Earth-Science Reviews 281 (2026) 105586

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Review Article

Hydrogeomorphology of headwater streams

Ellen Wohl *, Katie Larkin, Shayla Triantafillou

Department of Geosciences, Colorado State University, Fort Collins, CO 80523-1482, USA

A R T I C L E I N F O

Keywords:
channel head
stream head
flood
base flow
disturbance
sediment

A B S T R A C T

Headwater streams include first- and second-order channels with ephemeral, intermittent, or perennial flow. Delineation depends on accurate mapping of channel heads, which remains challenging. Consequently, headwaters are underrepresented in river network maps. Hydrology is governed by processes in adjacent uplands. Proportions of surface and groundwater contributions vary spatially and temporally, partly because of impeding layers. The wetted expanse varies seasonally and flows are likely to decline with climate warming. Morphology is temporally and spatially variable. Channels tend to be < 2 m wide but may not exhibit downstream hydraulic geometry. Headwaters can exhibit greater episodicity in sediment transport. Water chemistry is strongly influenced by factors external to the channel and can be variable or stable. The influence of riparian zones on biogeochemistry depends on the strength and location of hydrological connectivity. Hyporheic exchange typically affects a larger proportion of total stream flow, although this may be only 2% of discharge. Headwater gaseous emissions remain poorly quantified but have been estimated at more than 70% of global riverine CO_2, CH_4, and N_2O emissions. Headwaters may be particularly vulnerable to diverse stressors because their small catchment areas, close coupling to uplands, short channel lengths, and lack of floodplains limit buffering of inputs. Their small size and inaccurate delineation also limit regulatory protection and makes headwaters prone to obliteration. Headwater stream flows are likely to decline in magnitude and spatial extent as climate warms. Despite substantial gaps in understanding of headwaters, existing research clearly indicates their importance to the functioning of larger rivers.

Contents

* Corresponding author.
E-mail address: ellen.wohl@colostate.edu (E. Wohl).

https://doi.org/10.1016/j.earscirev.2026.105586
Received 14 January 2026; Received in revised form 8 June 2026; Accepted 14 June 2026
Available online 16 June 2026

1. Introduction

Hydrogeomorphology refers to the investigation of how geomorphic and hydrologic processes interact to shape the physical template of streams (Peterson et al., 2025). Our primary objective is to review what is known of the hydrogeomorphic, or physical and, to a lesser extent, biogeochemical characteristics of headwater streams, as well as the natural and anthropogenic stressors of these streams. Although there is an extensive literature on the chemistry of headwater streams, we review this literature mainly in the context of hydrogeomorphic interactions with water chemistry. We use this review to highlight the importance of headwater streams to terrestrial and downstream ecosystems and to identify gaps in our understanding of this part of river networks and associated research needs. Table 1 outlines the structure of the paper, key terms introduced in each section, and the research methods applied to specific topics.

Just as with higher-order streams, the literature on headwater streams reveals a diversity of stream characteristics investigated, as well as a range of methods used to investigate those characteristics. However, some of the topics in this review, such as hydrology, have been the topic of more research than other topics such as sediment dynamics or channel morphology. The relative length of the subsections within this review reflects this imbalance.

Table 1
Outline of the organization of this review and the key terms and research methods associated with each section of the paper.

Paper organization	Key terms/metrics	Research methods
Definition & importance	stream order	
Characteristics		
delineation & distribution	channel head, stream head	field mapping; remote (hillslope profile, numerical simulations of hillslope hydrology, S-A relations, machine learning)
formative processes	fluvial, non-fluvial	
hydrology	ephemeral, intermittent, flow permanence, wetted stream length	temperature sensing, electrical conductivity, tracers, stream hydrographs, repeat photos, stage sensors, numerical models field measurements
morphology	downstream hydraulic geometry, channel width, channel length, bedforms	tracer clasts, sediment sampling
sediment dynamics	suspended load, bedload	numerical models, tracers
biogeochemistry hyporheic exchanges gaseous emissions classification	solutes, carbon, nutrients carbon dioxide, methane	field measurements with sensors

1.1. What is a headwater stream?

The usage and definition of headwater streams varies widely in published studies (Golden et al., 2025), from a stream of any size that is in the upper part of a river network (e.g., Wohl and Goode, 2008; Imberger et al., 2023) to definitions based on Strahler stream order (e.g., Freeman et al., 2007; Nadeau and Rains, 2007; Christensen et al., 2022) or the presence of perennial flow (e.g., Richardson, 2019a, b). We use the definition common to many studies that headwater streams include first- and second-order streams in the Strahler (1957) stream ordering system, whether these streams are ephemeral, intermittent, or perennial.

Use of this definition still includes uncertainty, however, because of the spatial resolution of mapped channels from which stream orders are derived. As noted by many other investigators, national stream inventories such as the U.S. National Hydrography Dataset do not include all first- and second-order streams (Colvin et al., 2019) but the documentation of headwater streams is nonrandomly distributed due to the variability of mapping accuracy within this and other datasets (Fritz et al., 2013).

1.2. Why headwater streams matter

Headwater streams are important in at least two contexts: the functions provided by the stream corridors and the influence of headwaters

Table 2
Examples of functions provided by headwater stream corridors

Function	References
providing nutrient uptake that varies with flow magnitude, hydraulic conductivity & storage, & land use	Valett et al., 1996 Bernhardt et al., 2005 Graeber et al., 2012 Liu et al., 2022
retaining particulate organic matter from riparian & terrestrial environments	Brookshire and Dwire, 2003 Pfeiffer and Wohl, 2018 Richardson, 2019a Fogel and Lininger, 2023
retaining sediment	Cazzador et al., 2021
providing native-species refugia from invasive species	Colvin et al., 2019
providing predator- or competitor-free habitats	Richardson, 2019a
facilitating evolutionary radiation within & beyond headwater habitats characterized by isolation & small population size	Richardson, 2019a
hosting unique physical and chemical niche space in groundwater-fed systems that are physically stable and have low variation in flow and water temperature	Richardson, 2019a
increasing beta and gamma biodiversity (species diversity between sites & across a region)	Clarke et al., 2008
providing stream subsidies to adjacent terrestrial areas via provision of prey resources to terrestrial predators (e.g., insect-eating birds, spiders, & bats)	Richardson et al., 2005
attenuating peak flows	Gomi et al., 2002; Roa-Garcia et al., 2011
attenuating peak sediment fluxes	Clifton et al., 2022; Dunn et al., 2024
maintaining natural flow regimes & establishing a chemical signal for water quality via groundwater contributions	Lowe and Likens, 2005; Bush et al., 2025

on downstream portions of a river network. We use 'stream corridor' to describe the active channel(s) and the adjacent floodplain and underlying hyporheic zone (Harvey and Gooseff, 2015), where floodplains and hyporheic zones are present. We use 'function' in the ecological sense of a process performed by an organism, species, or entire ecosystem that benefits or maintains the ecosystem (e.g., Brodie et al., 2018). Table 2 lists examples of functions provided by headwater stream corridors. The physical functions listed in this table are explained in greater detail in subsequent sections of the text.

2. Materials and methods

2.1. Parameters of the literature review

We reviewed English-language literature on headwater streams, using Google Scholar as our primary search engine. As noted earlier, the definition of headwater stream varies between published sources. We primarily discuss findings from published sources that specified first- and second-order streams, although previous authors seldom note whether stream ordering is based on published datasets (e.g., US National Hydrography Dataset) or on field-mapped channel networks. Consequently, although we used sources that describe first- and second-order streams, these channels might be designated as third- or even fourth-order streams based on field mapping of channel heads and downstream channels. We also note relevant findings from streams designated as 'headwater' in the original source but likely of third order or higher even in published datasets.

3. Characteristics of headwater streams

3.1. Delineation and distribution

A first-order headwater stream starts at either a channel head or a stream head (Fig. 1). A channel head is the upslope-most point of concentrated water flow and sediment transport between definable banks with a longitudinally continuous channel downstream (Montgomery and Dietrich, 1988, 1989; Evrard et al., 2007; Antoine et al., 2012; Wohl, 2018). A channel head can have ephemeral and intermittent flow regimes, so delineation of the channel head is not contingent on the presence of flow at the time of mapping. If the channel head is formed by a groundwater spring and has perennial flow, it is also a stream head. Alternatively, the stream head – defined as the upstream-most point of perennial flow (Jaeger et al., 2007; Shaw, 2016) – may be located well downstream from the channel head.

Although the location of a channel or stream head may be influenced by non-fluvial processes such as debris flows or landslides, we do not include a longitudinal linear depression formed only by colluvial processes in our definition of headwater streams. Conversely, a longitudinal linear depression without definable, fluvially created banks – a shallow swale with diffuse flow from a groundwater seep, for example – is also not part of the headwater stream network. These zero-order depressions (Dietrich et al., 1987) associated with colluvial sediment transport or diffuse flow can exert important influences on headwater streams by concentrating fluxes of water, solute, and sediment to the start of the stream network (e.g., Benda et al., 2005; Grieve et al., 2018) and may become part of the headwater stream network following disturbance (Rengers et al., 2018), but we are not including them as part of the stream network.

Channel heads are not static features (Montgomery and Dietrich, 1994). They can move up- or downslope in response to substantial and relatively abrupt changes in precipitation and land cover that change rainfall-runoff relations, such as wildfire or hillslope mass movements (Montgomery et al., 2000; Kirkby et al., 2003; McNamara et al., 2006; Wohl, 2013; Hyde et al., 2014; Wohl and Scott, 2017) or abrupt changes in topography such as faulting (Morisawa, 1964). Channel heads can also move in response to longer-duration changes such as glacial retreat (Ruhe, 1952; Lai and Anders, 2018) or tectonic deformation that changes hillslope gradients (Talling and Sowter, 1999).

The average location of a channel head over years to decades represents a spatial transition from unchanneled to channeled regions of a landscape (Montgomery and Dietrich, 1994) and a threshold at which surface or subsurface flow concentrates and persists sufficiently to create

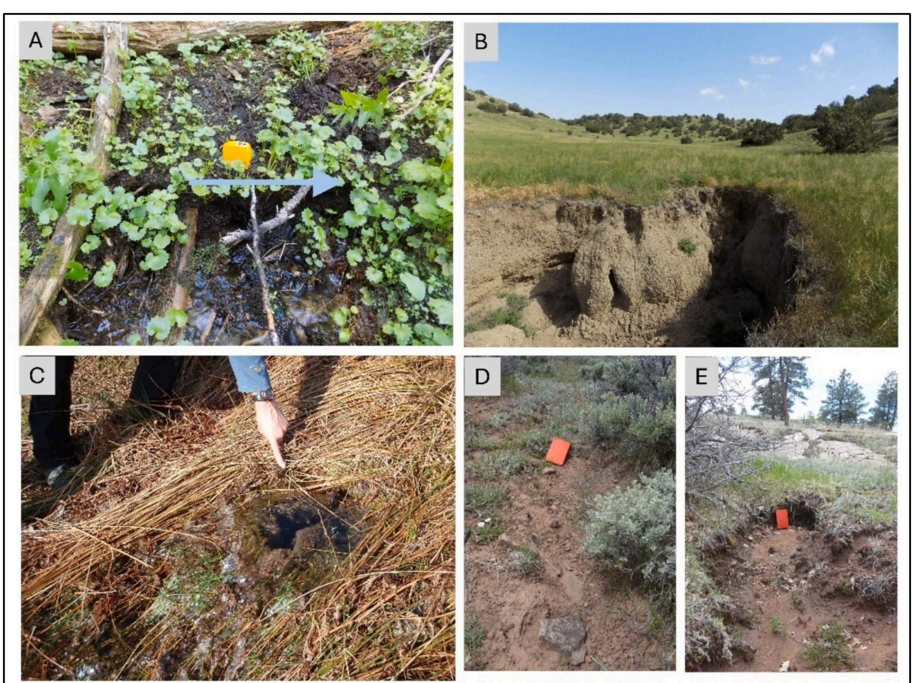

Fig. 1. Examples of stream heads (A, C) and channel heads (B, D, E). Channel heads in (B) and (E) result from subsurface flow and piping; channel head in (D) is generated by surface runoff. Blue arrow indicates flow direction in (A) and hand-tape indicates scale. Piping-induced channel head in (B) is ~ 1.5 m wide across each of the adjacent amphitheater-shaped headcuts. Orange field notebook in (D) and (E) is 15 cm wide.

the start of a headwater stream network. The delineation of a channel head is not based on size of the feature; individual channel heads may be as small as 10 cm wide and deep or more than a meter wide and deep (Fig. 1). The threshold represented by a channel head is commonly expressed as

$$AS^{\alpha} \geq C \quad (1)$$

where *A* is contributing catchment area, *S* is local hillslope gradient, and *C* is the channel initiation threshold (Dietrich et al., 1992). Values for *A* and *S* may vary substantially within a region. Mapping 78 channel heads in the Colorado Front Range at sites without recent disturbance, Henkle et al. (2011) identified a minimum contributing area of 10,000 m^2 but found some channel heads with contributing areas of ~ 600,000 m^2; local hillslope gradient ranged from 12% to 55%.

The ability to accurately locate channel heads is critical to the delineation of headwater streams as we define them, but the values of drainage area and local slope gradient at which channel heads form can vary substantially even within a few hectares in a catchment. Local variation in hillslope gradient, infiltration capacity, porosity, permeability, and cohesion of regolith, and underlying bedrock fracture density, topography, and hydraulic conductivity influence surface and subsurface flow paths and concentration, as well as erodibility of near-surface materials (Wohl, 2018). Across even a small hillslope, the location of individual channel heads can also reflect primary flow components that may be either surface flow, subsurface flow, or some combination of the two. Individual channel head locations can also reflect influences on hillslope morphology such as mass movements (Montgomery and Dietrich, 1994).

Channel heads are most reliably identified via field mapping (e.g., Roy et al., 2009; Brooks and Colburn, 2011; Henkle et al., 2011; Julian et al., 2012; Placzkowska et al., 2015), although error can still occur because channel heads can be obscure and difficult to locate and the location of a discrete point as a channel head may be subjective where the transition from diffuse to channelized flow is spatially gradual. Because field mapping channel heads is time- and labor-intensive, many remote methods of delineating, predicting, and classifying channel heads have been developed. Topographic data have been used to predict channel head locations at the transition from convex to concave hillslope profiles (Kirkby, 1971, 1980; Tarboton et al., 1991), although this transition may be more likely to reflect the start of valley development rather than channel heads (Montgomery and Foufoula-Georgiou, 1993). Assigning channel head locations to inflection points in averaged hillslope profiles (e.g., Ijjasz-Vasquez and Bras, 1995; Passalacqua et al., 2010; Sangireddy et al., 2016) can substantially over- or under-estimate the contributing area of actual channel heads mapped in the field, depending on the region and the balance between surface and subsurface processes that contribute to channel head formation (e.g., Tarolli and Dalla Fontana, 2009; Henkle et al., 2011). Field-mapped channel heads do not appear to exhibit systematic source area-slope relations within individual landscapes or bedrock lithologies (e.g., Jaeger et al., 2007; Henkle et al., 2011). Because of limited field validation, it remains unclear whether individual remote methods tend to consistently under- or over-predict the contributing area of channel heads.

Other approaches to delineating channel heads use numerical simulations of downslope water and sediment movement, such as TOPMODEL (Simpson and Castelltort, 2006; Smith, 2010); extract channel-head locations from digital elevation models based on *S-A* relations (Lin et al., 2006; Kim and Kim, 2007); or extrapolate from field data (Russell et al., 2015). Most of these approaches use a spatially constant threshold. More recent remote extraction approaches that are not threshold-based include clustering analyses of contour lines (Hooshyar et al., 2016), topographic indicators of flow convergence (Lurin et al., 2023), and machine learning methods that are designed to avoid the need for a threshold value of upslope area, slope-area relation, or topographic curvature (Wu et al., 2021). Remote extraction methods have also been applied to delineating stream heads by analyzing channel cross-sections (Shavers and Stanislawski, 2020) and ephemeral stream networks based on topographic openness and a wetness index (Metes et al., 2022). Most of these approaches incorporate field-mapped channel heads for initial validation of the approach, yet the problem remains that *S-A* relations are highly variable between geographic regions (Wohl, 2018; Lessard et al., 2024) and a limited calibration or validation data set may be misleading. Comparing multiple methods, for example, Metes et al. (2022) noted that small ephemeral channels with less-defined banks or originating at groundwater seeps are difficult to detect in all remote methods.

Despite the difficulties of determining where channels start, Nadeau and Rains (2007) estimate that channels with intermittent and ephemeral flow regimes account for about half of total headwater stream length. Syntheses from the United States (e.g., Fritz et al., 2013; Christensen et al., 2022) and from other countries (e.g., Bishop et al., 2008; van Meerveld et al., 2020; Messager et al., 2024) note a consistent tendency to underrepresent headwater and non-perennial stream segments in river network maps. Considering that first- and second-order channels are likely to be non-perennial even in wet regions, and that it remains difficult to accurately map channel heads and the associated first-order streams, headwater streams are likely to be substantially under-represented in stream network inventories. Given that likely under-representation, it is worth noting estimates that put the proportion of first- and second-order streams at 77% of the total length of rivers in the world (Downing et al., 2012), although studies of individual networks or regions estimate values ranging from 60 to 90% (MacDonald and Coe, 2007; Argerich et al., 2016). First-order streams may constitute 52% of total stream length globally (Downing et al., 2012) and 53% of total stream length in the conterminous United States (Nadeau and Rains, 2007).

Management and legal protection are unlikely to target streams that are not identified in inventories of river networks. In the US state of Washington, for example, forest practice regulations protect perennial streams. Inaccurate delineation of these streams can create potential economic losses from restricted land use in headwater areas where streams are assumed to exist but do not, and ecological losses where actual headwater streams are not protected because they are assumed to initiate at larger contributing areas (Jaeger et al., 2007).

Regional- to global-scale summaries of stream surface area that are used in the context of understanding the role of flowing streams in carbon and nutrient cycling are also improved by accurate mapping and channel-width estimation for headwater streams. Recent evaluations of global river emissions of carbon dioxide (Battin et al., 2023), methane (Rocher-Ros et al., 2023), and nitrous oxide (Marzadri et al., 2021) estimate cumulative fluxes by estimating reach-scale fluxes from individual river reaches based on stream surface area (Boyd and Allen, 2025).

In summary, it remains difficult to accurately delineate channel heads in many regions because the values of contributing area and local slope that combine to concentrate flow sufficiently to form a channel are highly variable through space and, to some extent, time. Lacking accurate delineation of first-order streams, it is reasonable to assume that headwaters are underrepresented in most maps of river networks. Regional- to global-scale estimates of the proportions of channel length in different stream orders nonetheless indicate that the majority of total length is in headwater streams.

3.2. Formative processes

A stream corridor can be evaluated in the context of how much it responds to existing topography and how much it shapes topography through fluvial erosion and deposition. Even many of the world's largest rivers both start in mountainous regions (respond to existing topography) and cut through mountain ranges or create extensive depositional terrains (shape topography) along their course. Remote methods of delineating channel heads that are not threshold-based imply that fluvial erosion at the channel head is altering very local topography at a scale that is topographically detectable. Channel heads can form at abrupt changes in hillslope gradient caused by a large boulder, bedrock outcrop, or downed wood (Wohl, 2018) on an otherwise relatively straight or convex hillslope, or they can form in topographically concave portions of the hillslope. Headwater streams in linear hillslope concavities may topographically alter only the area immediately adjacent to the active channel, or they may gradually deepen and widen the linear hillslope concavity. Little is known, however, about the efficacy of fluvial erosion versus other processes that could enlarge these surface flow paths, such as episodic debris flows (e.g., Wohl and Pearthree, 1991; May and Gresswell, 2003; Gomi et al., 2004) or subsurface weathering of fractured bedrock underlying the flow path (Eppes and Keanini, 2017). Consequently, it remains unclear to what extent headwater streams alter existing topography.

Questions also remain about the relative importance of non-fluvial sediment transport processes in headwater streams. Investigators working primarily in the Pacific Northwest region of the United States suggest that a transition from mass movement-dominated to fluvial-dominated stream reaches occurs in high relief drainage areas up to 1.0 km^2 (Benda and Dunne, 1987, 1997; Montgomery and Foufoula-Georgiou, 1993; Stock and Dietrich, 2003; May and Gresswell, 2004), although other studies indicate that debris flows may dominate in-channel transport and morphology at drainage areas up to 10 km^2 (Kostaschuk et al., 1986). The upper limit of drainage area at which debris flows dominate headwater stream processes remains poorly constrained in most high-relief regions that experience debris flows within channels. This partly reflects a lack of attention to the issue and partly reflects the challenges of characterizing both magnitude and frequency of colluvial versus fluvial sediment transport in headwater channels.

Fig. 3. A second-order stream (based on field mapping) fed by groundwater in the Rocky Mountains of Colorado, USA. Blue arrow indicates flow direction. Stream lacks a floodplain and transports materials downstream relatively efficiently. Channel is about 30 cm wide.

