denser patchwork of information about the still largely hidden subsurface and to better locate the "bottom of a watershed" (Condon, Markovich, et al., 2020). Growth in understanding and data availability has resulted in first attempts at mapping critical zone characteristics globally using topographic and other data (e.g., climatic and geological data). For example, Pelletier et al. (2016b) mapped soil, intact regolith, and sedimentary deposit depth using knowledge on topography-related geomorphic processes, while Shangguan et al. (2017) mapped depth to bedrock using machine learning methods trained with topography-related covariates, amongst others. Hengl et al. (2017) produced global soil maps (e.g., including soil texture) using an ensemble of machine learning methods, which also include topographic attributes and landforms as predictor variables. While these maps provide information at unprecedented resolution and scale, they can be highly uncertain and still have to be carefully evaluated. In addition, there are characteristics that are not yet included in any global map, such as soil stratigraphy or secondary porosity induced by fracturing and weathering, leaving us with considerable knowledge gaps over large areas of the land surface.

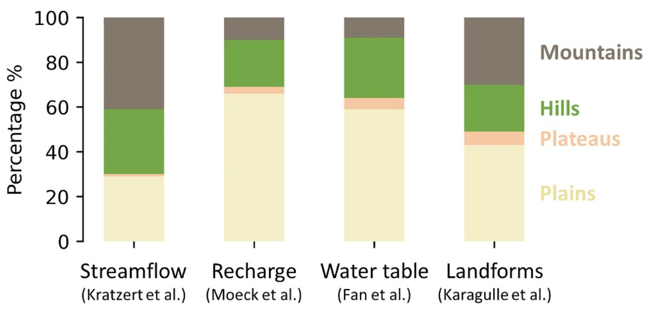

Figure 11. Comparison between the global distribution of major landforms (% land area; Karagulle et al., 2017) and how they are represented in current quasi-global data sets. The data sets shown focus on streamflow (6,830 catchments; Kratzert et al., 2023a), groundwater recharge (5,207 sites; Moeck et al., 2020b), and water table depth (1,603,781 wells; Fan et al., 2013), and are regularly used in hydrological research.

Observational data sets of hydrological fluxes are usually sparse and geographically biased. For example, Krabbenhoft et al. (2022) found that large perennial streams and human-occupied regions over-represented in the global distribution of stream gauges. Examining a recently published global data set of catchment-scale hydrological variables and landscape characteristics (Caravan; Kratzert et al., 2023a), we find that areas defined as mountains are over-represented compared to their global distribution (42% mountains vs. 31% globally; see Figure 11). However, Caravan only contains catchments larger than 100 km^2. Small headwaters, often located in uplands, are therefore likely under-represented despite the general over-representation of mountainous areas, a bias also found in other studies (Krabbenhoft et al., 2022; Poff et al., 2006). This bias may be problematic because headwaters make up the largest fraction of global stream length (Wohl, 2017), and because streamflow series from large streams—by integrating the signal from many headwaters—might have lost information critical to understanding the functioning of heterogeneous upland regions (van Werkhoven et al., 2008). Biases in gauge distributions towards large, perennial streams also result in limited understanding of when and where streams are gaining or losing, and how topography influences stream-aquifer connectivity (Krabbenhoft et al., 2022; Messager et al., 2021). Both, more stream gauges at non-perennial streams and alternative techniques (e.g., remote sensing) to map stream network dynamics will be necessary to better understand non-perennial streams and how they respond to climatic and anthropogenic pressures (Datry et al., 2023). New space missions, like the recently launched Surface Water and Ocean Topography satellite mission (SWOT; Biancamaria et al., 2016) can provide more even coverage of water elevations globally, but are typically limited to large streams (ca. 100 m on land for SWOT) and thus cannot compensate for the lack of observations in headwater catchments.