Numerous studies suggest that headwater streams are more influenced than higher order streams by local disturbances such as extreme precipitation, hillslope mass movements, wildfire (Fig. 2), or abrupt forest die-off. These streams can display the spatially and temporally variable adjustments to disturbance known as complex response (Schumm, 1973), in which different portions of the channel are simultaneously experiencing erosion and aggradation (Fig. 2).

Headwater streams are closely connected to adjacent uplands and

Fig. 2. Examples of headwater stream erosional (A,D) and depositional (B,C) responses to floods after wildfire. All views are from the same unnamed stream in the Rocky Mountains of Colorado, USA five years after a stand-killing wildfire. Images represent upstream (A) to downstream (D) views that also illustrate complex response, with spatially and temporally discontinuous patterns of erosion and aggradation. (A) Channel exhibits a 50-cm tall headcut in coarse alluvium. (B) Channel aggraded and avulsed. (C) Channel initially incised and then subsequently aggraded. Note large boulder deposited on upstream side of tree at middle left with orange field notebook (15 cm wide; in white oval) for scale. (D) Downstream-most portion of channel continues to erode, with bank collapse introducing trees to the channel, which is 400 cm wide and 50 cm deep. Blue arrows indicate flow direction. Field-mapping of channel heads and first- and second-order channels indicate that this is a third-order channel. The NHD Plus dataset does not recognize this channel, but the newer NHD Plus HR has it as a second-order channel.

typically lack the buffering provided by either floodplains or longer travel distances along the river network (Gomi et al., 2002; Burt and Pinay, 2005; Blume and van Meerveld, 2015). Although headwaters can store materials, they are usually conceptualized as the transport-dominated portion of a river network (Schumm, 1977; Montgomery and Buffington, 1997) in which increases in water, solutes, or sediment are transmitted downstream relatively efficiently (Fig. 3). In stream corridors with primarily fluvial (rather than additional, episodic debris-flow transport), however, relatively mobile materials of water, fine sediment, and fine particulate organic matter may move efficiently downstream whereas coarser sediment or large wood may be primarily stored in the headwaters (Wallace et al., 2001; Benda et al., 2005; Lancaster and Casebeer, 2007; MacDonald and Coe, 2007; May, 2007; Cadol et al., 2009; Nyman et al., 2020). Where headwater streams have segmented longitudinal profiles with alternating higher and lower gradient stream segments, the relative dominance of transport versus storage may vary between successive segments (Rengers et al., 2026). Transport or retention of finer sediment and organic matter also depend strongly on the physical complexity of the channel and the presence of retentive features such as large wood, pools, and secondary channels (Wallace et al., 2001; Pfeiffer and Wohl, 2018; Fogel and Lininger, 2023: Triantafillou and Wohl, 2024).

The transport efficiency of headwaters raises questions about the resistance or resilience of these streams to disturbance. Much of the literature related to natural or human-induced disturbances and resilience addresses the biogeochemistry (e.g., Houser et al., 2006; Larouche et al., 2015) or ecology (e.g., Wallace et al., 1986; Stout et al., 1993) of headwater streams. Consideration of morphological resilience has focused on changes following debris flows or landslides in high-relief headwater streams. In these systems, adjustment of channel morphology following a mass movement depends on the transport capacity of subsequent water flows (Kasai et al., 2004); sediment and wood inputs (Gomi et al., 2002; Jakob et al., 2005) to the channel; the spatial heterogeneity of the stream corridor and initial response to the mass movement (Triantafillou and Wohl, 2024); and the return interval and magnitude of mass movements (Benda, 1990; Wohl and Pearthree, 1991). Given the numerous interacting variables, it is not surprising that headwater channel morphologic resilience varies substantially between sites.

In summary, headwater channels may form on hillslope convexities or concavities and they do not always modify topography sufficiently to appear even on submeter-scale lidar representations of topography. Non-fluvial processes may strongly influence channel morphology and sediment transport in moderate- to high-relief terrains but there is no consistent threshold of drainage area that describes where fluvial processes become dominant. Downstream transport of diverse materials can be highly spatially variable in response to longitudinal variations in channel and valley morphology as well as the presence of relatively immobile features such as large wood. Headwater streams can display complex response following disturbance.

3.3. Hydrology

Headwater streams are likely to have intermittent or ephemeral flow, even in relatively wet climates, if they are supplied primarily by surface runoff (Golden et al., 2025; Botter et al., 2026). However, even ephemeral streams provide an important path for water and solutes to downstream portions of the river network. Models of the contiguous United States, for example, indicate that, on average, 55% of the discharge exported from regional river systems comes from ephemeral streams, with a higher proportion of total discharge in first- and second-order streams coming from ephemeral systems (Brinkerhoff et al., 2024).

Hydrology in first-order channels is governed by hydrologic processes on adjacent uplands (e.g., Sidle et al., 2000; Gomi et al., 2002; McGuire and McDonnell, 2010; Briggs et al., 2022), including the unchannelized slope concavities sometimes known as zero-order basins (e.g., Dietrich et al., 1987; Grieve et al., 2018). Runoff generation and surface and subsurface flow paths in uplands, which can extend far upslope during precipitation inputs (e.g., McGuire and McDonnell, 2010), govern the temporal and spatial distributions and rate of water supply to first-order streams. Changing precipitation and substrate conditions in uplands, along with limited surface and subsurface water storage along headwater streams, can create greater temporal variation in discharge in these streams than in streams with larger drainage areas (e.g., Woods et al., 1995; Lyon et al., 2012). Measurements and numerical models suggest that variation in unit area discharge at small contributing areas reflects hillslope processes whereas variation in larger catchments is more affected by routing processes and the presence of a floodplain (Wood et al., 1988; Woods et al., 1995; Wohl et al., 2025a).

The subsurface connectivity of uplands and channels have been investigated using field monitoring such as measurements of groundwater level, soil moisture, and flow in hillslope trenches. Fingerprints of connectivity based on characteristics such as minor trace elements that create chemical signatures that differ between specific portions of a catchment have also been used to trace hydrologic flow paths, as have tracer experiments using salts, fluorescent dyes, or specific isotopic signatures, and numerical modeling (Blume and van Meerveld, 2015). As with surface flow inputs, the magnitude of throughflow and groundwater inputs to headwater streams can vary substantially both spatially and temporally.

The relative contributions of groundwater to headwater stream flow, and thus the extent of perennial headwater streams, vary between catchments, in part because of the presence of impeding layers (e.g., McGlynn et al., 1999) and depth to bedrock (Giggy and Zimmer, 2025). Headwaters are more likely to have relatively shallow groundwater inputs because of shallow depths to bedrock (Hare et al., 2021). The relative contributions of different sources of surface water can also vary spatially and temporally within a headwater catchment. Studying a 2.65 km^2 semiarid mountain catchment in Colorado, Bush et al. (2023) found that the primary contributions to stream flow are surface water from upstream and groundwater, although the relative contributions from upstream decreased from the period of spring snowmelt to summer rainfall and base flow. They described this as an increasing importance of lateral contributions from groundwater and soil water adjacent to the stream as the runoff season progressed. Overall, however, groundwater dominates stream flow magnitude and chemical composition in ephemeral, intermittent, and perennial headwaters in the catchment (Bush et al., 2025).

Using fiber optic, spatially distributed temperature sensing to locate and quantify groundwater discharge, Simon et al. (2022) inferred that streamflow sourced from groundwater was concentrated mainly in the upstream part of a 2^{nd}-order catchment in southwestern Brittany, France, where the steepest slopes occurred, although local and highly contributive groundwater inflows were possibly driven by local heterogeneities. Measurements in first-order streams in New Mexico, USA, similarly indicate that the rate and extent of groundwater-surface water exchange increase with increasing hydraulic conductivity, as influenced by geologic setting and alluvial characteristics (Morrice et al., 1997). In assessing the temporal distribution of groundwater-fed surface flow, piezometers and shallow wells in a headwater catchment in Luxembourg indicated that near-stream groundwater responded rapidly to precipitation in fractured bedrock with low storage capacity (Bonanno et al., 2021). These portions of the streambed displayed complex groundwater-surface water connectivity, with groundwater moving away from the stream, which ceased flowing, during dry periods and groundwater moving toward the stream during wet periods (Bonanno et al., 2021).

The complexities of groundwater influences in headwater streams are illustrated by a study of 8 semiarid headwater catchments in Idaho, USA using surface flow observations and tracer-based groundwater residence times. Warix et al. (2021) found poor relations between groundwater residence time, topography, and extent of the flowing stream network. Old groundwater was present in all headwater streams, but each stream also exhibited surface drying, suggesting that old, deep flow paths are not sufficient to sustain surface flows. The timing of stream drying at any point typically coincided with a decrease in the contribution from near-surface sources and an increased relative contribution of groundwater to streamflow, so the spatial pattern of drying within the stream network correlated with locations where groundwater inputs were the most seasonally variable (Warix et al., 2021).

Another example of groundwater influencing flow paths on headwater streams comes from the Arakawa River, Japan, where baseflow-specific discharge, which reflects groundwater flux, increased with catchment size in the headwaters (Asano et al., 2020). Spatial variation in precipitation, stream hydrographs, and isotopic tracers imply that substantial amounts of water infiltrate into bedrock on the hillslopes in the headwaters but this water does not discharge into small streams. Instead, it feeds surface flow into a larger downstream catchment, creating an increase in specific discharge typical of catchments with permeable bedrock (Asano et al., 2020).Water isotopic ratios used to evaluate mean transit time and young water fractions indicate differences in transit time in relation to the type of precipitation anomaly. Working in 7 small mountain catchments in western Oregon, USA, Segura (2021) found that during relatively wet, cold years, intrinsic catchment characteristics such as catchment area and terrain roughness explained some of the variability in transit times. She found shorter transit times during periods of snow drought (abnormally low snowpack), although studies in other regions have indicated longer mean transit times under dry conditions (e.g., McGuire et al., 2002; Hrachowitz et al., 2009; Bansah and Ali, 2019). This suggests that snow drought may influence water transit times differently than other forms of drought.

The relatively few, site-specific quantitative measurements of surface versus subsurface flow contributions to hydrology in headwater streams indicate that generalizations across sites cannot yet be confidently developed. Site-specific conditions of bedrock and other impeding layers, seasonality and type of precipitation inputs, and specific position in the headwater channel network combine to create different hydrologic scenarios in each site studied.

A different form of headwater flow sources has been described for central California, USA, where vernal pools and swales – seasonal wetlands in low-relief headwaters – influence headwater stream wetness (Stepchinski et al., 2023). Winter peak stages in vernal pools propagate downstream through swales, which typically have less extensive inundation, to headwater channels. Analogously, wetland and lake headwaters supply many of the headwater streams in Florida, USA (White and Crisman, 2016).

In addition to sources of flow in headwater streams, another line of hydrologic investigation focuses on the extent of wetted stream length in headwaters. This has received particular attention in the United States because stream permanence classifications (perennial/intermittent/ephemeral) are a primary consideration for stream regulatory status under the Clean Water Act. Stream permanence classifications in the National Hydrography Dataset can exhibit up to 50% disagreement with *in situ* observations, in part because the NHD classifications were derived decades earlier and do not consider dynamic climate and land use in headwater environments (Hafen et al., 2022). Other measures of flow permanence have been proposed, such as continuous versus discontinuous, spatially or seasonally (Olson and Burton, 2019), or flow fraction – the fraction of time during which a stream flows, from 0 to 1 (Peterson et al., 2024), but none of these measures is yet consistently used across numerous studies or management agencies.

For headwaters in the Appalachian Highlands of the U.S., wet stream length and surface hydrologic connectivity of wet streams depend on local lithology, geologic structure, and the distribution of surface regolith such as glacial and colluvial deposits, as these influence hydraulic conductivity and depth of regolith (Jensen et al., 2017, 2018). Working in forested headwater streams of western Oregon, USA, Olson and Burton (2019) describe spatially intermittent streams that had spatially discontinuous surface flow at the upper and lower portions with intervening dry areas in the middle during the spring wet season. The dry portions extended in length during the dry summer season. In these streams, the percent dry length was associated with the heat: moisture index, mean minimum summer temperature, and catchment area. Other studies in western Oregon that combine measurements and modeling indicate that the controls on expansions and contractions of the wetted headwater network include upstream runoff production, hyporheic zone transmissivity (hydraulic conductivity times average conductive depth), channel width, and channel gradient (Ward et al., 2018). The influences of contributing area and channel geometry also appear in data from forested headwaters in the humid regions of the contiguous United States, where catchment area differentiates ephemeral from intermittent or perennial channels, and entrenchment ratio (the ratio of flood-prone width to bankfull channel width) discriminates intermittent from perennial sites (Fritz et al., 2008). Statistical models of observed flow fractions in northern Colorado indicate that snow persistence, summer precipitation, and drainage area are important predictors (Peterson et al., 2024).

In Alaskan headwater streams underlain by permafrost, flow variability may reflect the thickness of the active layer. Thirty years of discharge data from headwater streams in Alaskan boreal forest indicate that flow is variable and related to summer temperature in catchments with less extensive discontinuous permafrost, whereas flow relates more directly to precipitation in catchments with more extensive permafrost (Jones and Rinehart, 2010). More extensive permafrost and higher permafrost tables promote shallower subsurface flow paths and higher rates of evapotranspiration relative to uplands without permafrost, leading to greater responsiveness to both precipitation and air temperatures in permafrost catchments (Sjöberg et al., 2022).

The extent of wetted headwater streams has been measured directly at stream gauges. Indirect measurements can come from flow intermittency sensors that are modified temperature loggers able to detect the presence of water as a large increase in relative electrical conductivity (Jaeger and Olden, 2012; Jensen et al., 2019) or from flow detection sensors based on a vane design that closes a circuit when water is flowing and opens the circuit when water is absent or stagnant (Bhamjee et al., 2016). Paired resistance and multispectral satellite imagery using machine learning methods trained on local surveys may be able to detect wetted channels, even where channels are smaller than the imagery's spatial resolution (Dralle et al., 2023). Citizen science can also be used to collect data on surface flow either in regions where people live or recreate (e.g., hikers). A study in northern Colorado, USA that employed 11 stage sensors and 177 visual monitoring points (crowdsourcing of photos and written descriptions at road or trail stream crossings) indicated that the number of observations needed to compute accurate flow fractions increases as flow duration decreases (Peterson et al., 2024). This study found that statistical models of flow permanence perform best with $\geq$ 10 visual observations. Other studies using citizen scientists indicate that the usefulness or accuracy of citizen observations improves with clear definitions of flow state classifications, detailed information on the exact location for observations, and training (Scheller et al., 2024).

Numerical models based on rainfall-runoff or water balance have been applied to headwater flow permanence. Hafen et al. (2022) simulated flow permanence in headwaters of the U.S. Pacific Northwest using a modified Thornthwaite monthly water balance model with a flow threshold parameter. This model generates monthly runoff values by estimating the magnitude of hydrologic processes based on mean monthly temperature, total monthly precipitation, soil water holding capacity, and latitude. They found that this approach estimated stream permanence with high precision at only 40% of stream reaches, indicating the need for increased observations of surface water presence.

Much of the research on headwater flow sources and permanence has been conducted by stream ecologists because of the critical influence of flow extent, duration, and chemistry on stream communities. Examining macroinvertebrate communities in the Peak District of England, for example, Wood et al. (2005) found that communities differed significantly in the number of taxa, community abundance, and diversity indices between groundwater-dominated perennial and intermittent spring streams. More taxa were present in streams with perennial springs.

The persistence and flashiness of surface flows are also of interest because of the resultant influences on downstream flow magnitude, biogeochemical reactions, and sediment transport. Using flow intermittency sensors, Jensen et al. (2019) demonstrated hysteresis in wetted stream length in a headwater catchment in Virginia, USA. They found that the wet proportion of the stream network was up to 50% greater on the rising limb of storm events than on the falling limb for dry antecedent conditions, with sometimes a delay of several hours between the maximum wet proportion and peak runoff at the outlet of the 33-ha catchment outlet. Stream length hysteresis decreased during larger storms with higher event and antecedent precipitation. They noted that although topography did not fully explain spatial variations in flow duration along the stream network, entrenched valleys had longer periods of flow on the rising limbs of events than unconfined stream reaches. Larger upslope contributing areas also corresponded to higher flow duration on the falling limb (Jensen et al., 2019).

Flow flashiness can be challenging to characterize in headwaters because widely used methods such as the Richards-Baker Index use median daily flows that represent too long a timestep for small streams. Johnson et al. (2022) used number of days each stream flows above its 99th percentile flow for 1st-order streams in the US North Carolina Piedmont. They found that first-order streams were flashier than second- and third-order streams, and that first-order streams also became flashier during winter when evapotranspiration declines. Decline in evapotranspiration and decreased interception of precipitation associated with a lack of leaves on trees in winter likely increase soil moisture, raise the shallow water table, and decrease infiltration capacity in a manner that increases runoff and flashiness (Johnson et al., 2022). They also found that suburban streams are flashier than forested streams, an effect that has been documented in other studies showing that more urbanized headwaters tend to have higher peak flows (Stanfield and Jackson, 2011), as well as greater unit peak discharge, flashiness index, and runoff ratio (Wu et al., 2013). Comparing the effects of urbanization on headwaters in the area of Cincinnati, Ohio, USA, however, Roy et al. (2009) noted that urbanization can decrease (e.g., via reduced infiltration) or increase (e.g., via lawn watering and septic tanks) the permanence of headwater flows.

Given their long cumulative channel length, headwaters have the potential to substantially influence attenuation of peak flows transmitted to higher-order rivers. The shallow flow and high external resistance of small streams, as well as the potential for naturally occurring obstacles such as downed trees that can occupy a substantial portion of channel cross-sectional area, suggest that spatially heterogeneous headwater channels could be very important in attenuating peak flows (Triantafillou and Wohl, 2024). Most existing network-scale hydrologic models, however, assume simple downstream hydraulic geometry scaling in which channel width scales with stream order, and may not include first- and second-order streams (Wohl et al., 2025a). Consequently, it remains largely unknown how spatial heterogeneity in headwater channels, loss of headwater channels (e.g., through burial), or the details of headwater channel representation in network hydrologic models might influence estimates of peak flow attenuation (Wohl et al., 2025b).

In summary, measurements of groundwater-surface water interactions within individual channels and catchments reveal spatially and temporally complex relations that reflect site-specific conditions and are difficult to generalize across sites. Both measurements and modeling suggest that the wetted expanse of headwater streams expands and contracts seasonally in many networks, with controls of varying importance that include upstream runoff production, hyporheic zone transmissivity and hydraulic conductivity and connectivity to groundwater aquifers, and valley and channel geometry. The efficiency of conveyance of headwater stream flow to downstream portions of the network is influenced by the length and spatial arrangement of headwater channels, as well as the morphology (channel width/depth ratio, hydraulic roughness associated with grains and bedforms, presence of obstructions such as large wood) of the channels (Wohl et al., 2025a). Hydrological routing models suggest that naturally occurring (Christensen and Morrison, 2026) and engineered (Roberts et al., 2023) temporary storage areas in headwater networks can attenuate peak flow magnitudes by as much as 30%, largely through floodplain or ponded water storage along 2nd- or 3rd-order channels. It remains difficult to characterize or predict the extent and duration of wetted channels within small catchments without spatially detailed field measurements that span interannual variations in precipitation, including snowpack in cold regions. Studies from diverse regions, however, predict that headwater stream flows will decline in magnitude and extent with climate warming (Jones and Rinehart, 2010; Olson and Burton, 2019).

3.4. Morphology

The cross-sectional morphology and longitudinal trends of headwater streams can differ from higher-order streams because of the relatively low energy exerted by flow in headwater channels against the channel boundaries. Whether stream energy is expressed as critical shear stress, total stream power, or stream power per unit area, the ability of flow to shape the channel boundaries and downstream gradient is fundamentally a function of discharge and local gradient. Although local gradient may be quite steep, discharge is commonly very small, and headwater streams are more likely to be shaped by local factors such as large wood (Green et al., 2013; Chappell and Brierley, 2014), bedrock constrictions and varying erosional resistance (e.g., Adams and Spotila, 2005), spatial and temporal variability in sediment abundance and grain-size distribution associated with hillslope instability (Benda et al., 2005), and reach-scale gradient imposed by glacial history (Green et al., 2013), past debris flows, or bedrock lithology.

Under these circumstances of strong influences by local controls, headwater streams may not display statistically significant downstream trends in channel width, flow depth, or velocity, as conceptualized in downstream hydraulic geometry (Leopold and Maddock, 1953). The limited studies of downstream hydraulic geometry in headwater streams indicate that channel morphology and velocity are more spatially variable than in larger streams in both tropical (Thornes, 1970) and temperate latitudes (Chappell and Brierley, 2014). Working in headwater streams of Vermont, USA, Zimmerman et al. (1967) described a drainage area threshold for influences on channel width. At drainage areas of 0.5 to 2 km^2, channel width does not increase downstream, channels are not perennial, living tree roots cross the channel, and organic debris dams are common. At larger drainage areas up to 13 km^2, channel width increases downstream but channel morphology is highly variable because of the influence of living vegetation that alters the roughness and shear strength of the channel bed and banks. Brummer and Montgomery (2003) found that channel width increased with drainage area according to the basic downstream hydraulic geometry relation ($w = cA^b$, where w is channel width, A is drainage area, and b and c are empirical coefficients) for both debris flow-dominated and fluvially dominated channel reaches in high-relief areas of western Washington, USA. With the exception of one creek, the conventional value of $b = 0.5$ fell within the 95% confidence interval of b values calculated for their combined field data.

The location in a river network at which downstream hydraulic geometry trends become significant has also been related to a threshold ratio of stream power to coarse sediment size (Wohl, 2004). Although total and unit stream power may display progressive downstream trends in larger alluvial streams (Knighton, 1999), headwater streams in moderate- to high-relief environments are characterized by substantial longitudinal variability in stream power, primarily in relation to longitudinal variability in reach-scale gradient (e.g., Fonstad, 2003; Wohl et al., 2004; Adams and Spotila, 2005). Consequently, the minimum catchment area at which the stream power/sediment size ratio is exceeded varies substantially among headwater streams.

Investigators have also examined the range of channel widths and lengths in headwaters. Using global data, Downing et al. (2012) reported median values of 1.6 and 1.9 m (mean values 1.9 and 2.6 m) for first- and second-order streams, respectively, whereas Allen et al. (2018) reported measured perennial, first-order stream widths at thousands of locations within 7 catchments in North America and New Zealand as having a mode of 0.32 $\pm$ 0.07 m for wetted channel width. Boyd and Allen (2025) used field measurements and remote sensing to characterize wetted channel widths across all stream orders in the Mississippi River catchment and found that river widths within each stream order consistently follow a log-normal distribution. First-order wetted stream widths are mostly less than 1 m and second-order streams less than 2 m wide (Boyd and Allen, 2025). Jensen et al. (2017) reported mean bankfull channel width as a ratio of width to upstream contributing area. Values for 12 areas in the Appalachian Highlands of the eastern United States exhibit a narrow range of 0.24 to 0.47. Barefoot et al. (2019) examined the distribution of wetted channel widths in first- through third-order streams over time at an experimental forest in North Carolina, USA. As runoff increased from the 37th to 99th percentiles of flow, flow in streams both widened across the network and extended upstream to reactivate dry channels. Measured values ranged from 2 to 831 cm (median value of 25 cm of stream widening), with some measurement points varying by up to 787 cm among all surveys and others remaining unvarying.

Most of the studies of channel length focus on how wetted length changes rather than complete channel length starting from the channel head. The only compilation of total length values that we found was in Downing et al. (2012), which compiled global estimates of channel length by stream order. They reported mean values of 1.6 and 3.7 km for first- and second-order streams, respectively, based on known bifurcation ratios from Leopold (1962) and Welcomme (1976).

Fig. 4. Example of fallen wood creating steps and pools on a headwater channel in northern Colorado, USA. Channel is about 40 cm wide and 5-10 cm deep.

Large wood introduced to headwater streams is less likely to be fluvially redistributed into logjams than in larger streams because of the shallow flow depths relative to log diameter, narrow channel widths relative to log length, and generally limited transport capacity for wood in headwater channels (Benda et al., 2005; Wohl and Jaeger, 2009; Cadol and Wohl, 2010). Dixon and Sear (2014), however, discuss mobility of relatively small, simple (less branching complexity) pieces in a second-order stream in England. Debris flows in headwater streams can very effectively transport and redistribute large wood (e.g., Rengers et al., 2026).

Logjams may be present in headwater streams as a result of debris flows or forest blowdown but wood is otherwise likely to occur as individual pieces. These pieces can substantially influence hydraulics and sediment dynamics by creating local obstructions to flow that direct current toward the channel bed or banks or limit local bed erosion, creating a stepped morphology (e.g., Gomi et al., 2003) (Fig. 4). Large wood in headwaters commonly enhances local storage of sediment (e.g., Ryan et al., 2014) and particulate organic matter (Smock et al., 1989; Brookshire and Dwire, 2003; Entrekin et al., 2008; Pfeiffer and Wohl, 2018; Fogel and Lininger, 2023). The roots of living trees that are exposed in the channel (Hawley and MacMannis, 2019), sometimes referred to as livewood (Opperman et al., 2008), can create morphological influences similar to those of large wood in headwater streams.

Beaver dams can also create substantial reach-scale changes in headwater stream hydrology, morphology, and sediment dynamics. Beaver can build dams that pond water on even small, headwater seeps and springs. The dams reduce longitudinal connectivity but increase lateral and vertical connectivity within stream corridors, as well as increasing surface and subsurface water storage, sediment retention, nutrient uptake, and habitat diversity (Burchsted and Daniels, 2014; Larsen et al., 2021; Wohl and Inamdar, 2025). Beaver dams are most likely to be found on perennial or intermittent streams and are thus more common on second- than on first-order streams and on headwater channels fed by groundwater rather than surface runoff.

Bedforms imply the ability of streamflow to systematically redistribute bed sediment into downstream-recurring forms (Montgomery and Buffington, 1997). In moderate- to high-relief terrain, headwater streams are likely to have cascade, step-pool, or plane-bed morphology (e.g., Gomi et al., 2003; Galia and Hdradecký, 2014; Lisenby et al., 2014; Ryan et al., 2014) (Fig. 5). In lower relief catchments, headwaters can have pool-riffle or dune-ripple bedforms (Gelwick, 1990). In general, bedform type reflects the combined influences of flow competence to move sediment, grain-size distribution present in the channel, and local gradient as this influences both shear stress and grain size. In the Ashio Mountains of Japan, for example, streams in chert terrains with subsurface storm flow are more likely to have step-pool bedforms than lower-gradient streams in sandstone with groundwater flow because of the larger clasts and greater hydraulic force in the chert streams (Hattanji et al., 2012).

Although little has been published on this topic, our observations of headwater streams as defined in the field in the Southern Rockies, the Great Plains, the Basin and Range, the Colorado Plateau, and the Appalachian regions of the United States suggest that first-order streams seldom have a floodplain, despite sometimes having pronounced longitudinal alternations in channel width. We define a floodplain as a relatively flat alluvial surface adjacent to the channel that is inundated at least periodically by flows of the contemporary regime and is composed of river-deposited sediment (Wohl, 2021). Second-order streams may have a floodplain, but it is likely to be relatively narrow and longitudinally discontinuous (Fig. 6).

As noted earlier, headwater streams may be particularly sensitive to disturbances, including debris flows and debris torrents (Van Dine, 1985). The return interval of these disturbances may also be shorter in headwaters (Miller, 1990a; Tao and Barros, 2014) because individual

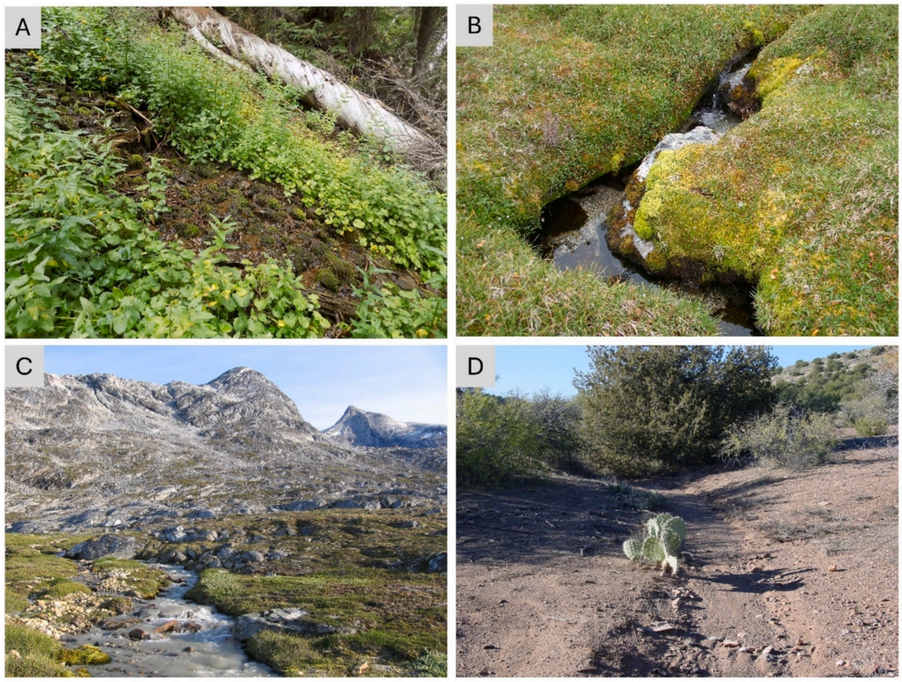

Fig. 5. Examples of bedforms in headwater streams. (A) Cascade channel with steep, coarse-grained bed lacking bedforms in Colorado, USA; channel is approximately 60 cm wide. (B) Step-pool channel in tundra, Greenland; channel is approximately 20 cm wide. (C) Pool-riffle sequence, Greenland (this channel fed by glacial meltwater is likely a third-order stream). (D) Ephemeral channel with dune-ripple bedforms, central Arizona, USA; channel is approximately 70 cm wide.

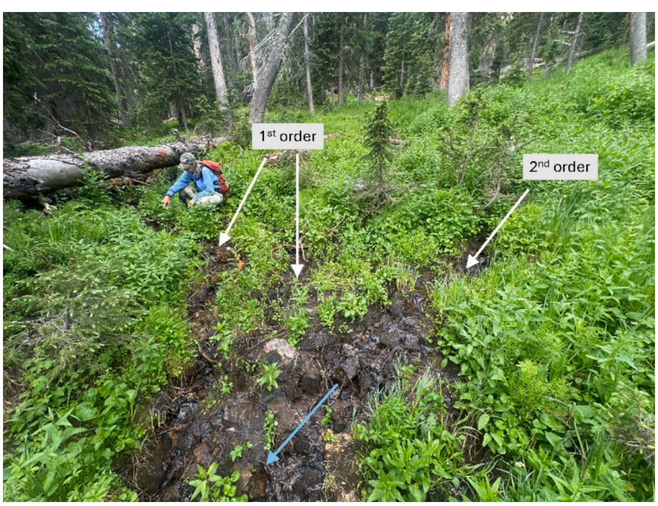

Fig. 6. Field-mapped first- and second-order channels in the Colorado Rocky Mountains, illustrating the lack of floodplains. Although the herbaceous vegetation obscures the areas beyond the active channel, there is no evidence of these areas being shaped by fluvial erosion and deposition. Blue arrow indicates flow direction. First-order averaged width and depth in the photo are 31 cm and 2.5 cm, respectively; second-order width and depth are 70 cm and 3 cm, respectively.

convective storms can produce runoff over much or all of the drainage area. Consequently, the morphology of headwater channels and valley floors may undergo substantial abrupt, episodic changes and the geomorphic signature of disturbances may persist for at least a decade (Costa and Jarrett, 1981; Davies et al., 2005; Triantafillou and Wohl, 2024). The low transport capacity for coarse sediment in headwater streams can allow the channel to act as a sediment reservoir for decades to centuries, with stored sediment mobilized abruptly during intense precipitation and contributing to the occurrence of a debris flow (Wohl and Pearthree, 1991; Benda et al., 2005; Gorr et al., 2024) that is primarily erosive in the steep reaches of headwaters (e.g., Miller, 1990b) but can deliver substantial volumes of sediment to downstream portions of the river network.

In summary, headwater stream morphology is temporally and spatially variable, in part because of the strong influences of geomorphic history and imposed gradient and morphology, as well as disturbances and local forms (e.g., fallen trees). Headwater streams can display consistent downstream trends such as hydraulic geometry, but they also commonly lack trends characteristic of larger rivers, including downstream fining, increasing profile concavity, and progressive changes in stream power. The characteristics of headwater network morphology (length and spatial arrangement of channels) and channel morphology (channel width/depth ratio, hydraulic roughness, lateral connectivity with floodplains where these are present, presence of instream obstructions) can attenuate peak flows, as noted in the summary for hydrology (section 3.3), as well as strongly influencing storage of sediment (Ryan et al., 2014) and particulate organic matter (Fogel and Lininger, 2023), and biogeochemical processes that create aquatic and riparian nutrient uptake.

3.5. Sediment dynamics

Sediment movement in most rivers is episodic in time and space and these discontinuities may be even more pronounced in headwater channels characterized by coarse-grained substrate or limited transport capacity because of small discharge values. Sediment movement in headwaters is also more likely to be non-fluvial (e.g., debris flows or snow avalanches) than it is in higher-order channels. Headwater channels are, however, likely to be primarily transfer zones for sediment (Montgomery and Buffington, 1997), although the time intervals between transporting events can last for decades to centuries. In headwater channels in southeastern Alaska, USA, for example, periodic landslides and debris flows both introduced large wood and sediment to the channel network and removed stored wood and sediment (Gomi et al., 2001, 2004). Erosive mass movements also created headwater channel segments with exposed bedrock, logjams, alluvial fans, and abandoned

Fig. 7. Convective storms following wildfire produced substantial inputs of water and sediment from adjacent uplands into this first-order, ephemeral stream in northern Colorado, USA. The small tree trunk in the center of the channel was sufficient to trap a small piece of burned wood (white dashed line), which then caused upstream sediment aggradation and created a vertical downstep of 25 cm height. Blue arrow indicates flow direction.

channels. Channels affected by recent mass movements exhibited greater volumes (2 to 10 times greater) and finer grain sizes of bedload transport because of the progressive increase in wood load and associated roughness and storage of bed material in channels following mass movement, as well as progressive regrowth of riparian vegetation that decoupled channels and hillslopes (Gomi et al., 2004).

Individual pieces of large wood can be particularly important in creating roughness and sediment storage in headwater channels because of the small channel dimensions relative to the size of the wood piece (Ryan et al., 2014) (Fig. 7). Snow avalanches, landslides, or debris flows can also introduce substantial quantities of large wood to headwater streams (e.g., Kemper and Scamardo, 2023).

Other mass movements besides debris flows can influence sediment dynamics in headwater streams. Moore et al. (2013) documented snow avalanches transferring rockfall- or landslide-generated sediment stored in channels from the headwaters to the alluvial fan and main river system in the Swiss Alps. Woodhurst and de Scally (2017) described the transfer of upland sediment to headwater channels via snow avalanches in the Canadian Rocky Mountains. Snow avalanches from hillslopes bordering headwater streams in eastern Japan create substantial sediment inputs that become suspended sediment and create counterclockwise hysteresis loops in concentration-discharge relationships (Iida et al., 2012).

Limited data exist to quantify the magnitude and episodicity of sediment inputs and transfer downstream in headwater streams. Use of pebbles with passive integrated transponders (PITs) in the headwaters of Italy's Rio Cordon indicates that ordinary floods (return intervals circa 2 years) maintain dynamic stability with balanced volumes of erosion and deposition (Cazzador et al., 2021). High-magnitude floods (return interval > 50 years) have bedload fluxes that are an order of magnitude greater than ordinary floods and create net erosion in the channels. Whiting et al. (1999) measured bedload movement in snowmelt-dominated headwaters and higher-order streams in Idaho, USA. They found that bedload sediment was finer than surface and subsurface material, although the majority of the load was sand at all discharges, with progressive coarsening as discharge increased. These streams had a limited sediment supply and exhibited surface armoring and clockwise hysteresis in bedload transport during spring snowmelt. Flows above the morphological bankfull stage moved 37% of the bedload and the return interval for bedload transport averaged 2 years. The only headwater stream (using our definition) in this dataset had an annual bedload yield of 7.65 t/km^2/yr. Larger streams in the dataset had bedload yields ranging from 0.21 t/km^2/yr (drainage area 293 km^2) to15.66 t/km^2/yr (drainage area 381 km^2) (Whiting et al., 1999), reflecting the lack of correlation between the drainage area of headwaters and sediment yield. Working in first- and second-order channels of the Fraser Experimental Forest in Colorado, Ryan et al. (2014) used Helley-Smith bedload samplers for bedload transport rates and weir ponds to estimate annual sediment yield. Measured bedload transport rate was ~0.01 kg/s (range 0.001-0.32; Ryan et al., 2002, 2005) and annual sediment yield averaged 0.015 m^3/ha of drainage area (assuming sediment density of 1.65 g/cm^3, this equates to 2.48 tons/km^2/yr).

Changes in primary erosional process or underlying lithology can produce downstream shifts in median bed surface grain size. Headwater streams in western Washington, USA display downstream coarsening as drainage area increases to approximately 10 km^2, beyond which they display downstream fining as the channels shift from debris-flow-dominated to fluvially dominated (Brummer and Montgomery, 2003). Working across diverse lithologies on the Appalachian Plateau in West Virginia, USA, Golden and Springer (2006) found that median bed grain size correlated with unit stream power but not with drainage area. They interpreted the correlation between grain size and stream power as reflecting mutual adjustments among channel gradient (which partly reflects lithology), width, and bed grain size as a function of discharge.

Examining particle shapes in first-order and higher streams in northeastern Japan, Takahashi et al. (2025) found that particle roundness and circularity initially increased rapidly downstream and then remained nearly constant. They interpreted these patterns as reflecting changes in the dominant process affecting particle shape. Hillslope sediment supply and the addition of rock fragments produced by chipping and fragmentation were more important in upstream portions of the network, whereas increasing fluvial transport and residence time in the channel exerted greater influence on particle shape in downstream areas. The rate at which particles became rounded downstream depended on lithology (Pokhrel et al., 2024; Takahashi et al., 2025).

Headwater streams in the rapidly warming Arctic regions may also experience sediment loading from increasing thermokarst activity (Fig. 8). Bowden et al. (2008) found that one small thermokarst gully that formed in 2003 in a headwaters tributary (0.9 km^2 catchment) of the Toolik River, Alaska, USA, delivered more sediment to the Toolik than was normally delivered in 18 years from 132 km^2 of catchment in an adjacent, long-term monitoring site. One year after initial failure, total suspended solids increased from background conditions of 1.2-2.0

Fig. 8. Example of a thermokarst slump on the north side of the Brooks Range, Alaska, USA. A side channel of the Hula Hula River, into which the sediment from the slump is emptying, is seen at upper left in this view.

mg/L to 25-26 mg/L (Bowden et al., 2008). As thermokarst – the abrupt collapse of ice-rich permafrost – accelerates in high-latitude and high-altitude regions globally (Olefeldt et al., 2016; Chen et al., 2021), headwater streams in these regions may experience substantial changes in sediment inputs.

In summary, variable flow volumes and transporting processes (e.g., debris flow vs fluvial), local obstructions to flow (e.g., large wood, immobile boulders), and temporal and spatial variations in sediment inputs from adjacent uplands can cause headwater streams to exhibit even greater episodicity in sediment transport than exhibited by higher-order streams. Bed material in headwaters may reflect predominantly non-fluvial processes, such as colluvial coarse sediment inputs or *in situ* weathering, and may not exhibit well-developed downstream fining and rounding of bed substrate clasts. As noted in the summary for section 3.4, the details of headwater channel morphology, particularly substrate grain-size, bedforms, and in-channel obstruction such as large wood, along with the occurrence of sediment movement during non-fluvial mass movements such as debris flows, can strongly influence the ability of headwater streams to attenuate downstream sediment movement and store sediment for varying lengths of time.

3.6. Biogeochemistry

Most carbon and nutrients enter river networks through headwater streams (Alexander et al., 2007; Abbott et al., 2018) and biogeochemical reactions then occur via interactions along surface and hyporheic flow paths. Because of the close coupling between uplands and headwater channels, as well as the limited length of individual first- and second-order streams, water chemistry in headwater channels is likely to be strongly influenced by external sources and pathways. These include atmospheric inputs, land use, land cover, lithology, and surface and subsurface flow paths from uplands through riparian areas and into stream corridors (Johnson et al., 1997; Alexander et al., 2007; Petrin et al., 2007; Nelson et al., 2011; Walker et al., 2012; Dupas et al., 2021). Consequently, headwaters can display spatially and temporally variable water chemistry (e.g., Bernal et al., 2015), or relatively stable water chemistry, with limited temporal variability and spatial patterns on annual to decadal timescales (Abbott et al., 2018). Catchments with subsurface biogeochemical stratification may exhibit dilution patterns (concentration decreases with increasing discharge) for solutes that are abundant at depth and flushing patterns (concentration increases with increasing discharge) for solutes enriched in shallow soils (Stewart et al., 2022). Despite the importance of upland influences, water chemistry in headwater channels is influenced by within-channel processes that in turn reflect the hydrogeomorphology of the stream, as revealed in studies of in-stream retention times and transient storage in headwaters.

Because solutes are delivered primarily to headwaters, only a proportion of reactive constituents is carried downstream under low flows (Wollheim et al., 2018). A greater proportion of constituents moves downstream as flow increases but the relationship between flow and downstream transport depends on characteristics such as the wetted length of headwater streams, which can change through time, and transient storage in either lentic waters (e.g., floodplain wetlands, ponds), areas of flow separation in the channel, or hyporheic exchanges. This is expressed in the river network saturation concept, which explores how river networks become saturated as the supply of constituents exceeds demand under high flow conditions (Wollheim et al., 2018).