In contrast to streamflow observations, the largest literature-compiled data set of groundwater recharge estimates (Moeck et al., 2020b) greatly over-represents plains and hardly features any mountainous regions (10% mountains vs. 31% globally; see Figure 11)—apart from being biased towards water-limited regions (not shown here). Similarly, the largest data set on water table depth (Fan et al., 2013) over-represents plains in favor of mountains (9% mountains vs. 31% globally; see Figure 11). While this probably reflects the higher societal relevance of groundwater in lowlands, such as dry agricultural plains with high irrigation water use, it is a critical limitation when it comes to understanding subsurface fluxes and groundwater dynamics in mountains. Observations become especially scarce once we look at recharge components such as mountain block recharge, recharge below thawing permafrost, or groundwater fluxes in mountain regions and across surface catchment boundaries (Markovich et al., 2019; Somers & McKenzie, 2020). Here, so far sparsely used techniques such as passive seismic interferometry for measuring soil moisture and recharge (Illien et al., 2021), different types of tracers (Somers & McKenzie, 2020) including new combinations of tracers like helium, vanadium and environmental DNA (Schilling et al., 2023), or detailed water balance studies (Cochand et al., 2019; Hood & Hayashi, 2015) have shown potential for mapping previously poorly quantified fluxes. Such field measurements can provide important process insights and a means to ground-truth larger scale assessments, and thus are an important basis for synthesis studies aimed at deriving a more general picture of subsurface fluxes in mountain regions (Hayashi, 2020; Markovich et al., 2019; Somers & McKenzie, 2020).

In summary, current data sets often exhibit considerable (though rarely quantified) uncertainties, are small or non-existent for certain important variables, and are geographically biased. One reason for this problem is that field sites or observatories (where many variables are measured simultaneously) have historically rarely been designed as networks, though this is slowly changing (e.g., Brantley et al., 2017; Zacharias et al., 2011). There is a clear need for assessment of existing biases in large data sets and for a strategic design of new measurement networks—for instance along different topographic gradients and contrasts—that balances operational and scientific requirements (Krabbenhoft et al., 2022; Thornton et al., 2021). In addition, a more systematic collection of soft data, including local knowledge, crowd-sourced data, and perceptual models, will provide a useful complement to physical measurements which are notoriously hard to obtain in many environments of high interest, including mountains (Drenkhan et al., 2022; McMillan et al., 2023; Shahgedanova et al., 2021; Wagener et al., 2021).

5.5. Knowledge Gaps

Throughout this review we have seen that topography influences the water cycle all the way from the atmosphere down to the groundwater. So, what key knowledge gaps still exist? In Table 2 we present some open questions which we think should be prioritized in future research. Answering these questions will both help to improve our understanding of the water cycle as a key component of the Earth system and address the many societal challenges ahead of us, especially regarding climate change (Section 5.2) and human interactions with the water cycle (Section 5.3). Many open questions require new or improved data sets (Section 5.4), highlighting that hydrology is in many ways still a data-limited science, especially when it comes to subsurface properties and dynamics (Beven et al., 2020). But there are also gaps in our conceptual understanding and modeling capabilities that are independent of new developments in measurement technology and need to be addressed in order to answer the questions posed in Table 2.

Table 2
Open Research Questions on the Influence of Topography on the Global Terrestrial Water Cycle

Nr.	Topic	Question
1	Planetary scale stationary waves	How will climate change alter topography-induced stationary wave patterns and their associated precipitation patterns?
2	Orographic effects on precipitation	How does precipitation vary along elevational gradients (at different time scales) and how will climate change affect elevational patterns of different precipitation regimes (e.g. frontal, convective)?
3	Potential evaporation	How will elevational patterns in atmospheric water demand change with climate change and what are the dominant drivers (e.g. temperature, net radiation, vapor pressure deficit, wind speed)?
4	Land-atmosphere fluxes	How will changes in water and energy supply along elevational gradients translate into changes in actual evaporation, and how will this be modulated by plant physiological responses and topographically induced moisture redistribution?
5	Critical zone characteristics	How does topography influence the critical zone (e.g. soil and regolith depth, weathered and fractured bedrock), and how can we use it to help mapping critical zone characteristics globally?
6	Water towers	What is the role of groundwater in sourcing the water towers of the world, and how will groundwater dynamics change with thawing permafrost and melting snowpacks and glaciers?
7	Groundwater-stream connectivity	How does the interplay of topography with climate and geology influence the water table and its connection to the surface, that is, where and when are streams gaining or losing? What is the spatio-temporal sensitivity of that connectivity to climate change?
8	Regional groundwater systems	What is the relative importance of topography (vs. climate and geology) in driving groundwater flow dynamics across scales, and how does topography influence inter-catchment groundwater flow and mountain block recharge?
9	Human impacts	Apart from climate change, how do humans influence relationships between topography and the water cycle, and are there patterns in human behavior that are related to topography, making them to some degree predictable?
10	Dominant gradients and contrasts	Which gradients and contrasts (e.g. topographic, climatic, geologic) are dominant at which spatial and temporal scales, and how can we conceptualize the role of topography in the global water cycle in a way to be used in models?