Although channel form and in-channel processes influence nutrient uptake and water chemistry in headwater streams, understanding of how channel geometry influences uptake and the network-scale proportion of this uptake remains limited (Bernhardt and Palmer, 2011; Bernal et al., 2015). Among the primary influences of channel geometry on water chemistry are in-stream retention times and exchanges between free-flowing water and transient storage zones (Drummond et al., 2016). The area of transient storage relative to cross-sectional area can be greater in headwaters than in higher-order streams because of the relative cross-sectional area occupied by features such as individual large boulders or pieces of wood (D'Angelo et al., 1993). Surface water exchanges with storage zones can be rapid and extensive in steep headwater streams (D'Angelo et al., 1993).

The hydraulic roughness of headwater streams can be a critical influence on transient storage, as illustrated by restoration of first- and second-order streams in Finland. Adding large wood and boulders to these streams brought them closer to reference streams with respect to the ratio of cross-sectional area in storage zones and channel cross-sectional area, as well as the fraction of median travel time attributable to transient storage (Marttila et al., 2018). Restored streams lacking these features, as well as aquatic mosses that can increase retentiveness, remained less retentive than natural streams (Muotka and Laasonen, 2002).

Rates of instream chemical reactions may also be influenced by water temperature. Narrow channel widths and riparian forest can block incoming solar radiation and limit its effects on stream temperatures in headwaters, so that these streams are cooler than higher-order streams during summer (Leach et al., 2023). Stream temperature may also be strongly influenced by discharge, with higher stream temperatures corresponding to periods of lower discharge (MacDonald et al., 2014), despite the buffering influence of groundwater inputs and shading of narrow channels.

3.6.1. Riparian zone influences

As multiple studies note (e.g., Ledesma et al., 2013; Fritz et al., 2018; Ledesma et al., 2025), the physical and chemical connectivity between riparian wetlands and stream channels is well documented, with major hydrological flow paths for soil water via saturated flow through the stream bank, through the unsaturated zone, and macropore transfer of soil water from farther back in the riparian zone (Fiebig et al., 1990), as well as groundwater flow paths. Riparian vegetation can influence stream water chemistry by supplying organic matter, modifying hydrologic flow paths, and stabilizing soil (Dosskey et al., 2010), as well as influencing the microbial biomass and associated biogeochemistry of the riparian soils (Ledesma et al., 2018; Reidy et al., 2025a). Early studies posited that, as the last few meters of soil through which water flows before entering a gaining stream, riparian zones must exert a strong influence on stream water chemistry (e.g., Seibert et al., 2009). Because the hillslope and river corridors are closely coupled in headwater streams, headwaters may be dominant in this respect. Dodds and Oakes (2008) found that water chemistry parameters in downstream reaches correlated most strongly with riparian land cover adjacent to first-order streams rather than riparian zones immediately adjacent to downstream reaches, even if the headwater streams were dry.

However, subsequent work from diverse field settings indicates that the influence of riparian vegetation and soils on instream biogeochemistry is complicated and site-specific. First, high-relief catchments with laterally confined headwater valleys may not have well-defined riparian zones, so that riparian influence on stream water chemistry may be negligible (e.g., Tsujimura et al., 2001). Second, solute concentrations in groundwater entering streams may predominantly reflect the mixing of shallow and deep groundwater rather than riparian soils and vegetation (e.g., Hill, 1990). Third, the strength and location of hydrological connectivity within the riparian zone matter (Ledesma et al., 2018; Bujak-Ozga et al., 2026). Examining the transport of biodegradable dissolved organic carbon, for example, Reidy et al. (2025b) found that riparian organic-rich soils with weak hydrological connectivity to the stream likely only contributed organic carbon during floods, whereas sites with stronger lateral hydrologic connectivity could serve as persistent conduits for carbon generated farther upslope even if the riparian zone did not generate much carbon.

Ledesma et al. (2018) described hydrological connectivity with respect to the four dimensions of (i) lateral connectivity along hillslopes, (ii) longitudinal connectivity along the stream, (iii) vertical connectivity within the riparian profile, and (iv) temporal connectivity through event-based and seasonal changes in hydrology. Within the vertical dimension, they posited that a dominant source layer through which most water and solutes are routed laterally results in the highest contribution of water and solute fluxes to streams. At some sites, however, stream chemistry may not reflect the chemistry of this riparian dominant source layer because of water sources that bypass the riparian zone (Ledesma et al., 2025). Again, the strength and location of hydrological connectivity within the riparian zone govern whether stream chemistry reflects a strong signal from the riparian zone, and the depth to impeding layers and steepness and lateral confinement of the adjacent topography may govern whether a riparian zone is present.

3.6.2. Hyporheic exchanges

The hyporheic zone provides a form of transient storage in stream corridors and hyporheic exchange flows in headwater streams can strongly influence water temperature and chemistry. Modeling hyporheic exchanges across stream orders in western Oregon, USA, for example, Wondzell (2011) found that the size of the exchange flows relative to stream discharge was substantial only in very small streams at low flow. Expressed as a ratio of hyporheic exchange discharge to stream discharge, headwater streams at low flow had values of 0.019 and 0.013, whereas larger streams had values of 0.00002. These simulations indicated that biogeochemical processes in the hyporheic zone of small streams can substantially influence the stream's solute load, but the processes become hydrologically constrained at high discharge or in larger channels (Wondzell, 2011).

Tracer-based measurements of second- to fourth-order streams in southern Germany similarly indicated a decrease in the ratio of hyporheic area/channel cross-sectional area with increasing stream order but did not reveal any correlation between hyporheic area and discharge (Glaser et al., 2024). Smaller hyporheic areas in headwater channels during summer compared to other seasons coincided with increased groundwater contributions to stream flow and decreased stream discharge. These measurements also indicated that the greatest temporal variability in hyporheic exchange flows occurred in headwater streams (Glaser et al., 2024).

Numerous factors beyond discharge can influence the magnitude of hyporheic exchange flows. Accumulated leaf litter decreased hyporheic connectivity in second-order streams in Spain (Algerich et al., 2011), whereas increasing discharge increased connectivity. Bedform (step-pool) spacing influenced the locations of measured hyporheic exchanges along a second-order stream in British Columbia, Canada, creating downwelling above steps and upwelling below steps, although transient storage exchange fluxes in the pools were an order of magnitude greater than hyporheic exchanges (Scordo and Moore, 2009). Other studies also indicate that longitudinal bed topography influences hyporheic exchanges in headwaters (e.g., Zarnetske et al., 2008). Confluence geometry, hydrodynamics, and morphodynamics all influenced hyporheic exchange rates and patterns in a first-order, low-gradient stream in New York, USA (Martone et al., 2020). Downstream changes in underlying lithology that correspond to changes in valley geometry and riparian vegetation can also correlate with spatial variations in exchanges between instream water and subsurface flow (Payn et al., 2009). Permanently frozen ground can behave similarly to bedrock in having very low permeability. Comparing a high-energy alluvial stream with a low-energy, peat-lined stream in Alaska, USA, Zarnetske et al. (2008) found greater permafrost degradation under the alluvial stream, with longer flow paths but shorter residence times for hyporheic exchanges.

The complex interactions that influence hyporheic exchanges are illustrated by tracer experiments in western Oregon, USA, in which the extent of the hyporheic zone increased with decreasing vertical gradients away from the stream, although the hyporheic extent increased with both increasing and decreasing down-valley and cross-valley hydraulic gradients (Ward et al., 2012). Modeling for the same study area suggested that groundwater inflow decreased the length and path residence time of hyporheic exchange flows, although flow paths driven by large hydraulic gradients associated with substantial morphological features (e.g., step-pool sequences) were less sensitive to changes in groundwater inflow than were those driven by hydraulic gradients similar to the valley gradient (Schmadel et al., 2017).

Restoration of channel form complexity via creation of an inset floodplain and meandering planform can increase hyporheic exchange on headwater streams, although an example from a second-order stream in Virginia, USA found that structure-induced hyporheic zone denitrification did not exceed 3.1% of the mass flowing in from the upstream channel (Hester et al., 2016).

As with riparian zone influences on headwater stream chemistry, the relative importance of hyporheic exchange flows and their effects on stream chemistry are strongly influenced by the hydrogeomorphology of a channel. Specifically, the relative contributions of groundwater and surface water to total flow, the depth and configuration of hydraulically conductive materials, and the hydraulic roughness of the channel can all influence spatial distribution and magnitude of hyporheic exchanges.

3.6.3. Gaseous emissions

Terrestrial carbon export via streams is an important part of the global carbon cycle (Aufdenkampe et al., 2011; Raymond et al., 2013). Carbon dynamics in streams include loss of carbon (carbon dioxide CO_2, methane CH_4) to the atmosphere via outgassing from rivers; carbon fixation in the water column and sediments of river corridors; and downstream transport of particulate organic matter (Cole et al., 2007; Marx et al., 2017; Wohl et al., 2017). Headwaters are important in this context because their stream biogeochemistry directly reflects carbon input from soils, which are the largest terrestrial reservoir of carbon, and from groundwaters (Hotchkiss et al., 2015; Marx et al., 2017).

Headwaters can exhibit high spatiotemporal variability in carbon dioxide partial pressure (pCO_2) because of the interplay of biological, chemical, and physical processes that influence CO_2, including aquatic biodegradation and photodegradation that reflect solar radiation and temperature (Crawford et al., 2013; Porcal et al., 2015; Marx et al., 2017). The global river average value of pCO_2 is more often exceeded in contributions from small streams than larger rivers and, because of their large proportion in river networks, headwaters contribute large amounts of CO_2 to the atmosphere (Crawford et al., 2013; Hotchkiss et al., 2015; Marx et al., 2017; Li et al., 2021). Although these magnitudes remain poorly quantified, they have been conservatively estimated at 36% of total global CO_2 outgassing from rivers (Raymond et al., 2013; Marx et al., 2017; Sawakuchi et al., 2017). More recently, Li et al. (2021) estimated that first-, second-, and third-order streams emit approximately 72%, 75.5%, and 77% of the global riverine CO_2, CH_4, and N_2O emissions, respectively.

Inland waters are also the largest natural source of methane to the atmosphere, yet the contribution of small streams to this flux remains poorly defined. Robison et al. (2022) proposed a conceptual model of methane dynamics in stream ecosystems in which flowing water and shallow depths promote hyporheic exchange and high gas exchange rates and most methane is emitted via diffusion across the water-air interface, especially in small streams. They noted that small streams can emit methane at similar rates to larger rivers on a per area basis, but with different dominant processes.

Peaks of carbon gas concentrations can occur downstream from each groundwater input zone (Lupon et al., 2019) and emissions can increase during higher flows (Conroy et al., 2023; Lupon et al., 2019; Taillardat et al., 2022; Woodrow et al., 2024) and at night during higher groundwater inputs (Woodrow et al., 2024). Variable stream morphology can also influence local-scale gas emissions, with higher rates at steep portions of a stream where turbulent flow simultaneously oxygenates and releases excess carbon dioxide (Vautier et al., 2020). Where a floodplain or riparian zone is present, gas emissions may be substantially (5X) higher than emission rates from in-stream sites (Vidon and Serchan, 2016).

The interactions within headwaters influence the relative proportions of greenhouse gas emissions: carbon inputs drives total greenhouse gas production, for example, but nitrate (NO_3) input, by suppressing methanogenesis and stimulating denitrification, regulates the relative importance of methane and nitrous oxide (N_2O) (Schade et al., 2016). Adjacent land use patterns can also influence gaseous emissions from small streams. Carbon emissions (CH_4 and CO_2 outgassing rates) tend to be much higher from streams surrounded by urban or agricultural areas because of greater nutrient inputs (Mwanake et al., 2023; Zhao et al., 2026). As might be expected, emissions can also be higher from streams draining carbon-rich soils such as boreal streams underlain by permafrost (Crawford et al., 2013) and streams in peatland soils (Piatka et al., 2024). In general, the shallow depths, large cumulative surface area of headwater streams, and turbulent flow in hydraulically rough channels can all facilitate the contributions of headwaters to gaseous emissions of carbon and nitrogen.

In summary, the water chemistry and biogeochemical processes of headwater streams are strongly influenced by factors external to the channel, such as characteristics of upland regolith and bedrock and groundwater flow paths. Headwaters can nonetheless exhibit relatively stable water chemistry or they can exhibit high spatiotemporal variability in properties such as pCO_2. Hyporheic exchange flows are likely to affect a larger proportion of total stream flow than in higher-order channels, although local controls can strongly influence the magnitude and location of hyporheic exchanges, and surface transient storage is likely to be of greater magnitude than transient storage in the hyporheic zone. Headwater streams can promote nutrient uptake to the extent that they are hydrologically connected to riparian zones and floodplains, and to the extent that heterogeneities within the channel such as bedforms and obstructions are associated with an underlying hydraulically conductive layer that facilitates hyporheic exchange flows.

3.7. Headwater stream classification

As with larger streams located downstream from headwaters, there is no single classification that captures all relevant parameters that might be used to distinguish streams. We propose that the hydrogeomorphology of a headwater stream at the reach-scale could be adequately categorized using the choices in Fig. 9. Under each of the parameters in bold font, one category would be chosen, so that a headwater stream reach could be a perennial, confined stream with cascade bedforms and no evidence of mass movements, or an ephemeral, confined stream with dune-ripple bedforms and no evidence of mass movements, for example.

In this classification scheme, flow regime categories are designed to reflect likely hydrologic flow paths to the stream (perennial and intermittent streams will be more influenced by groundwater and ephemeral streams by surface runoff) and length of permanent flow. Lateral confinement refers to the proximity of non-fluvial landforms (e.g., valley walls) and substrate not deposited by the contemporary channel (e.g., colluvial sediment, bedrock). Lateral confinement is intended to reflect the potential presence of a floodplain or riparian zone (more likely to be present with less lateral confinement), potential lateral channel mobility and sinuosity (likely to be greater with less lateral confinement), hyporheic exchange flows (likely to be more important with less lateral confinement that typically correlate with greater thickness of alluvium underlying the stream corridor), and channel width/depth ratio. If a headwater channel is deeply incised into an alluvial fan, for example, and shows no evidence of recent lateral channel movement, it could be designated as being confined. Bedform type corresponds closely to reach-scale gradient (Montgomery and Buffington, 1997), especially in moderate to high-relief environments, and bedform types in turn reflect whether the reach is predominantly a transport or response segment of the stream, the relative stability of the streambed and the relative grain size of the channel substrate. Cascade and step-pool bedforms, for example, occur in transport-dominated reaches with a relatively stable bed of coarse (boulder to cobble-size) sediment (Montgomery and Buffington, 1997). Noting whether there is evidence of past movements, such as debris-flow levees or avalanche chutes and deposits, can also provide insight into the stability of the channel form and the potential for episodic movement of substantial volumes of sediment. Flow regime and relative contributions of groundwater and surface water will influence stream biogeochemistry, but another highly relevant and easily assessed parameter is riparian vegetation, which can influence shading of the stream and organic matter inputs to the channel.

4. Stressors and vulnerability in headwater streams

As noted above, headwater streams are typically underrepresented in mapped river networks. First- and even second-order channels can also be difficult to recognize on the ground, especially if they are ephemeral (see Fig. 1A and 1D). Headwaters also typically lack legal protection either because they are unrecognized or are considered too small to be important, or because – given their long cumulative length in any river network – protection of small channels would require protection of large areas of land surface. In the United States, for example, most state guidelines recommend riparian management zones for perennial and intermittent streams, but not ephemeral streams (Kampf et al., 2021). Richardson (2019a) also noted that headwaters in developed regions are "small and easily engineered physical spaces" likely to be altered by

Physical	**Flow regime**	**Lateral confinement**	**Gradient/bedforms**	**Mass movements**
	perennial	confined	cascade	yes
	intermittent	moderately confined	step-pool	no
	ephemeral	unconfined	plane bed	
			pool-riffle	
			dune-ripple	
Biogeochemical	**Riparian vegetation**			
	absent			
	present – herbaceous			
	present – forest			

Fig. 9. Proposed hydrogeomorphic classification scheme for headwater stream reaches. One term in each group in bold font is used to categorize a stream. Confined channel reaches have some non-channel boundary within ≤ 2X channel width. Moderately confined reaches have a boundary 2-5X channel width. Bedform types are described in Montgomery and Buffington (1997). If biogeochemistry and water temperature are of interest, a categorical description of riparian vegetation can also be added.

channelization, land drainage, and burial.

Consequently, one of the stressors that is perhaps unique to headwater streams is complete obliteration of the channel via burial, piping underground, or simply plowing or paving over the channel and adjacent surfaces (Stammler et al., 2013; Napieralski et al., 2015). Systematic investigation of a 3500 km^2 catchment that drains to Chesapeake Bay in the eastern United States, for example, found that 20% of all streams were buried, with headwater streams more extensively buried than larger streams (Elmore and Kaushal, 2008). Within the city boundaries of the major urban area (Baltimore) in the catchment, 66% of all streams and 70% of streams in catchments smaller than 260 ha were buried. Other studies in the eastern US have found that stream burial correlates with impervious surface area and areas above 30% impervious surface area commonly have elevated ratios of stream burial (Weitzell et al., 2016). Stream burial increases catchment-scale nitrate export (Beaulieu et al., 2015) and reduces gross primary productivity and ecosystem respiration of the stream (Pennino et al., 2014), as well as changing the concentration and attenuation of storm runoff (Wohl et al., 2025a).

Most of the other primary stressors affecting headwater streams also affect higher-order river corridors (Wohl, 2006). These include changes in land cover and land use in all or part of the catchment. Within the stream corridor, multiple human alterations can affect headwaters, including: flow diversion and damming; in-channel structures such as check dams; log floating and removal of naturally occurring in-channel obstructions; placer mining; channelization; transportation corridors and road crossings; introduced exotic species; riparian grazing; the presence of contaminants including excess fine sediment, excess nutrients, and other pollutants; and drought and human-induced drying. Each of these is discussed below.

Changes in land cover alter water and sediment inputs to headwater streams and, because the catchment area of these streams is typically small, land cover for the entire contributing area can change rapidly. In forested catchments, clearcutting can create persistent (multidecadal) changes in the species and structure of riparian vegetation, channel geometry and habitat diversity, channel entrenchment, and streambed substrate with increasing water and sediment inputs from adjacent uplands to the stream corridor (Jackson et al., 2001; Davies et al., 2005; Gomi et al., 2006). Local deforestation for commercial skiing, accompanied by artificial snowmaking that increases snowmelt runoff to headwaters, can trigger channel erosion (David et al., 2009). Lode and coal mining, mountaintop removal for coal, and coalbed methane, hydraulic fracturing, or other forms of oil and gas mining within the contributing area of headwater streams can contribute excess sediment and spills or produced water containing an array of toxins including trace metals (Maloney et al., 2018; Michaels et al., 2022; Shobe et al., 2024) (Fig. 10). Alternatively, water may be extracted from headwater streams for mining activities (Brittingham et al., 2014; Entrekin et al., 2015). These activities can also completely obliterate headwater channels and alter hydrologic regimes downstream from the mining fill, especially in areally extensive and disruptive activities such as mountaintop removal (Hartman et al., 2005).

Fig. 10. Example of headwaters (here a spring-fed first-order tributary of the East Branch Rausch Creek in Pennsylvania, USA) contaminated by acid mine drainage. The spring-head is upstream (to the left) in a small, confined depression. Flow spreads to 2-3 m wide and 10-20 cm deep (but still occurs within a defined channel) in the downstream portion shown here, before concentrating into a narrower channel downstream.

Urbanization can either decrease (via reduced infiltration) or increase (via lawn irrigation and septic tanks) the permanence of headwater stream flows (Roy et al., 2009). Analogously, vertical accretion of the streambed following urbanization can result in loss of channel capacity as increased fine sediment inputs outpace increased runoff (Ebisemiju, 1989) or urbanization can result in greater erosive energy because of increased runoff, resulting in greater sediment mobility and bed coarsening (Utz and Hilderbrand, 2011), channel enlargement, and local scour, especially downstream from road crossings (Chin and Gregory, 2001). Urbanization can also correspond to increased water temperature (Rice et al., 2011), increased greenhouse gas emissions (Dai et al., 2024), altered composition of dissolved organic matter and stream microbial communities (Parr et al., 2015), and contamination with excess nutrients, microplastics, trace metals, synthetic chemicals, pathogens, and other toxins (Roy and Bickerton, 2011; Wohl, 2015; Williams and Filoso, 2023).

Flow diversion and damming are less common on headwater streams than on higher-order channels but second-order streams are sometimes affected. In drylands with mountain water towers (Immerzeel et al., 2020), diversions can be placed at high elevations on very small streams with the intent of collecting water for transfer to lowland urban and agricultural areas (Caskey et al., 2015). These diversions can remove all flow from the channel. Diversion of flow during peak snowmelt or glacial-melt also occurs in wetter climates and has a history that may extend back to the Iron Age in regions such as the Valais canton of Switzerland (Crook and Jones, 1999). More recent Swiss flow diversions include hydroelectric facilities on small glacial meltwater streams where mountain glaciers are rapidly retreating (Fig. 11). Headwaters may also be dammed with earthen embankments to create stock or farm ponds (Renwick et al., 2005; Florsheim et al., 2013), and with check dams or grade-control structures to limit channel incision and downstream sediment movement (Galia, 2021; Lucas-Borja et al., 2021).

Floating cut logs downstream to collection points and sawmills was historically widespread in parts of Eurasia and North America, as documented for Sweden (Törnlund and Östlund, 2002) and several forested regions of the contiguous United States (Cowan, 2003; McMahon and Karamanski, 2009; Wohl, 2014). As long as a headwater channel was sufficiently wide to contain a single log oriented parallel to the channel, it could be used for log floating. Naturally occurring in-channel obstructions including large wood, logjams, beaver dams, and large boulders were commonly removed from channels used for log floating, and connectivity with secondary channels and overbank areas was blocked. These alterations reduced channel spatial heterogeneity and associated functions including water and sediment storage, hyporheic exchange flows, habitat diversity, and channel stability (Nilsson et al., 2005). In many regions, beaver populations had already been decimated for the commercial fur trade, and beaver dams had collapsed (Halley and Rosell, 2002; Backhouse, 2015), prior to commercial timber

Fig. 11. Example of hydroelectric development in headwaters; here, the Maggia Valley in Switzerland, showing the dam at a glacial cirque (left) and the de-watered channel downstream (right).

harvest and log floating.

In regions with alluvial placer deposits, disruption of channel and valley-floor sediment for placer mining can also substantially disrupt or even obliterate headwater channels, or diversion of water to work placer deposits can dewater channels (Bjerklie and LaPerriere, 1985; Reynolds et al., 1989; Stubblefield et al., 2005). Excess suspended and bedload sediments from mining areas, along with diverse contaminants, typically affect downstream portions of the river network (Smolders et al., 2003; Dethier et al., 2023). Although much of this activity was historical in Europe and North America, placer or alluvial mining of headwaters continues at present in parts of South America and Africa (Donkor et al., 2005; Dethier et al., 2023).

As with flow regulation, channelization is less common on headwater streams than on higher-order channels, but second-order streams can be channelized. These are likely to be in agricultural regions that naturally had high water tables and in which channelization or ditching was designed to drain crop fields (Landwehr and Rhoads, 2003; Smiley et al., 2011) or enhance forest productivity (Åström et al., 2001). Channelization typically causes channel erosion and downstream aggradation (e.g., Brookes, 1988), as well as degrading habitat quality (Lau et al., 2006) and increasing concentrations of nutrients and pesticides in stream water (Smiley et al., 2010, 2011).

Road crossings on headwater streams, typically in the form of culverts, are an important and widespread form of alteration (Roy and Sahu, 2018; Frankiewicz et al., 2021; Lehrter et al., 2023). Culverts can form local base levels with downstream vertical drops that interrupt longitudinal sediment connectivity, as well as creating substantial barriers to movement for a variety of aquatic organisms (Wood et al., 2018). Transportation corridors can also affect headwater streams via constriction or displacement of the stream corridor and increased runoff, sediment, and contaminants from road surfaces into streams (Blanton and Marcus, 2014; Thomas and Peretto, 2016).

As in higher-order streams, introduced invasive species can influence water and sediment inputs to headwater streams, channel form and stability, and aquatic and riparian foodwebs (Little et al., 2021). The primary difference between headwater and higher-order stream responses may be that headwaters are likely to be more sensitive to invasive species in the uplands that alter fluxes into stream corridors (Rubio-Rios et al., 2025).

Riparian grazing or upland grazing near a headwater stream can substantially alter the water and sediment inputs, channel form and stability, water quality, and aquatic and riparian communities in the

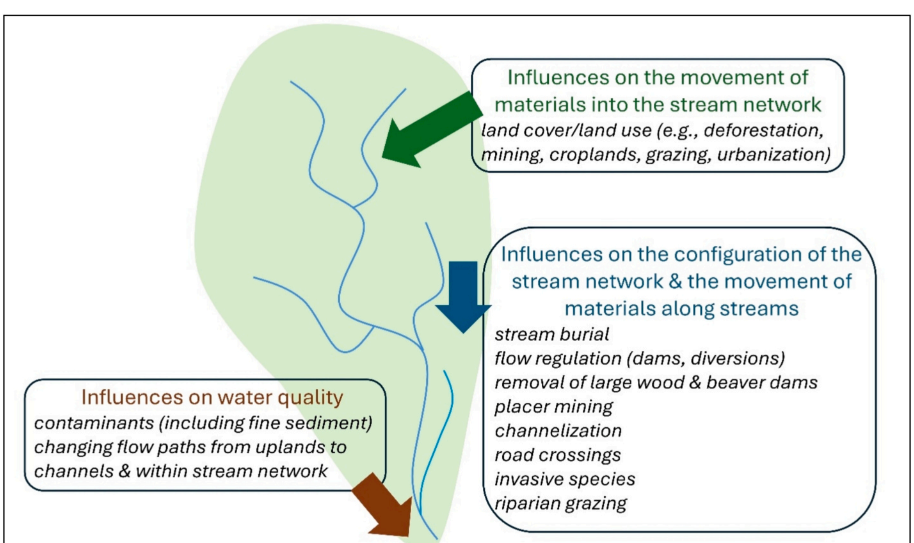

Fig. 12. Summary of diverse types of stressors that influence headwater streams.

stream (Riley et al., 2003; Booth et al., 2022; Lenhart et al., 2023). Headwaters may be especially vulnerable to these effects if they are not protected by any type of vegetation exclosure or riparian buffer zone (Giraldo et al., 2022).

As noted previously, headwater streams even in humid temperate and tropical regions are more likely to be intermittent or ephemeral than are higher-order streams (e.g., Leach et al., 2024). Headwaters fed primarily by surface runoff or by shallow groundwater can go dry for much of the year under 'normal' conditions (e.g., Warix et al., 2021) but the spatial extent and duration of drying can be exacerbated by drought, warming climate (Datry et al., 2023), or human-induced changes in infiltration capacity, runoff (Johnson et al., 2022), ecohydrological coupling between plants and available moisture (Newcomb and Godsey, 2023), and soil moisture (Carey et al., 2021; Zipper et al., 2021). Much of the literature on drying in headwater streams focuses on the biogeochemical and ecological implications but drying can also alter downstream transmission of sediment and channel form and stability (Hakala and Hartman, 2004).

The diverse types of stressors to headwater streams can be classified as those that influence the movement of water, solutes, sediment, and organic matter from uplands into the stream network; those that influence the configuration of the stream network and the movement of materials along streams; and those that influence water quality (Fig. 12).

In summary, headwater streams may be particularly vulnerable to a variety of natural and human-induced stressors. Their small catchment areas, close coupling to adjacent uplands and short channel lengths relative to downstream portions of the river network, as well as lack of floodplains, limit the ability of headwaters to buffer changing inputs of water, solutes, sediment, and contaminants. Their small size also limits the regulatory protection accorded to headwater channels and makes them more prone to complete obliteration via burial, diversion, or other alterations. Although there is no published estimate of the proportion of headwater streams that have been altered by diverse human activities, it is a reasonable assumption that headwaters outside of any type of protected area (e.g., national parks or nature reserves) within the temperate latitudes have been moderately to extensively affected by multiple types of human activities.

4.1. Protection and legal recognition

Because headwater streams are commonly ephemeral or intermittent and non-navigable, they lack the legal protection afforded to higher-order streams. Under the 1972 US Clean Water Act, any tributary of a navigable river was protected until 2001 (Nadeau and Rains, 2007). After a multi-year legal debate, this was changed by legal decisions such as the 2001 SWANCC, 2006 Rapanos, and 2023 Sackett decisions by the US Supreme Court, which significantly narrowed the scope of the US Clean Water Act and largely stripped protections from small and particularly from ephemeral or intermittent streams (Leibowitz et al., 2008; Fritz et al., 2017; Walsh and Ward, 2022; Sullivan et al., 2025). Comte et al. (2026) estimate that just over one-tenth of the river length of the contiguous United States are currently protected at a level deemed viable, with headwater streams consistently under protected.

In the EU, the Water Framework Directive mandates improvements in the status of streams through identification of bodies of surface water to be used for quality diagnosis and management. Because of their small size, headwater streams are not usually recognized as bodies of surface water and are excluded from the measures implemented for higher-order streams through river basin management plans (Lassaletta et al., 2010). The European Commission recommended, however, that small water bodies be included in management plans when they significantly impact downstream waters (European Commission, 2003). Within individual EU countries that do recognize headwater streams in river basin management plans, such as Denmark, inclusion of headwaters has led to concerns that the comprehensive alterations of these streams by actions such as channelization and dredging can limit their ability to fulfill ecological quality objectives of the Water Framework Directive (Baattrup-Pedersen et al., 2018). This concern has caused the Danish Environmental Protection Agency to consider excluding many headwaters from management plans (Baattrup-Pedersen et al., 2018).

Most other regions of the world also have little or no legal protection for headwaters, although individual countries such as Mongolia (Surenkhorloo et al., 2021) can be exceptions to this generalization. The 'Headwater Control' movement initiated in 1989 promoted self-sustainable management strategies for headwater catchments in the context of alterations in land cover and streamflow regimes (Haigh, 2004; Haigh et al., 2004). Although the movement has gradually spread from Europe to other regions, it lacks legal underpinning and associated protection mechanisms. Much of the protection that headwater streams may receive stems from their inclusion in protected ecosystems, such as mountain nature reserves, rather than explicit legal protection for the streams themselves. If the legislation governing protected areas changes, streams may be dammed: Perry et al. (2021) noted that more than 1200 dams exist within protected areas, with another 500 under construction or planned in the next two decades. As Perry et al. (2021) also noted, 70% of rivers globally are outside of protected areas and only 11.1% are entirely protected.

Referring back to the list of functions provided by headwater streams (Table 1), the consensus among investigators is that these functions can be improved or conserved by focusing on protection and restoration of three primary properties: land cover in contributing areas (Qiu et al., 2013), with an emphasis on riparian buffers (Adams, 2007; Jyväsjärvi et al., 2020); connectivity between uplands and streams and within the stream network (Sullivan et al., 2025); and flow regimes in headwater streams (Golden et al., 2025). By focusing on the area that contributes materials to headwater streams and the factors that influence movements of materials within these streams, additional characteristics including water quality, attenuation of peak flows, nutrient uptake, retention of particulate organic matter and sediment, habitat abundance and diversity, and provision of refugia in headwaters will also be enhanced.

5. Research gaps and needs

The great majority of the references cited in this paper have been published in the past two decades. This reflects the increase in research on headwater streams in response to lack of legal protection and recognition of headwater streams. The increased research attention also reflects the scientific recognition of the diverse functions provided by ephemeral and intermittent streams (e.g., Datry et al., 2017, 2018; Steward et al., 2022), coupled with increasing recognition that these streams are widespread and account for a large majority of the total length of stream channels globally but are nonetheless underrepresented in most catchment-, regional-, or global-scale maps of rivers.

Much of the research summarized in this review focuses on the hydrology and biogeochemistry of headwater streams. These topics, along with stream ecology, have received more attention than the morphology, sediment dynamics, substrate-flow-biotic interactions as these influence stream corridor forms, or the resilience/resistance of headwater stream corridors to disturbances. Nonetheless, there remain notable research gaps with respect to all aspects of headwater streams.

Imberger et al. (2023) highlight the need for characterization of headwater stream typologies across diverse climates, geologies, and biomes. Characterizing the forms, processes, and function of headwaters, especially in understudied regions such as the tropics and ephemeral and intermittent headwaters, can facilitate identifying dominant drivers of stream structure and function at different spatial scales, as well as the relative sensitivity of headwater streams types to disturbances associated with land use and climate change. Here, we proposed a headwater stream classification using characteristics that are also applied to classification of larger rivers, but additional studies focused on channel width and length, downstream hydraulic geometry, bedforms, and substrate types in headwater streams could provide data to put this classification on a more quantitative basis.

With respect to hydrology, characterizing and predicting the location and extent of the basic headwater channel network, as well as the extent and duration of surface flow in headwaters, remains a challenge (Imberger et al., 2023), especially as urbanization and warming climate change patterns of flow intermittency in headwaters. Although headwater stream flows are likely to decline in magnitude and spatial extent as climate warms (e.g., Xu et al., 2009; Olson and Burton, 2019; López-de Sancha et al., 2022), the details of potential changes are poorly constrained and we are challenged to identify potential tipping points such as levels of urbanization where hydrologic effects rapidly increase (Imberger et al., 2023). In addition, in some regions warming climate equates to greater intensity and volume of rainfall and, if combined with increased urbanized area, this will likely lead to greater unit area peak discharge and flashiness of flow (e.g., Wu et al., 2013). Where glaciers are retreating under warming climate, headwater stream flow and groundwater storage may increase at least temporarily, until the glacier is gone (Lin et al., 2020).

Although groundwater inputs can buffer stream temperatures against increased air temperatures (e.g., Snyder et al., 2015), this effect may be limited in headwater streams because small streams typically receive shallower groundwater inputs than larger rivers (Kurylyk et al., 2015; Hare et al., 2021). Modeling the effects of shallow groundwater seepage and air temperature on stream temperatures across 9 headwater catchments, Johnson et al. (2017) found that shallow groundwater effects exhibited more variation within catchments than between them because of site-specific interactions among geomorphic features such as channel slope and contributing area, and seasonal precipitation patterns. This type of variation in groundwater inputs to headwaters suggests that the effects of warming climate on the volume and temperature of groundwater additions to streams will be difficult to quantitatively predict.

For biogeochemistry, numerous studies indicate that water chemistry in headwaters can be strongly influenced by external sources and pathways. The conditions under which headwaters display relatively stable water chemistry remain poorly constrained, however, as does understanding of how channel geometry influences nutrient uptake. As noted by Reidy et al. (2025a), comparison between sites to understand the mechanisms underlying observed differences in stream biogeochemical variability is hampered by a lack of standardized methods and few studies from headwater streams during base flow.

As air temperatures warm, the shading provided by riparian vegetation can mitigate warming of stream temperatures and associated ecological degradation (Turunen et al., 2021). Warming climate may also change riparian vegetation communities, however, in ways that can affect not only shading but also organic matter and solute inputs to streams (e.g., Salinas et al., 2018). The effects of warming climate on riparian zones have received little attention and constitute an important research gap.

As with groundwater inputs and riparian shading, hyporheic exchange flows can buffer increases in stream temperature associated with warmer air temperatures (e.g., Leach et al., 2023; Moore et al., 2023). The effects of warming climate on hyporheic exchange flows are likely to be site-specific, however, as demonstrated in a modeling study of two Arctic headwater streams. Average thaw depths of permafrost were two-fold greater under the higher energy, alluvial stream than under the low-energy, peat-lined stream, resulting in shorter residence times and longer flow paths under the alluvial stream (Zarnetske et al., 2008). However, simulations of deeper thaw under a warming climate only influenced hyporheic exchange until a threshold depth determined by hydraulic head gradients resulting from stream morphology (Zarnetske et al., 2008). The network-scale proportion of nutrient uptake and gaseous emissions associated with headwaters also constitute gaps in understanding. These gaps have important implications for headwater stream management and restoration. Finally, as noted by Battin et al. (2023) in the context of carbon biogeochemistry, scaling laws often resolve only steady-state conditions and fail to account for the dynamic nature of river networks, including the expansion and contraction of wetted area in headwaters. Because scaling relationships require validation across the entire range of river sizes, the development of integrated global field campaigns to resolve problems with scaling laws and unify the scales of ground and satellite observations in small rivers constitutes a research priority.

With respect to geomorphology, it remains unclear to what extent and under what conditions headwater streams alter existing topography rather than responding to topography. The relative importance of non-fluvial processes in shaping channel morphology and transporting sediment is poorly characterized with respect to potential thresholds associated with catchment steepness and drainage area. The location, width, and longitudinal continuity of floodplains are poorly constrained, which limits our ability to estimate the potential for headwater streams corridors to attenuate downstream fluxes of water and sediment.

Improving our understanding of headwater stream functions such as organic matter processing and nutrient uptake can inform estimates of the ecosystem services provided by headwaters (Imberger et al., 2023). This feeds directly into the need to better understand the most effective spatial distribution and the aggregate proportion of stream corridor length for headwater restoration projects designed to create catchment-scale cumulative effects in peak flow attenuation (Follett et al., 2024; Wohl et al., 2025a, 2025b), nutrient uptake (Wollheim et al., 2018), and sustainable river ecosystems. These integrative issues are increasingly crucial to maintaining functional river networks into the future. First- and second-order streams may be less likely targets for restoration than higher-order streams because individual channels are typically so small and/or lack perennial flow. Headwaters are more likely to be substantially altered or obliterated, however, than larger streams, suggesting that they should be targeted in restoration efforts.

Headwater streams are currently subject to a diverse array of stressors, many of which will become more severe as climate warms and urbanization continues to increase. The potential effects of warming climate on precipitation and stream flow can be assessed using climate projections and numerical rainfall-runoff models to simulate effects on stream flow and on groundwater recharge (e.g., Xu et al., 2009; Levison et al., 2014; Yifru et al., 2022), but this approach includes high degrees of uncertainty in climate and the precipitation of water through the catchment and into streams, as well as interacting effects such as changes in the disturbance regime (e.g., wildfire, insects) of land cover (e.g., Mahat and Anderson, 2013) or changes in permafrost characteristics (e.g., Jones and Rinehart, 2010) and the associated changes in water balance. The physical and biogeochemical implications of changed stream flow are even less likely to be simulated because of the need to develop a long-term continuous sediment transport model to examine channel stability (Khan et al., 2025), for example. It is also important to note that most studies of the potential effects of warming climate on stream flow, sediment transport, and other stream processes focus on the downstream portions of river networks rather than on the poorly studied stream flow in headwaters.

In summary, on every topic covered in this review, far less is known about headwaters than about larger rivers. Measurements of channel distribution and size; the extent of flow permanence within the headwater stream network; sources, quantities, and spatial and temporal variations of groundwater inputs; channel gradient, bedforms, and substrate; suspended and bedload transport; the influence of riparian vegetation and soils on stream chemistry; locations and magnitudes of hyporheic exchange flows; and the spatial extent and details of headwater stream alteration by human activities are all limited to a relatively small number of the headwater streams present globally. The spatial and temporal extent of these types of basic data must be expanded to increase our ability to quantify and model the contributions of headwater streams to downstream river networks and ecosystems.

6. Conclusions

Delineation of first- and second-order streams as measured based on channel head locations remains challenging and headwater streams remain underrepresented in most maps of river networks. Nonetheless, these small streams clearly constitute the majority of total stream channel length globally and, as such, influence greenhouse gas emissions from channels; habitat and biodiversity within river networks; supply of flow, nutrients, and sediment to downstream portions of river networks; and resilience of higher-order rivers to natural and anthropogenic disturbances. The growing body of literature on headwater channels and ephemeral and intermittent streams supports the contention that headwaters deserve more legal protection and efforts to restore their forms and processes than they currently receive in most countries. Just as permanently removing all the needles or leaves from a tree might be expected to eventually kill the tree, so removing or comprising the functions of headwaters has and will continue to contribute to substantial loss of ecosystem functions in downstream portions of river networks. Additional research targeted specifically at processes in headwater streams is vital, but it is equally vital that research findings inform efforts to protect and manage headwaters.

Open research

No original data collection or analyses were conducted for this review paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We appreciate the invitation from Emily Iskin and Anna Marshall to give a presentation on this topic at the 2025 American Geophysical Union conference, which led to this paper. Comments from two anonymous reviewers and an associate editor improved the first draft of the manuscript.

Data availability

No data was used for the research described in the article.

References

Abbott, B.W., Gruau, G., Zarnetske, J.P., Moatar, F., Barbe, L., Thomas, Z., Fovet, O., Kolbe, T., Gu, S., Pierson-Wickmann, A.C., Davy, P., Pinay, G., 2018. Unexpected spatial stability of water chemistry in headwater stream networks. Ecol. Lett. 21, 296–308. https://doi.org/10.1111/ele.12897.

Adams, P.W., 2007. Policy and management of headwater streams in the Pacific Northwest: synthesis and reflection. For. Sci. 53, 104–118. https://doi.org/10.1093/forestscience/53.2.104.

Adams, R.K., Spotila, J.A., 2005. The form and function of headwater streams based on field and modeling investigations in the southern Appalachian Mountains. Earth Surf. Process. Landf. 30, 1521–1546. https://doi.org/10.1002/esp.1211.

Alexander, R.B., Boyer, E.W., Smith, R.A., Schwarz, G.E., Moore, R.B., 2007. The role of headwater streams in downstream water quality. J. Am. Water Resour. Assoc. 43, 41–59. https://doi.org/10.1111/j.1752-1688.2007.00005.x.

Algerich, A., Marti, E., Sabater, F., Ribot, M., 2011. Temporal variation of hydrological exchange and hyporheic biogeochemistry in a headwater stream during autumn. Freshwater Sci. 30, 635–652. https://doi.org/10.1899/10-078.1.