Precipitation is central to virtually any hydrological application. It will therefore be crucial to improve our understanding of orographic effects on precipitation in different climate regions, on different time scales, and with climate change. Besides the precipitation profiles of the mid-latitudes and the tropics shown here (Figure 2), trade wind, monsoon, and polar regimes have been identified in the literature (Anders & Nesbitt, 2015; Barry, 2008). While such profiles are simplifications, they provide a useful way of organizing orographic effects on precipitation and a starting point for exploring underlying process controls. As precipitation gradients can be dynamic (Lundquist et al., 2010) and may even reverse for extreme precipitation (Avanzi et al., 2015; Marra et al., 2021, 2022), it will be important to better understand how and why precipitation gradients depend on time scale. This is especially critical for floods and threshold-dependent sediment transport processes, which are strongly influenced by event characteristics. Lastly, differences in precipitation gradients between climatic regions and time scales lead to an expectation of different responses to climate change. Changes in precipitation gradients and rain shadows have already been observed and modeled (see Section 5.2), yet our understanding of topography-dependent climate change effects remains limited. Data synthesis as well as theoretical and idealized model-based research is required to understand and predict how both local profiles of precipitation (Pepin et al., 2022) and regional precipitation variations from mountain-induced stationary wave patterns are affected by climate change (Wills et al., 2019).

We currently lack a comprehensive global overview of elevational gradients in potential evaporation, and it is not yet clear if changes in potential evaporation will show elevation dependence (J. Sun et al., 2020), as hypothesized and partly observed for temperature (Pepin et al., 2015, 2022). We also do not know exactly how changes in atmospheric water demand will translate into changes in land surface fluxes. The so-called drought paradox, the observation that evaporation in the European Alps was above average during the 2003 summer drought (Mastrotheodoros et al., 2020), illustrates how the interplay of water and energy availability controls actual evaporation (Bales et al., 2018; Jolly et al., 2005; Mastrotheodoros et al., 2020). Studying this phenomenon more widely through analysis of land surface fluxes along elevation gradients, especially in regions that show different elevational patterns in the climatic water balance (see Figure 2), might provide insights into how changes in the climatic water balance will affect land surface fluxes and water resources in mountain and downstream regions. Vegetation-related influences on land surface fluxes, such as reductions in stomatal conductance (Milly & Dunne, 2016) or increasing tree mortality due to drought and wildfire (Bales et al., 2018), as well as moisture redistribution along topographic gradients (Fan et al., 2019; Maxwell & Kollet, 2008), will have to be incorporated into climate change impact assessments to obtain a more holistic picture of future changes.

The subsurface is usually the least observed part of the water cycle and observations of subsurface properties, fluxes, and storages will be crucial to address many existing knowledge gaps (see Section 5.4). To complement costly observations, detailed modeling studies of increasingly larger regions (Carroll et al., 2024; J. M. Gilbert & Maxwell, 2018) can help to elucidate the role of subsurface water fluxes for land-surface and hydrological processes (e.g., groundwater discharge to streams). The growing amount of observations, data sets, and modeling results also make synthesis efforts increasingly feasible. For instance, by compiling observations from millions of existing wells, Jasechko et al. (2021) could map the potential for gaining and losing streams across the USA and identify dominant continental scale controls, including topographic slope. Combining large-scale (gridded or catchment-based) data sets has also enabled the mapping of groundwater-climate interactions (Cuthbert et al., 2019) or the prevalence of non-perennial streams (Messager et al., 2021) globally for the first time. While not necessarily applicable locally, such synthesis efforts can reveal dominant drivers across large scales, put place-based studies into context, and thus advance our understanding of the terrestrial water cycle.