Allen, G.H., Pavelsky, T.M., Barefoot, E.A., Lamb, M.P., Butman, D., Tashie, A., Gleason, C.J., 2018. Similarity of stream width distributions across headwater systems. Nat. Commun. 9, 610. https://doi.org/10.1038/s41467-018-02991-w.

Antoine, M., Chalon, C., Darboux, F., Javaux, M., Bielders, C., 2012. Estimating changes in effective values of surface detention, depression storage and friction factor at the interrill scale, using a cheap and fast method to mold the soil surface micro-topography. Catena 91, 10–20. https://doi.org/10.1016/j.catena.2010.11.003.

Argerich, A., Haggerty, R., Johnson, S.L., Wondzell, S.M., Dosch, N., Corson-Rikert, H., Ashkenas, L.R., Pennington, R., Thomas, C.K., 2016. Comprehensive multiyear carbon budget of a temperate headwater stream. J. Geophys. Res. Biogeosci. 121, 1306–1315. https://doi.org/10.1002/2015JG003050.

Asano, Y., Kawasaki, M., Saito, T., Haraguchi, R., Takatoku, K., Saiki, M., Kimura, K., 2020. An increase in specific discharge with catchment area implies that bedrock infiltration feeds large rather than small mountain headwater streams. Water Resour. Res. 56, e2019WR025658. https://doi.org/10.1029/2019WR025658.

Åström, M., Aaltonen, E.K., Koivusaari, J., 2001. Effect of ditching operations on stream-water chemistry in a boreal forested catchment. Sci. Total Environ. 279, 117–129. https://doi.org/10.1016/S0048-9697(01)00757-4.

Aufdenkampe, A.K., Mayorga, E., Raymond, P.A., Melack, J.M., Doney, S.C., Alin, S.R., Aalto, R.E., Yoo, K., 2011. Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. Front. Ecol. Environ. 9, 53–60. https://doi.org/10.1890/100014.

Baattrup-Pedersen, A., Larsen, S.E., Andersen, D.K., Jepsen, N., Nielsen, J., Rasmussen, J. J., 2018. Headwater streams in the EU Water Framework Directive: evidence-based decision support to select streams for river basin management plans. Sci. Total Environ. 613-614, 1048–1054. https://doi.org/10.1016/j.scitotenv.2017.09.199.

Backhouse, F., 2015. Once They Were Hats. In: Search of the Mighty Beaver. ECW Press, Toronto, Ontario, Canada.

Bansah, S., Ali, G., 2019. Streamwater ages in nested, seasonally cold Canadian watersheds. Hydrol. Process. 33, 495–511.

Barefoot, E., Pavelsky, T.M., Allen, G.H., Zimmer, M.A., McGlynn, B.L., 2019. Temporally variable stream width and surface area distributions in a headwater catchment. Water Resour. Res. 55, 7166–7181. https://doi.org/10.1029/2018WR023877.

Battin, T.J., Lauerwald, R., Bernhardt, E.S., Bertuzzi, E., Gener, L.G., Hall, R.O., Hotchkiss, E.R., Maavara, T., Pavelsky, T.M., Ran, L., Raymond, P., Rosentreter, J.A., Regnier, P., 2023. River ecosystem metabolism and carbon biogeochemistry in a changing world. Nature 613, 449–459. https://doi.org/10.1038/s41586-022-05500-8.

Beaulieu, J.J., Golden, H.E., Knightes, C.D., Mayer, P.M., Kaushal, S.S., Pennino, M.J., Arango, C.P., Balz, D.A., Elonen, C.M., Fritz, K.M., Hill, B.H., 2015. Urban stream burial increases watershed-scale nitrate export. PLoS One 10, e0132256. https://doi.org/10.1371/journal.pone.0132256.

Benda, L., 1990. The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA. Earth Surf. Process. Landf. 15, 457–466. https://doi.org/10.1002/esp.3290150508.

Benda, L., Dunne, T., 1987. Sediment routing by debris flows. In: Beschta, R.L., Blinn, T., Grant, G.E., Ice, G.G., Swanson, F.J. (Eds.), Erosion and Sedimentation in the Pacific Rim, 165. *International Association of Hydrological Science Publication*, pp. 213–223.

Benda, L., Dunne, T., 1997. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. Water Resour. Res. 33, 2849–2863. https://doi.org/10.1029/97WR02388.

Benda, L., Hassan, M.A., Church, M., May, C.L., 2005. Geomorphology of steepland headwaters: the transition from hillslopes to channels. J. Am. Water Resour. Assoc. 41, 835–851. https://doi.org/10.1111/j.1752-1688.2005.tb03773.x.

Bernal, S., Lupon, A., Ribot, M., Sabater, F., Marti, E., 2015. Riparian and in-stream controls on nutrient concentrations and fluxes in a headwater forested stream. Biogeosciences 12, 1941–1954. https://doi.org/10.5194/bg-12-1941-2015.

Bernhardt, E.S., Palmer, M.A., 2011. River restoration: the fuzzy logic of repairing reaches to reverse catchment scale degradation. Ecol. Appl. 21, 1926–1931. https://doi.org/10.1890/10-1574.1.

Bernhardt, E.S., Likens, G.E., Hall, R.O., Buso, D.C., Fisher, S.G., Burton, T.M., Meyer, J. L., McDowell, W.H., Mayer, M.S., Bowden, W.B., Findlay, S.E.G., Macneale, K.H., Stelzer, R.S., Lowe, W.H., 2005. Can't see the forest for the stream? In-stream processing and terrestrial nitrogen exports. BioScience 55, 219–230. https://doi.org/10.1641/0006-3568(2005)055[0219:ACSTFF]2.0.CO;2.

Bhamjee, R., Lindsay, J.B., Cockburn, J., 2016. Monitoring ephemeral headwater streams: a paired-sensor approach. Hydrol. Process. 30, 888–898. https://doi.org/10.1002/hyp.10677.

Bishop, K., Buffam, I., Erlandson, M., Folster, J., Laudon, H., Seibert, J., Temnerud, J., 2008. Aqua Incognita: the unknown headwaters. Hydrol. Process. 22, 1239–1242. https://doi.org/10.1002/hyp.7049.

Bjerklie, D.M., LaPerriere, J.D., 1985. Gold-mining effects on stream hydrology and water quality, Circle Quadrangle, Alaska. J. Am. Water Resour. Assoc. 21, 235–242. https://doi.org/10.1111/j.1752-1688.1985.tb00133.x.

Blanton, P., Marcus, W.A., 2014. Roads, railroads, and floodplain fragmentation due to transportation infrastructure along rivers. Ann. Assoc. Am. Geogr. 104, 413–431. https://doi.org/10.1080/00045608.2014.892319.

Blume, T., van Meerveld, H.J., 2015. From hillslope to stream: methods to investigate subsurface connectivity. WIREs Water 2, 177–198. https://doi.org/10.1002/wat2.1071.

Bonanno, E., Bloschl, G., Klaus, J., 2021. Flow directions of stream-groundwater exchange in a headwater catchment during the hydrologic year. Hydrol. Process. 35, e14310. https://doi.org/10.1002/hyp.14310.

Booth, D.T., Likins, J.C., Cox, S.E., Norton, J.B., Anderson-Sprecher, R.C., 2022. Grazing increases soil warming in headwater wetlands: importance to land managers and water users. Ecosystems 25, 1052–1065. https://doi.org/10.1007/s10021-021-00701-0.

Botter, G., Barone, F., Durighetto, N., 2026. Headwater streams control the non-perennial fraction of the global river network. *Nature Water*. https://doi.org/10.1038/s44221-025-00549-x.

Bowden, W.B., Gooseff, M.N., Balser, A., Green, A., Peterson, B.J., Bradford, J., 2008. Sediment and nutrient delivery from thermokarst features in the foothills of hte North Slope, Alaska: potential impacts on headwater stream ecosystems. J. Geophys. Res. 113, G02026. https://doi.org/10.1029/2007JG000470.

Boyd, C.A., Allen, G.H., 2025. The widths of rivers and streams across spatial scales: a framework for improving river-atmosphere biogeochemical exchange estimates. Geophys. Res. Lett. 52, e2025GL115713. https://doi.org/10.1029/2025GL115713.
Briggs, M.A., Goodling, P., Johnson, Z.C., Rogers, K.M., Hitt, N.P., Fair, J.B., Snyder, C. D., 2022. Bedrock depth influences spatial patterns of summer baseflow, temperature and flow disconnection for mountainous headwater streams. Hydrol. Earth Syst. Sci. 26, 3989–4011. https://doi.org/10.5194/hess-26-3989-2022.
Brinkerhoff, C.B., Gleason, C.J., Kotchen, M.J., Kysar, D.A., Raymond, P.A., 2024. Ephemeral stream water contributions to United States drainage networks. Science 384, 1476–1482. https://doi.org/10.1126/science.adg9430.
Brittingham, M.C., Maloney, K.O., Farag, A.M., Harper, D.D., Bowen, Z.H., 2014. Ecological risks of shale oil and gas developments to wildlife, aquatic resources and their habitats. Environ. Sci. Technol. 48, 11034–11047. https://doi.org/10.1021/es5020482.
Brodie, J.F., Redford, K.H., Doak, D.F., 2018. Ecological function analysis: incorporating species roles into conservation. Trends Ecol. Evol. 33, 840–850. https://doi.org/10.1016/j.tree.2018.08.013.
Brookes, A., 1988. Channelized Rivers: Perspectives for Environmental Management. Wiley, New York.
Brooks, R.T., Colburn, E.A., 2011. Extent and channel morphology of unmapped headwater stream segments of the Quabbin Watershed, Massachusetts. J. Am. Water Resour. Assoc. 47, 158–168. https://doi.org/10.1111/j.1752-1688.2010.00499.x.
Brookshire, E.N.J., Dwire, K.A., 2003. Controls on patterns of coarse organic particle retention in headwater streams. J. N. Am. Benthol. Soc. 22, 17–34. https://doi.org/10.2307/1467975.
Brummer, C.J., Montgomery, D.R., 2003. Downstream coarsening in headwater channels. Water Resour. Res. 39, 1294. https://doi.org/10.1029/2003WR001981.
Bujak-Ozga, I., von Freyberg, J., Rinaldo, A., van Meerveld, I., 2026. Comparison of the dynamics of the flowing drainage network and water chemistry for our headwater catchments. Ecohydrology *18*, e2734. https://doi.org/10.1002/eco.2734.
Burchsted, D., Daniels, M.D., 2014. Classification of the alterations of beaver dams to headwater streams in northeastern Connecticut, USA. Geomorphology 205, 36–50. https://doi.org/10.1016/j.geomorph.2012.12.029.
Burt, T.P., Pinay, G., 2005. Linking hydrology and biogeochemistry in complex landscapes. Prog. Phys. Geogr. 29, 297–316. https://doi.org/10.1191/0309133305pp450ra.
Bush, S.A., Birch, A.L., Warix, S.R., Sullivan, P.L., Gooseff, M.N., McKnight, D.M., Barnard, H.R., 2023. Dominant source areas shift seasonally from longitudinal to lateral contributions in a montane headwater stream. J. Hydrol. 617, 129134. https://doi.org/10.1016/j.jhydrol.2023.129134.
Bush, S.A., Birch, A.L., Warix, S., Lininger, K.B., Musselman, K.N., Barnard, H.R., 2025. Runoff composition is insensitive to summer rain contributions in a montane headwater stream. J. Hydrol. Reg.l Stud. 61, 102622. https://doi.org/10.1016/j.ejrh.2025.102622.
Cadol, D., Wohl, E., 2010. Wood retention and transport in tropical, headwater streams, La Selva Biological Station, Costa Rica. Geomorphology 123, 61–73. https://doi.org/10.1016/j.geomorph.2010.06.015.
Cadol, D., Wohl, E., Goode, J.R., Jaeger, K.L., 2009. Wood distribution in neotropical forested headwater streams of La Selva, Costa Rica. Earth Surf. Process. Landf. 34, 1198–1215. https://doi.org/10.1002/esp.1800.
Carey, N., Chester, E.T., Robson, B.J., 2021. Flow regime changes alters shredder identity but not leaf litter decomposition in headwater streams affected by severe, permanent drying. Freshw. Biol. 66, 1813–1830. https://doi.org/10.1111/fwb.13794.
Caskey, S.T., Blaschak, T.S., Wohl, E., Schnackenberg, E., Merritt, D.M., Dwire, K.A., 2015. Downstream effects of stream flow diversion on channel characteristics and riparian vegetation in the Colorado Rocky Mountains, USA. Earth Surf. Process. Landf. 40, 586–598. https://doi.org/10.1002/esp.3651.
Cazzador, D.O., Rainato, R., Mao, L., Martini, L., Picco, L., 2021. Coarse sediment transfer and geomorphic changes in an alpine headwater stream. Geomorphology 376, 107569. https://doi.org/10.1016/j.geomorph.2020.107569.
Chappell, P.R., Brierley, G.J., 2014. Multi-scalar controls on channel geometry of headwater streams in New Zealand hill country. Catena 113, 341–352. https://doi.org/10.1016/j.catena.2013.08.017.
Chen, Y., Lara, M.J., Jones, B.M., Frost, G.V., Hu, F.S., 2021. Thermokarst acceleration in Arctic tundra driven by climate change and fire disturbance. One Earth 4, 1718–1729. https://doi.org/10.1016/j.oneear.2021.11.011.
Chin, A., Gregory, K.J., 2001. Urbanization and adjustment of ephemeral stream channels. Ann. Assoc. Am. Geogr. 91, 595–608. https://doi.org/10.1111/0004-5608.00260.
Christensen, J.R., Golden, H.E., Alexander, L.C., Pickard, B.R., Fritz, K.M., Lane, C.R., Weber, M.H., Kwok, R.M., Keefer, M.N., 2022. Headwater streams and inland wetlands: Status and advancements of geospatial datasets and maps across the United States. Earth Sci. Rev. 235, 104230. https://doi.org/10.1016/j.earscirev.2022.104230.
Christensen, N., Morrison, R.R., 2026. The relative importance of floodplain storage and flow path dispersion on flood attenuation in mountain streams. Water Resour. Res. 62, e2024WR039628. https://doi.org/10.1029/2024WR039628.
Clarke, A., MacNally, R., Bond, N., Lake, P.S., 2008. Macroinvertebrate diversity in headwater streams: a review. Freshw. Biol. 53, 1707–1721. https://doi.org/10.1111/j.1365-2427.2008.02041.x.
Clifton, Z.J., Cashman, M.J., Gellis, A.C., Katoski, M.P., Nibert, L.A., Noe, G.A., 2022. Quantifying connectivity and its effects on sediment budgeting for an agricultural basin, Chesapeake Bay watershed, United States. Hydrol. Process. 36, e14777. https://doi.org/10.1002/hyp.14777.
Cole, J.J., Prairie, Y.T., Caraco, N.F., McDowell, W.H., Tranvik, L.J., Striegl, R.G., Duarte, C.M., et al., 2007. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. Ecosystems 10, 172–185. https://doi.org/10.1007/s10021-006-9013-8.
Colvin, S.A.R., Sullivan, S.M.P., Shirey, P.D., Colvin, R.W., Winemiller, K.O., Hughes, R. M., Fausch, K.D., Infante, D.M., Olden, J.D., Bestgen, K.R., Danehy, R.J., Eby, L., 2019. Headwater streams and wetlands are critical for sustaining fish, fisheries, and ecosystem services. Fisheries 44, 73–91. https://doi.org/10.1002/fsh.10229.
Comte, L., Olden, J.D., Littlefield, C., Dickson, B.G., Zablocki, J., Moryc, D., 2026. National assessment of river protection in the United States. Nat. Sustainability 9, 395–406. https://doi.org/10.1038/s41893-025-01693-8.
Conroy, H.D., Hotchkiss, E.R., Cawley, K.M., Goodman, K., Hall, R.O., Jones, J.B., Wollheim, W.M., Butman, D., 2023. Seasonality drives carbon emissions along a stream network. J. Geophys. Res. Biogeosci. 128, e2023JG007439. https://doi.org/10.1029/2023JG007439.
Costa, J.E., Jarrett, R.D., 1981. Debris flows in small mountain stream channels of Colorado and their hydrologic implications. Bull. Assoc. Eng. Geol. 18, 309–322. https://doi.org/10.2113/gseegeosci.xviii.3.309.
Cowan, M.M., 2003. Timberrr … A History of Logging in New England. The Millbrook Press, Brookfield, CT.
Crawford, J.T., Striegl, R.G., Wickland, K.P., Dornblaser, M.M., Stanley, E.H., 2013. Emissions of carbon dioxide and methane from a headwater stream network of interior Alaska. J. Geophys. Res. Biogeosci. 118, 482–494. https://doi.org/10.1002/jgrg.20034.
Crook, D.S., Jones, A.M., 1999. Design principles from traditional mountain irrigation systems (bisses) in the Valais, Switzerland. Mt. Res. Dev. 19, 79–99. https://doi.org/10.2307/3674250.
D'Angelo, D.J., Webster, J.R., Gregory, S.V., Meyer, J.L., 1993. Transient storage in Appalachian and Cascade Mountain streams as related to hydraulic characteristics. Freshwater Sci. 12, 223–235. https://doi.org/10.2307/1467457.
Dai, M., Xu, Y., Genjebay, Y., Lu, L., Wang, C., Yang, H., Huang, C., Huang, T., 2024. Urbanization significantly increases greenhouse gas emissions from a subtropical headwater streams in southeast China. Sci. Total Environ. 945, 173508. https://doi.org/10.1016/j.scitotenv.2024.173508.
Datry, T., Singer, G., Sauquet, E., Jorda-Capdevila, D., Von Schiller, D., Stubbington, R., Magand, C., Paril, P., et al., 2017. Science and management of intermittent rivers and ephemeral streams (SMIRES). Res. Ideas Outcomes 3, e21774. https://doi.org/10.3897/rio.3.e21774.
Datry, T., Boulton, A.J., Bonada, N., Fritz, K., Leigh, C., Sauquet, E., Tockner, K., Hugueny, B., Dahm, C.N., 2018. Flow intermittence and ecosystem services in rivers of the Anthropocene. J. Appl. Ecol. 55, 353–364. https://doi.org/10.1111/1365-2664.12941.
Datry, T., Boulton, A.J., Fritz, K., Stubbington, R., Cid, N., Crabot, J., Tockner, K., 2023. Non-perennial segments in river networks. Nat. Rev. Earth Environ. 4, 815–830. https://doi.org/10.1038/s43017-023-00495-w.
David, G.C.L., Bledsoe, B.P., Merritt, D.M., Wohl, E., 2009. The impacts of ski slope development on stream channel morphology in the White River National Forest, Colorado, USA. Geomorphology 103, 375–388. https://doi.org/10.1016/j.geomorph.2008.07.003.
Davies, P.E., McIntosh, P.D., Wapstra, M., Bunce, S.E.H., Cook, L.S.J., French, B., Munks, S.A., 2005. Changes to headwater stream morphology, habitats and riparian vegetation recorded 15 years after pre-Forest Practices Code forest clearfelling in upland granite terrain, Tasmania, Australia. Forest Ecol. Maintenance 217, 331–350. https://doi.org/10.1016/j.foreco.2005.06.015.
Dethier, E.N., Silman, M., Leiva, J.D., Alqahtani, S., Fernandez, L.E., Pauca, P., Camalan, S., Tomhave, P., Magilligan, F.J., Renshaw, C.E., Lutz, D.A., 2023. A global rise in alluvial mining increases sediment load in tropical rivers. Nature 620, 787–793. https://doi.org/10.1038/s41586-023-06309-9.
Dietrich, W.E., Reneau, S.L., Wilson, C.J., 1987. Overview: 'zero-order basins' and problems of drainage density, sediment transport and hillslope morphology. In: Beschta, R.L., Blinn, T., Grant, G.E., Ice, G.G., Swanson, F.J. (Eds.), Erosion and Sedimentation in the Pacific Rim, 165. *International Association of Hydrological Science Publication*, pp. 27–37.
Dietrich, W.E., Wilson, C.J., Montgomery, D.R., McKean, J., Bauer, R., 1992. Erosion thresholds and land surface morphology. Geology 20, 675–679. https://doi.org/10.1130/0091-7613(1992)020%3C0675:ETALSM%3E2.3.CO;2.
Dixon, S.J., Sear, D.A., 2014. The influence of geomorphology on large wood dynamics in a low gradient headwater stream. Water Resour. Res. 50, 9194–9210. https://doi.org/10.1002/2014WR015947.
Dodds, W.K., Oakes, R.M., 2008. Headwater influences on downstream water quality. Environ. Manag. 41, 367–377. https://doi.org/10.1007/s00267-007-9033-y.
Donkor, A.K., Bonzongo, J.C.J., Nartey, V.K., Adotey, D.K., 2005. Heavy metals in sediments of the gold mining impacted Pra River basin, Ghana, West Africa. Soil Sediment Contam. Int. J. 14, 479–503. https://doi.org/10.1080/15320380500263675.
Dosskey, M.G., Vidon, P., Gurwick, N.P., Allan, C.J., Duval, T.P., Lowrance, R., 2010. The role of riparian vegetation in protecting and improving chemical water quality in streams. J. Am. Water Resour. Assoc. 46, 261–277. https://doi.org/10.1111/j.1752-1688.2010.00419.x.
Downing, J.A., Cole, J.J., Duarte, C.M., Middelburg, J.J., Melack, J.M., Prairie, Y.T., Kortelainen, P., Striegl, R.G., McDowell, W.H., Tranvik, L.J., 2012. Global abundance and size distribution of streams and rivers. Inland Waters 2, 229–236. https://doi.org/10.5268/IW-2.4.502.
Dralle, D.N., Lapides, D.A., Rempe, D.M., Hahm, W.J., 2023. Mapping surface water presence and hyporheic flow properties of headwater stream networks with multispectral satellite imagery. Water Resour. Res. 59, e2022WR034169. https://doi.org/10.1029/2022WR034169.

Drummond, J.D., Bernal, S., von Schiller, D., Marti, E., 2016. Linking in-stream nutrient uptake to hydrologic retention in two headwater streams. Freshwater Sci. 35, 1176–1188. https://doi.org/10.1086/688599.
Dunn, S.B., Rathburn, S.L., Wohl, E., 2024. Post-fire sediment attenuation in beaver ponds, Rocky Mountains, CO and WY, USA. Earth Surf. Process. Landf. 49, 4340–4354. https://doi.org/10.1002/esp.5970.
Dupas, R., Causse, J., Jaffrezic, A., Aquilina, L., Durand, P., 2021. Flowpath controls on high-spatial-resolution water-chemistry profiles in headwater streams. Hydrol. Process. 35, e14247. https://doi.org/10.1002/hyp.14247.
Ebisemiju, F.S., 1989. The response of headwater stream channels to urbanization in the humid tropics. Hydrol. Process. 3, 237–253. https://doi.org/10.1002/hyp.3360030304.
Elmore, A.J., Kaushal, S.S., 2008. Disappearing headwaters: patterns of stream burial due to urbanization. Front. Ecol. Environ. 6, 308–312. https://doi.org/10.1890/070101.
Entrekin, S.A., Tank, J.L., Rosi-Marshall, E.J., Hoellein, T.J., Lamberti, G.A., 2008. Responses in organic matter accumulation and processing to an experimental wood addition in three headwater streams. Freshw. Biol. 53, 1642–1657. https://doi.org/10.1111/j.1365-2427.2008.01984.x.
Entrekin, S.A., Maloney, K.O., Kapo, K.E., Walters, A.W., Evans-White, M.A., Klemow, K. M., 2015. Stream vulnerability to widespread and emergent stressors: a focus on unconventional oil and gas. PLoS One 10, e0137416. https://doi.org/10.1371/journal.pone.0137416.
Eppes, M.C., Keanini, R., 2017. Mechanical weathering and rock erosion by climate-dependent subcritical cracking. Rev. Geophys. 55, 470–508. https://doi.org/10.1002/2017RG000557.
European Commission, 2003. Common Implementation Strategy for the Water Framework Directive. Guidance Document No. 2, Identification of Water Bodies. The Working Group on Water Bodies, Directorate General Environment, European Commission, Brussels.
Evrard, O., Bielders, C.L., Vandaele, K., Van Wesemael, B., 2007. Spatial and temporal variation of muddy floods in central Belgium, off-site impacts and potential control measures. Catena 70, 443–454. https://doi.org/10.1016/j.catena.2006.11.011.
Fiebig, D.M., Lock, M.A., Neal, C., 1990. Soil water in the riparian zone as a source of carbon for a headwater stream. J. Hydrol. 116, 217–237. https://doi.org/10.1016/0022-1694(90)90124-G.
Florsheim, J.L., Chin, A., Nichols, A., 2013. Effects of multiple small stock-pond dams in a coastal watershed in central California: Implications for removing small dams for restoration. In: De Graff, J.V., Evans, J.E. (Eds.), The Challenges of Dam Removal and River Restoration. GSA Reviews in Engineering Geology, Geological Society of America, Boulder, CO. https://doi.org/10.1130/2013.4121(12).
Fogel, C.B., Lininger, K.B., 2023. Geomorphic complexity influences coarse particulate organic matter transport and storage in headwater streams. Front. Water 5, 1227167. https://doi.org/10.3389/frwa.2023.1227167.
Follett, E., Beven, K., Hankin, B., Mindham, D., Chappell, N., 2024. The importance of retention times in natural flood management interventions. Proc. IAHS 385, 197–201. https://doi.org/10.5194/piahs-385-197-2024.
Fonstad, M.A., 2003. Spatial variation in the power of mountain streams in the Sangre de Cristo Mountains, New Mexico. Geomorphology 55, 75–96. https://doi.org/10.1016/S0169-555X(03)00133-8.
Frankiewicz, P., Radecki-Pawlik, A., Walega, A., Lapinska, M., Wojtal-Frankiewicz, A., 2021. Small hydraulic structures, big environmental problems: is it possible to mitigate the negative impacts of culverts on stream biota? Environ. Rev. 29, 510–528. https://doi.org/10.1139/er-2020-0126.
Freeman, M.C., Pringle, C.M., Jackson, C.R., 2007. Hydrologic connectivity and the contribution of headwaters to ecological integrity at regional scales. J. Am. Water Resour. Assoc. 43, 5–14. https://doi.org/10.1111/j.1752-1688.2007.00002.x.
Fritz, K., Cid, N., Autrey, B., 2017. In: Intermittent Rivers and Ephemeral Streams, Datry, T., Bonada, N., Boulton, A. (Eds.), Governance, legislation, and protection of intermittent rivers and ephemeral streams. Academic Press, London, UK, pp. 477–507. https://doi.org/10.1016/B978-0-12-803835-2.00019-X.
Fritz, K.M., Johnson, B.R., Walters, D.M., 2008. Physical indicators of hydrologic permanence in forested headwater streams. J. N. Am. Benthol. Soc. 27, 690–704. https://doi.org/10.1899/07-117.1.
Fritz, K.M., Hagenbuch, E., D'Amico, E., Reif, M., Wigington, P.J., Leibowitz, S.G., Comeleo, R.L., Ebersole, J.L., Nadeau, T.L., 2013. Comparing the extent and permanence of headwater streams from two field surveys to values from hydrographic databases and maps. J. Am. Water Resour. Assoc. 49, 867–882. https://doi.org/10.1111/jawr.12040.
Fritz, K.M., Schofield, K.A., Alexander, L.C., McManus, M.G., Golden, H.E., Lane, C.R., Kepner, W.G., LeDuc, S.D., DeMeester, J.E., Pollard, A.I., 2018. Physical and chemical connectivity of streams and riparian wetlands to downstream waters: a synthesis. J. Am. Water Resour. Assoc. 54, 323–345. https://doi.org/10.1111/1752-1688.12632.
Galia, T., 2021. Legacy of human impact on geomorphic processes in mountain headwater streams in the perspective of European cultural landscapes. Geosciences 11, 253. https://doi.org/10.3390/geosciences11060253.
Galia, T., Hdradecký, J., 2014. Channel-reach morphology controls of headwater streams based in flysch geologic structures: an example from the Outer Western Carpathians, Czech Republic. Geomorphology 216, 1–12. https://doi.org/10.1016/j.geomorph.2014.03.026.
Gelwick, F.P., 1990. Longitudinal and temporal comparisons of riffle and pool fish assemblagese in a northeastern Oklahoma Ozark stream. Copeia 1990, 1072–1082. https://doi.org/10.2307/1446491.
Giggy, L., Zimmer, M., 2025. The role of lithology on concentration-discharge relationships and carbon export in two adjacent headwater catchments. Water Resour. Res. 61, e2024WR037086. https://doi.org/10.1029/2024WR037086.
Giraldo, L.P., Chara, J., Zoraida, C.C., Chara-Serna, A.M., 2022. Riparian forests: longitudinal biodiversity islands in agricultural landscapes. Top. Biodivers. Conserv. 20, 139–156. https://doi.org/10.1007/978-3-030-92234-4_6#DOI.
Glaser, C., Gilfedder, B.S., Zarfl, C., 2024. Spatio-temporal variability of hyporheic exchange processes across a stream network. Hydrol. Process. 38, e15337. https://doi.org/10.1002/hyp.15337.
Golden, H.E., Christensen, J.R., McMillan, H.K., Kelleher, C.A., Lane, C.R., Husic, A., Li, L., Ward, A.S., Hammond, J., Seybold, E.C., Jaeger, K.L., Zimmer, M., Sando, R., Jones, C.N., Segura, C., Mahoney, D.T., Price, A.N., Cheng, F., 2025. Advancing the science of headwater streamflow for global water protection. Nature Water 3, 16–26. https://doi.org/10.1038/s44221-024-00351-1.
Golden, L.A., Springer, G.S., 2006. Channel geometry, median grain size, and stream power in small mountain streams. Geomorphology 78, 64–76. https://doi.org/10.1016/j.geomorph.2006.01.031.
Gomi, T., Sidle, R.C., Bryant, M.D., Woodsmith, R.D., 2001. The characteristics of woody debris and sediment distribution in headwater streams, southeastern Alaska. Can. J. For. Res. 31, 1386–1399. https://doi.org/10.1139/x01-070.
Gomi, T., Sidle, R.C., Richardson, J.S., 2002. Understanding processes and downstream linkages of headwater systems. BioScience 52, 905–916. https://doi.org/10.1641/0006-3568(2002)052[0905:UPADLO]2.0.CO;2.
Gomi, T., Sidle, R.C., Woodsmith, R.D., Bryant, M.D., 2003. Characteristics of channel steps and reach morphology in headwater streams, southeast Alaska. Geomorphology 51, 225–242. https://doi.org/10.1016/S0169-555X(02)00338-0.
Gomi, T., Sidle, R.C., Swanston, D.N., 2004. Hydrogeomorphic linkages of sediment transport in headwater streams, Maybeso Experimental Forest, southeast Alaska. Hydrol. Process. 18, 667–683. https://doi.org/10.1002/hyp.1366.
Gomi, T., Sidle, R.C., Noguchi, S., Negishi, J.N., Nik, A.R., Sasaki, S., 2006. Sediment and wood accumulations in humid tropical headwater streams: effects of logging and riparian buffers. For. Ecol. Manag. 224, 166–175. https://doi.org/10.1016/j.foreco.2005.12.016.
Gorr, A.N., McGuire, L.A., Youberg, A.M., Beers, R., Liu, T., 2024. Inundation and flow properties of a runoff-generated debris flow following successive high-severity wildfires in northern Arizona, USA. Earth Surf. Process. Landf. 49, 622–641. https://doi.org/10.1002/esp.5724.
Graeber, D., Gelbrecht, J., Pusch, M.T., Anlanger, C., von Schiller, D., 2012. Agriculture has changed the amount and composition of dissolved organic matter in Central European headwater streams. Sci. Total Environ. 438, 435–446. https://doi.org/10.1016/j.scitotenv.2012.08.087.
Green, K.C., Brardinoni, F., Alila, Y., 2013. Channel morphology and bedload yield in fluvial, formerly glaciated headwater streams of the Columbia Mountains, Canada. Geomorphology 188, 96–109. https://doi.org/10.1016/j.geomorph.2012.05.004.
Grieve, S.W.D., Hales, T.C., Parker, R.N., Mudd, S.M., Clubb, F.J., 2018. Controls on zero-order basin morphology. J. Geophys. Res. Earth Surf. 123, 3269–3291. https://doi.org/10.1029/2017JF004453.
Hafen, K.C., Blasch, K.W., Gessler, P.E., Sando, R., Rea, A., 2022. Precision of headwater stream permanence estimates from a monthly water balance model in the Pacific Northwest, USA. Water 14, 895. https://doi.org/10.3390/w14060895.
Haigh, M.J., 2004. Sustainable management of headwater resources: the Nairobi 'Headwater' Declaration (2002) and beyond. Asian J. Water Environ. Pollut. 1. https://doi.org/10.3233/AJW-2004-1_1-2_05.
Haigh, M.J., Jansky, L., Hellin, J., 2004. Headwater deforestation: a challenge for environmental management. Glob. Environ. Chang. 14, 51–61. https://doi.org/10.1016/j.gloenvcha.2003.11.004.
Hakala, J.P., Hartman, K.J., 2004. Drought effect on stream morphology and brook trout (Salvelinus fontinalis) populations in forested headwater streams. Hydrobiologia 515, 203–213. https://doi.org/10.1023/B:HYDR.0000027330.12182.24.
Halley, D.J., Rosell, F., 2002. The beaver's reconquest of Eurasia: status, population development and management of a conservation success. Mammal Rev. 32, 153–178. https://doi.org/10.1046/j.1365-2907.2002.00106.x.
Hare, D.K., Helton, A.M., Johnson, Z.C., Lane, J.W., Briggs, M.A., 2021. Continental-scale analysis of shallow and deep groundwater contributions to streams. Nat. Commun. 12, 1450. https://doi.org/10.1038/s41467-021-21651-0.
Hartman, K.J., Kaller, M.D., Howell, J.W., Sweka, J.A., 2005. How much do valley fills influence headwater streams? Hydrobiologia 532, 91–102. https://doi.org/10.1007/s10750-004-9019-1.
Harvey, J., Gooseff, M., 2015. River corridor science: Hydrologic exchange and ecological consequences from bedforms to basins. Water Resour. Res. 51, 6893–6922. https://doi.org/10.1002/2015WR017617.
Hattanji, T., Wasklewicz, T.A., Hayakawa, Y.S., Wester, T., Hegi, Y., 2012. Hydrogeomorphic effects of basin lithology on development of channel steps in first-order basins of the Ashio Mountains, Japan. Phys. Geogr. 33, 536–560. https://doi.org/10.2747/0272-3646.33.6.536.
Hawley, R.J., MacMannis, K.R., 2019. Tree roots as a dominant agent of streambed habitat, profile pattern, and grade control. Geomorphology 343, 81–91. https://doi.org/10.1016/j.geomorph.2019.06.021.
Henkle, J.E., Wohl, E., Beckman, N.D., 2011. Locations of channel heads in the semiarid Colorado Front Range, USA. Geomorphology 129, 309–319. https://doi.org/10.1016/j.geomorph.2011.02.026.
Hester, E.T., Hammond, B., Scott, D.T., 2016. Effects of inset floodplains and hyporheic exchange induced by in-stream structures on nitrate removal in a headwater stream. Ecol. Eng. 97, 452–464. https://doi.org/10.1016/j.ecoleng.2016.10.036.
Hill, A.R., 1990. Groundwater cation concentrations in the riparian zone of a forested headwater stream. Hydrol. Process. 4, 121–130. https://doi.org/10.1002/hyp.3360040203.
Hooshyar, M., Wang, D., Kim, S., Medeiros, S.C., Hagen, S.C., 2016. Valley and channel networks extraction based on local topographic curvature and k-means clustering of

contours. Water Resour. Res. 52, 8081–8102. https://doi.org/10.1002/2015WR018479.

Hotchkiss, E.R., Hall, R.O., Sponseller, R.A., Butman, D., Klaminder, J., Laudon, H., et al., 2015. Sources and processes controlling CO_2 emissions change with the size of streams and rivers. Nat. Geosci. 8, 696–699. https://doi.org/10.1038/ngeo2507.

Houser, J.N., Mulholland, P.J., Maloney, K.O., 2006. Upland disturbance affects headwater stream nutrients and suspended sediment during baseflow and stormflow. J. Environ. Qual. 35, 352–365. https://doi.org/10.2134/jeq2005.0102.

Hrachowitz, M., Soulsby, C., Tetzlaff, D., Dawson, J.J.C., Malcolm, I.A., 2009. Regionalization of transit time estimates in montane catchments by integrating landscape controls. Water Resour. Res. 45, W05421. https://doi.org/10.1029/2008WR007496.

Hyde, K.D., Wilcox, A.C., Jencso, K., Woods, S., 2014. Effects of vegetation disturbance by fire on channel initiation thresholds. Geomorphology 214, 84–96. https://doi.org/10.1016/j.geomorph.2014.03.013.

Iida, T., Kajijara, A., Okubo, H., Okajima, K., 2012. Effect of seasonal snow cover on suspended sediment runoff in a mountainous catchment. J. Hydrol. 428-429, 116–128. https://doi.org/10.1016/j.jhydrol.2012.01.029.

Ijjasz-Vasquez, E.J., Bras, R., 1995. Scaling regimes of local slope versus contributing area in digital elevation models. Geomorphology 12, 299–311. https://doi.org/10.1016/0169-555X(95)00012-T.

Imberger, M., Hatt, B.E., Brown, S., Burns, M.J., Burrows, R.M., Walsh, C.J., 2023. Headwater streams in an urbanizing world. Freshwater Sci. 42, 323–336. https://doi.org/10.1086/726682.

Immerzeel, W.W., Lutz, A.F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B.J., et al., 2020. Importance and vulnerability of the world's water towers. Nature 577, 364–369. https://doi.org/10.1038/s41586-019-1822-y.

Jackson, C.R., Sturm, C.A., Ward, J.M., 2001. Timber harvest impacts on small headwater stream channels in the Coast Ranges of Washington. J. Am. Water Resour. Assoc. 37, 1533–1549. https://doi.org/10.1111/j.1752-1688.2001.tb03658.x.

Jaeger, K.L., Olden, J.D., 2012. Electrical resistance sensor arrays as a means to quantify longitudinal connectivity of rivers. River Res. Appl. 28, 1843–1852. https://doi.org/10.1002/rra.1554.

Jaeger, K.L., Montgomery, D.R., Bolton, S.M., 2007. Channel and perennial flow initiation in headwater streams: management implications of variability in source-area size. Environ. Manag. 40, 775–786. https://doi.org/10.1007/s00267-005-0311-2.

Jakob, M., Bovis, M., Oden, M., 2005. The significance of channel recharge rates for estimating debris-flow magnitude and frequency. Earth Surf. Process. Landf. 30, 755–766. https://doi.org/10.1002/esp.1188.

Jensen, C.K., McGuire, K.J., Prince, P.S., 2017. Headwater stream length dynamics across four physiographic provinces of the Appalachian Highlands. Hydrol. Process. 31, 3350–3363. https://doi.org/10.1002/hyp.11259.

Jensen, C.K., McGuire, K.J., Shao, Y., Dolloff, C.A., 2018. Modeling wet headwater stream networks across multiple flow conditions in the Appalachian Highlands. Earth Surf. Process. Landf. 43, 2762–2778. https://doi.org/10.1002/esp.4431.

Jensen, C.K., McGuire, K.J., McLaughlin, D.L., Scott, D.T., 2019. Quantifying spatiotemporal variation in headwater stream length using flow intermittency sensors. Environ. Monit. Assess. 191, 226. https://doi.org/10.1007/s10661-019-7373-8.

Johnson, B.G., Morris, C.S., Mase, H.L., Whitehouse, P.S., Paradise, C.J., 2022. Seasonal flashiness and high frequency discharge events in headwater streams in the North Carolina Piedmont (United States). Hydrol. Process. 36, e14550. https://doi.org/10.1002/hyp.14550.

Johnson, L., Richards, C., Host, G., Arthur, J., 1997. Landscape influences on water chemistry in Midwestern stream ecosystems. Freshw. Biol. 37, 193–208. https://doi.org/10.1046/j.1365-2427.1997.d01-539.x.

Johnson, Z.C., Snyder, C.D., Hitt, N.P., 2017. Landform features and seasonal precipitation predict shallow groundwater influence on temperature in headwater streams. Water Resour. Res. 53, 5788–5812. https://doi.org/10.1002/2017WR020455.

Jones, J.B., Rinehart, A.J., 2010. The long-term response of stream flow to climatic warming in headwater streams of interior Alaska. Can. J. For. Res. 40, 1210–1218. https://doi.org/10.1139/X10-047.

Julian, J.P., Elmore, A.J., Guinn, S.M., 2012. Channel head locations in forested watersheds across the mid-Atlantic United States: a physiographic analysis. Geomorphology 177-178, 194–203. https://doi.org/10.1016/j.geomorph.2012.07.029.

Jyväsjärvi, J., Koivunen, I., Muotka, T., 2020. Does the buffer width matter: Testing the effectiveness of forest certificates in the protection of headwater stream ecosystems. For. Ecol. Manag. 478, 118532. https://doi.org/10.1016/j.foreco.2020.118532.

Kampf, S.K., Dwire, K.A., Fairchild, M.P., Dunham, J., Snyder, C.D., Jaeger, K.L., Luce, C. H., Hammond, J.C., Wilson, C., Zimmer, M.A., Sidell, M., 2021. Managing nonperennial headwater streams in temperate forests of the United States. For. Ecol. Manag. 497, 119523. https://doi.org/10.1016/j.foreco.2021.119523.

Kasai, M., Marutani, T., Brierley, G., 2004. Channel bed adjustments following major aggradation in a steep headwater setting: findings from Oyabu Creek, Kyushu, Japan. Geomorphology 62, 199–215. https://doi.org/10.1016/j.geomorph.2004.03.001.