Ultimately, both empirical patterns and conceptual understanding provide information that should be incorporated into simulation models. This information may be used to decide on model structures or to constrain feasible parameter ranges, or as part of evaluation strategies, especially in situations where local observations of system dynamics and characteristics are lacking (see Section 5.1). Even in absence of direct observations, we can test the sensitivity of model outputs to variations in model inputs or parameter values, that is, we can investigate model response rather than model fit (Wagener et al., 2022). For example, how much would model outputs like evaporation, recharge or streamflow differ if we were to use topography-informed estimates of regolith depth instead of assuming a 2 m soil column globally (Pelletier et al., 2016b)? A promising opportunity lies in the use of relative information that describes how system form and function vary along gradients and across contrasts, especially when modeling many catchments or locations simultaneously (Fan et al., 2019; Peel & Blöschl, 2011). For instance, if we expect more baseflow in steeper regions (see Figure 6), we can use this knowledge to constrain model outputs by only keeping model structures or parameter sets that replicate this pattern (at least in relative terms). Finally, we can leverage empirical patterns and conceptual understanding to evaluate models. Large-scale, spatially distributed models are currently unconstrained over large parts of the modeling domain due to a lack of observations (see Section 5.4), yet these models should replicate empirical or expert-derived patterns along topographic and other gradients even if they are not directly built into them. This provides a regionalized evaluation strategy that complements the more commonly used place-by-place evaluation and focuses more explicitly on model functioning (Gleeson et al., 2021; Gnann et al., 2023; Reinecke et al., 2024; Wagener et al., 2021).

5.6. Concluding Remarks

In the thousands of years since Aristotle, Wang Chong, and the epic Ramayana, we have accumulated a wealth of knowledge about terrestrial hydrology. And yet, the role of topography in shaping the water cycle continues to puzzle and surprise us. Some results of our review were perhaps to be expected, while others challenge common rules of thumb. It is clear that a number of fundamental findings still lie ahead of us, particularly with regard to the poorly characterized subsurface. Whether we collect field observations in yet unmonitored places, synthesize existing information into large scale overviews, or create new or updated simulation models, studying the role of topography in the water cycle will remain a central, fruitful, and exciting part of hydrological research.

While some of the research questions identified in Table 2 translate rather directly into new research projects, others should be seen as community challenges that require concerted long-term efforts. In particular, questions regarding land-atmosphere fluxes, the critical zone, the mountain water cycle, and human impacts will have to be addressed in an interdisciplinary manner, as they involve the hydrosphere, atmosphere, biosphere, cryosphere, lithosphere and anthroposphere, and are thus really questions of Earth system science. Such interdisciplinary efforts begin with community debates to establish and refine critical research needs (Thornton et al., 2021; van Tiel et al., 2024). They further involve the planning, installation, and maintenance of multi-variable measurement networks (e.g., S. P. Anderson et al., 2008; Shahgedanova et al., 2021), and the collection and dissemination of quantitative and qualitative data via databases or platforms (e.g., Addor et al., 2020; Baldocchi et al., 2001; McMillan et al., 2023; Zipper et al., 2023). And lastly, they require coordinated data analysis and modeling efforts, for instance using model intercomparison and benchmarking projects, to push forward our collective understanding and predictive capabilities (e.g., Collier et al., 2018; Meehl et al., 2000; Warszawski et al., 2014).

A particular challenge is that these research efforts should ideally be not only long-term and interdisciplinary, but also international in scope, which can be difficult to reconcile with existing funding structures. This is crucial, however, as environmental systems and gradients exist across country borders, and as research capacities themselves vary from country to country due to socio-economic differences (Stein et al., 2024). Finally, as with most scientific endeavors, progress is only likely to be possible with grassroots initiatives by committed individuals or small groups, independent of large funding. This will be a major challenge, but has the potential to considerably advance hydrological science in the coming decades.

Data Availability Statement

CHELSA data are available from https://chelsa-climate.org/downloads/ (Brun et al., 2022a; Karger et al., 2021). WorldClim data are available from https://www.worldclim.org/data/worldclim21.html. Caravan data are available from https://doi.org/10.5281/zenodo.7944025 (Kratzert et al., 2023b) and signatures based on Caravan including BFI are available from https://doi.org/10.5281/zenodo.7763180. Groundwater recharge data are available from https://opendata.eawag.ch/dataset/globalscale_groundwater_moeck (Moeck et al., 2020a). Geomorpho90m data are available from https://doi.pangaea.de/10.1594/PANGAEA.899135 (Amatulli, 2019). Global DEM derivatives at 250 m based on the MERIT DEM are available from https://doi.org/10.5281/zenodo.1447209 (Hengl, 2018). Geomorphic landforms are available from https://rmgsc.cr.usgs.gov/outgoing/ecosystems/Global/. Upland/lowland classification is available from https://daac.ornl.gov/SOILS/guides/Global_Soil_Regolith_Sediment.html (Pelletier et al., 2016a). Global Lakes and Wetlands are available from https://www.worldwildlife.org/publications/global-lakes-and-wetlands-database-large-lake-polygons-level-1. The figures were made with QGIS and Python; Python code is available on GitHub from https://github.com/SebastianGnann/Topography.

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