Kemper, J.T., Scamardo, J.E., 2023. Snow avalanches as a driver of large wood dynamics in mountain streams. Geophys. Res. Lett. 50, e2023GL106355. https://doi.org/10.1029/2023GL106355.

Khan, S.T., Sample, D.J., Wynn-Thompson, T., Butcher, J., 2025. Impacts of climate change on storm event-based flow regime and channel stability of urban headwater streams. J. Environ. Manag. 374, 123994. https://doi.org/10.1016/j.jenvman.2024.123994.

Kim, J.C., Kim, J.H., 2007. Analysis of drainage structure based on the geometric characteristics of drainage density and source basin. J. Korean Water Resour. Assoc. 40, 373–382.

Kirkby, M.J., 1971. Hillslope process-response models based on the continuity equation. Inst. British Geographers Spec. Publ. 3, 15–30.

Kirkby, M.J., R., D., 1980. The stream head as a significant geomorphic threshold. In: Coates, D.R., Vitek, J.D. (Eds.), Thresholds in Geomorphology. George Allen & Unwin, London, pp. 53–73.

Kirkby, M.J., Bull, L.J., Poesen, J., Nachtergade, J., Vandekerckhove, L., 2003. Observed and modelled distributions of channel and gully heads – with examples from SE Spain and Belgium. Catena 50, 415–434. https://doi.org/10.1016/S0341-8162(02)00128-5.

Knighton, A.D., 1999. Downstream variation in stream power. Geomorphology 29, 293–306. https://doi.org/10.1016/S0169-555X(99)00015-X.

Kostaschuk, R.A., MacDonald, G.M., Putnam, P.E., 1986. Depositional process and alluvial fan-drainage basin morphometric relationships near Banff, Alberta, Canada. Earth Surf. Process. Landf. 11, 471–484. https://doi.org/10.1002/esp.3290110502.

Kurylyk, B.L., MacQuarrie, K.T.B., Caissie, D., McKenzie, J.M., 2015. Shallow groundwater thermal sensitivity to climate change and land cover disturbances: derivation of analytical expressions and implications for stream temperature modeling. Hydrol. Earth Syst. Sci. 19, 2469–2489. https://doi.org/10.5194/hess-19-2469-2015.

Lai, J., Anders, A.M., 2018. Modeled postglacial landscape evolution at the southern margin of the Laurentide Ice Sheet: hydrological connection of uplands controls the pace and style of fluvial network expansion. J. Geophys. Res. Earth Surf. 123, 9670984. https://doi.org/10.1029/2017JF004509.

Lancaster, S.T., Casebeer, N.E., 2007. Sediment storage and evacuation in headwater valleys at the transition between debris-flow and fluvial processes. Geology 35, 1027–1030. https://doi.org/10.1130/G239365A.1.

Landwehr, K., Rhoads, B.L., 2003. Depositional response of a headwater stream to channelization, east central Illinois, USA. River Res. Appl. 19, 77–100. https://doi.org/10.1002/rra.699.

Larouche, J.R., Abbott, B.W., Bowden, W.B., Jones, J.B., 2015. The role of watershed characteristics, permafrost thaw, and wildfire on dissolved organic carbon biodegradability and water chemistry in Arctic headwater streams. Biogeosciences 12, 4221–4233. https://doi.org/10.5194/bg-12-4221-2015.

Larsen, A., Larsen, J.R., Lane, S.N., 2021. Dam builders and their works: beaver influences on the structure and function of river corridor hydrology, geomorphology, biogeochemistry and ecosystems. Earth Sci. Rev. 218, 103623. https://doi.org/10.1016/j.earscirev.2021.103623.

Lassaletta, L., Garcia-Gomez, H., Gimeno, B.S., Rovira, J.V., 2010. Headwater streams: neglected ecosystems in the EU Water Framework Directive. Implications for nitrate pollution control. Environ. Sci. Pol. 13, 423–433. https://doi.org/10.1016/j.envsci.2010.04.005.

Lau, J.K., Lauer, T.E., Weinman, M.L., 2006. Impacts of channelization on stream habitats and associated fish assemblages in east central Indiana. Am. Midl. Nat. 156, 319–330. https://doi.org/10.1674/0003-0031(2006)156[319:IOCOSH]2.0.CO;2.

Leach, J.A., Kelleher, C., Kurylyk, B.L., Moore, R.D., Neilson, B.T., 2023. A primer on stream temperature processes. WIREs Water 10, e1643. https://doi.org/10.1002/wat2.1643.

Leach, J.A., Webster, K.L., Hudson, D.T., Buttle, J., Nehemy, M., 2024. Zero-flow dynamics for headwater streams in a humid forested landscape. Hydrol. Process. 38, e70025. https://doi.org/10.1002/hyp.70025.

Ledesma, J.L.J., Grabs, T., Futter, M.N., Bishop, K.H., Laudon, H., Kohler, S.J., 2013. Riparian zone control on base cation concentration in boreal streams. Biogeosciences 10, 3849–3868. https://doi.org/10.5194/bg-10-3849-2013.

Ledesma, J.L.J., Futter, M.N., Blackburn, M., Lidman, F., Grabs, T., Sponseller, R.A., Laudon, H., Bishop, K.H., Kohler, S.J., 2018. Towards an improved conceptualization of riparian zones in boreal forest headwaters. Ecosystems 21, 297–315. https://doi.org/10.1007/s10021-017-0149-5.

Ledesma, J.L.J., Musolff, A., Sponseller, R.A., Lupon, A., Penarroya, X., Jativa, C., Bernal, S., 2025. The riparian zone controls headwater hydrology and biogeochemistry, doesn't it? Reassessing linkages across European ecoregions. Glob. Biogeochem. Cycles 39, e2024GB008250. https://doi.org/10.1029/2024GB008250.

Lehrter, R.J., Rutherford, T.K., Dunham, J.B., Johnston, A.N., Wood, D.J.A., Haby, T.S., Carter, S.K., 2023. Effects of culverts on habitat connectivity in streams – a science synthesis to inform National Environmental Policy Act analyses. In: Scientific Investigations Report 2023-5132. US Geological Survey, Reston, VA. https://doi.org/10.3133/sir20235132.

Leibowitz, S.G., Wigington, P.J., Rains, M.C., Downing, D.M., 2008. Non-navigable streams and adjacent wetlands: addressing science needs following the Supreme Court's Rapanos decision. Front. Ecol. Environ. 6, 364–371. https://doi.org/10.1890/070068.

Lenhart, C., Blann, K., Ehlert, K., 2023. Intermittent prairie streams in the northern Great Plains: a case of an undervalued ecosystem. Case Stud. Environ. 7, 2006981. https://doi.org/10.1525/cse.2023.2006981.

Leopold, L.B., 1962. Rivers. In: American Scientist, 50, pp. 511–537. https://www.jstor.org/stable/27838523.

Leopold, L.B., Maddock, T., 1953. The hydraulic geometry of stream channels and some physiographic implications. In: U.S. Geological Survey Professional Paper 252. U.S. Government Printing Office, Washington, D.C.. https://doi.org/10.3133/pp252

Lessard, F., Perreault, N., Jutras, S., 2024. High-resolution automated detection of headwater streambeds for large watersheds. Hydrol. Earth Syst. Sci. 28, 1027–1040. https://doi.org/10.5194/hess-28-1027-2024.

Levison, J., Larocque, M., Fournier, V., Gagne, S., Pellerin, S., Ouellet, M.A., 2014. Dynamics of a headwater system and peatland under current conditions and with

climate change. Hydrol. Process. 28, 4808–4822. https://doi.org/10.1002/hyp.9978.
Li, M., Peng, C., Zhang, K., Xu, L., Wang, J., Yang, Y., Li, P., Liu, Z., He, N., 2021. Headwater stream ecosystem: an important source of greenhouse gases to the atmosphere. Water Res. 190, 116738. https://doi.org/10.1016/j.watres.2020.116738.
Lin, L., Gao, M., Liu, J., Wang, J., Wang, S., Chen, X., Liu, H., 2020. Understanding the effects of climate warming on streamflow and active groundwater storage in an alpine catchment: the upper Lhasa River. Hydrol. Earth Syst. Sci. 24, 1145–1157. https://doi.org/10.5194/hess-24-1145-2020.
Lin, W.T., Chou, W.C., Lin, C.Y., Huang, P.H., Tsai, J.S., 2006. Automated suitable drainage network extraction from digital elevation models in Taiwan's upstream watersheds. Hydrol. Process. 20, 289–306. https://doi.org/10.1002/hyp.5911.
Lisenby, P.E., Slattery, M.C., Wasklewicz, T.A., 2014. Morphological organization of a steep, tropical headwater stream: the aspect of channel bifurcation. Geomorphology 213, 245–260. https://doi.org/10.1016/j.geomorph.2014.02.009.
Little, M.N., Custer, K.W., Borth, E.B., Chapman, J.I., Kukla, M.J., Kuminecz, C., Maloney, M.E., Woods, M.J., McEwan, R.W., 2021. The influence of riparian invasion by the terrestrial shrub Lonicera maackii on aquatic macroinvertebrates in temperate forest headwater streams. Biol. Invasions 23, 25–35. https://doi.org/10.1007/s10530-020-02349-8.
Liu, S., Kuhn, C., Amatulli, G., Aho, K., Butman, D.E., Allen, G.H., Lin, P., Pan, M., Yamazaki, D., Brinkerhoff, C., Gleason, C., Xia, X., Raymond, P.A., 2022. The importance of hydrology in routing terrestrial carbon to the atmosphere via global streams and rivers. Proc. Natl. Acad. Sci. 119, e2106322119. https://doi.org/10.1073/pnas.2106322119.
López-de Sancha, A., Roig, R., Jimenez, I., Vila-Gispert, A., Guasch, H., 2022. Impacts of damming and climate change on the ecosystem structure of headwater streams: a case study from the Pyrenees. Inland Waters 12, 434–450. https://doi.org/10.1080/20442041.2021.2021776.
Lowe, W.H., Likens, G.E., 2005. Moving headwater streams to the head of the class. BioScience 55, 196–197. https://doi.org/10.1641/0006-3568(2005)055[0196:MHSTTH]2.0.CO;2.
Lucas-Borja, M.E., Piton, G., Yu, Y., Castillo, C., Zema, D.A., 2021. Check dams worldwide: Objectives, functions, effectiveness and undesired effects. Catena 204, 105390. https://doi.org/10.1016/j.catena.2021.105390.
Lupon, A., Denfeld, B.A., Laudon, H., Leach, J., Karlsson, J., Sponseller, R.A., 2019. Groundwater inflows control patterns and sources of greenhouse gas emissions from streams. Limnol. Oceanogr. 64, 1545–1557. https://doi.org/10.1002/lno.11134.
Lurin, A., Marc, O., Meunier, P., Carretier, S., 2023. A robust channel head extraction method based on high-resolution topographic convergence, suitable for both slowly and fastly eroding landscapes. J. Geophys. Res. Earth Surf. 128, e2022JF006999. https://doi.org/10.1029/2022JF006999.
Lyon, S.W., Nathanson, M., Spans, A., Grabs, T., Laudon, H., Temnerud, J., Bishop, K.H., Seibert, J., 2012. Specific discharge variability in a boreal landscape. Water Resour. Res. 48, W08506. https://doi.org/10.1029/2011WR011073.
MacDonald, L.H., Coe, D., 2007. Influence of headwater streams on downstream reaches in forested areas. For. Sci. 53, 148–168. https://doi.org/10.1093/forestscience/53.2.148.
MacDonald, R.J., Boon, S., Byrne, J.M., Silins, U., 2014. A comparison of surface and subsurface controls on summer temperature in a headwater stream. Hydrol. Process. 28, 2338–2347. https://doi.org/10.1002/hyp.9756.
Mahat, V., Anderson, A., 2013. Impacts of climate and catastrophic forest changes on streamflow and water balance in a mountainous headwater streams in southern Alberta. Hydrol. Earth Syst. Sci. 17, 4941–4956. https://doi.org/10.5194/hess-17-4941-2013.
Maloney, K.O., Young, J.A., Faulkner, S.P., Hailegiorgis, A., Slonecker, E.T., Milheim, L. E., 2018. A detailed risk assessment of shale gas development on headwater streams in the Pennsylvania portion of the Upper Susquehanna River Basin, USA. Sci. Total Environ. 610-611, 154–166. https://doi.org/10.1016/j.scitotenv.2017.07.247.
Martone, I., Gualtieri, C., Endreny, T., 2020. Characterization of hyporheic exchange drivers and patterns within a low-gradient, first-order, river confluence during low and high flow. Water 12, 649. https://doi.org/10.3390/w12030649.
Marttila, H., Turunen, J., Aroviita, J., Tammela, S., Luhta, P.L., Muotka, T., Klove, B., 2018. Restoration increases transient storages in boreal headwater streams. River Res. Appl. 34, 1278–1285. https://doi.org/10.1002/rra.3364.
Marx, A., Dusek, J., Jankovec, J., Sanda, M., Vogel, T., van Geldern, R., Hartmann, J., Barth, J.A.C., 2017. A review of CO_2 and associated carbon dynamics in headwater streams: A global perspective. Rev. Geophys. 55, 560–585. https://doi.org/10.1002/2016RG000547.
Marzadri, A., Amatulli, G., Tonina, D., Bellin, A., Shen, L.Q., Allen, G.H., Raymond, P.A., 2021. Global riverine nitrous oxide emissions: the role of small streams and large rivers. Sci. Total Environ. 776, 145148. https://doi.org/10.1016/j.scitotenv.2021.145148.
May, C., 2007. Sediment and wood routing in steep headwater streams: an overview of geomorphic processes and their topographic signatures. For. Sci. 53, 119–130. https://doi.org/10.1093/forestscience/53.2.119.
May, C.L., Gresswell, R.E., 2003. Processes and rates of sediment and wood accumulation in headwater streams of the Oregon Coast Range, USA. Earth Surf. Process. Landf. 28, 409–424. https://doi.org/10.1002/esp.450.
May, C.L., Gresswell, R.E., 2004. Spatial and temporal patterns of debris-flow deposition in the Oregon Coast Range, USA. Geomorphology 57, 135–149. https://doi.org/10.1016/S0169-555X(03)00086-2.
McGlynn, B.L., McDonnell, J.J., Shanley, J.B., Kendall, C., 1999. Riparian flow path dynamics during snowmelt in a small headwater catchment. J. Hydrol. 222, 75–92. https://doi.org/10.1016/S0022-1694(99)00102-X.
McGuire, K.J., McDonnell, J.J., 2010. Hydrological connectivity of hillslopes and streams: Characteristic time scales and nonlinearities. Water Resour. Res. 46, W10543. https://doi.org/10.1029/2010WR009341.
McGuire, K.J., DeWalle, D.R., Gburek, W.J., 2002. Evaluation of mean residence time in subsurface waters using oxygen-18 fluctuations during drought conditions in the mid-Appalachians. J. Hydrol. 261, 132–149.
McMahon, E.M., Karamanski, T.J., 2009. North Woods River: The St. Croix River in Upper Midwest History. University of Wisconsin Press, Madison, WI.
McNamara, J.P., Ziegler, A.D., Wood, S.H., Vogler, J.B., 2006. Channel head locations with respect to geomorphologic thresholds derived from a digital elevation model: a case study in northern Thailand. For. Ecol. Manag. 224, 147–156. https://doi.org/10.1016/j.foreco.2005.12.014.
van Meerveld, H.J.I., Sauquet, E., Gallart, F., Sefton, C., Seibert, J., Bishop, K., 2020. Aqua temporaria incognita. Hydrol. Process. 34, 5704–5711. https://doi.org/10.1002/hyp.13979.
Messager, M.L., Pella, H., Datry, T., 2024. Inconsistent regulatory mapping quietly threatens rivers and streams. Environ. Sci. Technol. 58, 17201–17214. https://doi.org/10.1021/acs.est.4c01859.
Metes, M.J., Jones, D.K., Baker, M.E., Miller, A.J., Hogan, D.M., Loperfido, J.V., Hopkins, K.G., 2022. Ephemeral stream network extraction from lidar-derived elevation and topographic attributes in urban and forested landscapes. J. Am. Water Resour. Assoc. 58, 547–565. https://doi.org/10.1111/1752-1688.13012.
Michaels, R., Eliason, K., Kuzniar, T., Petty, J.T., Strager, M.P., Ziemkiewicz, P.F., Morrissey, E., 2022. Microbial communities reveal impacts of unconventional oil and gas development on headwater streams. Water Res. 212, 118073. https://doi.org/10.1016/j.watres.2022.118073.
Miller, A.J., 1990a. Flood hydrology and geomorphic effectiveness in the central Appalachians. Earth Surf. Process. Landf. 15, 119–134. https://doi.org/10.1002/esp.3290150203.
Miller, A.J., 1990b. Fluvial response to debris associated with mass wasting during extreme floods. Geology 18, 599–602. https://doi.org/10.1130/0091-7613(1990)018%3C0599:FRTDAW%3E2.3.CO;2.
Montgomery, D.R., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. Geol. Soc. Am. Bull. 109, 596–611. https://doi.org/10.1130/0016-7606(1997)109%3C0596:CRMIMD%3E2.3.CO;2.
Montgomery, D.R., Dietrich, W.E., 1988. Where do channels begin? Nature 336, 232–234. https://doi.org/10.1038/336232a0.
Montgomery, D.R., Dietrich, W.E., 1989. Source areas, drainage density, and channel initiation. Water Resour. Res. 25, 1907–1918. https://doi.org/10.1029/WR025i008p01907.
Montgomery, D.R., Dietrich, W.E., 1994. Landscape dissection and drainage area-slope thresholds. In: Kirkby, M.J. (Ed.), Process Models and Theoretical Geomorphology. John Wiley & Sons, pp. 221–246.
Montgomery, D.R., Foufoula-Georgiou, E., 1993. Channel network source representation using digital elevation models. Water Resour. Res. 29, 3925–3934. https://doi.org/10.1029/93WR02463.
Montgomery, D.R., Schmidt, K.M., Greenberg, H.M., Dietrich, W.E., 2000. Forest clearing and regional landsliding. Geology 28, 311–314. https://doi.org/10.1130/0091-7613(2000)28%3C311:FCARL%3E2.0.CO;2.
Moore, J.R., Egloff, J., Nagelisen, J., Hunziker, M., Aerne, U., Christen, M., 2013. Sediment transport and bedrock erosion by wet snow avalanches in the Guggigraben, Matter Valley, Switzerland. Arct. Antarct. Alp. Res. 45, 350–362. https://doi.org/10.1657/1938-4246-45.3.350.
Moore, R.D., Guenther, S.M., Gomi, T., Leach, J.A., 2023. Headwater stream temperature response to forest harvesting: do lower flows cause greater warming? Hydrol. Process. 37, e15025. https://doi.org/10.1002/hyp.15025.
Morisawa, M., 1964. Development of drainage systems on an upraised lake floor. Am. J. Sci. 262, 340–354.
Morrice, J.A., Valett, H.M., Dahm, C.N., Campana, M.E., 1997. Alluvial characteristics, groundwater-surface water exchange and hydrological retention in headwater streams. Hydrol. Process. 11, 253–267. https://doi.org/10.1002/(SICI)1099-1085(19970315)11:3%3C253::AID-HYP439%3E3.0.CO;2-J.
Muotka, T., Laasonen, P., 2002. Ecosystem recovery in restored headwater streams: the role of enhanced leaf retention. J. Appl. Ecol. 39, 145–156. https://doi.org/10.1046/j.1365-2664.2002.00698.x.
Mwanake, R.M., Gettel, G.M., Wangari, E.G., Glaser, C., Houska, T., Breuer, L., Butterbach-Bahl, K., Kiese, R., 2023. Anthropogenic activities significantly increase annual greenhouse gas (GHG) fluxes from temperate headwater streams in Germany. Biogeosciences 20, 3395–3422. https://doi.org/10.5194/bg-20-3395-2023.
Nadeau, T.L., Rains, M.C., 2007. Hydrological connectivity between headwater streams and downstream waters: how science can inform policy. J. Am. Water Resour. Assoc. 43, 118–133. https://doi.org/10.1111/j.1752-1688.2007.00010.x.
Napieralski, J., Keeling, R., Dziekan, M., Rhodes, C., Kelly, A., Kobberstad, K., 2015. Urban stream deserts as a consequence of excess stream burial in urban watersheds. Ann. Assoc. Am. Geogr. 105, 649–664. https://doi.org/10.1080/00045608.2015.1050753.
Nelson, M.L., Rhoades, C.C., Dwire, K.A., 2011. Influence of bedrock geology on water chemistry of slope wetlands and headwater streams in the Southern Rocky Mountains. Wetlands 31, 251–261. https://doi.org/10.1007/s13157-011-0157-8.
Newcomb, S.K., Godsey, S.E., 2023. Nonlinear riparian interactions drive changes in headwater streamflow. Water Resour. Res. 59, e2023WR034870. https://doi.org/10.1029/2023WR034870.
Nilsson, C., Lepori, F., Malmqvist, B., Törnlund, E., Hjerdt, N., Helfield, J.M., Palm, D., Östergren, J., Jansson, R., Brännäs, E., Lundqvist, H., 2005. Forecasting environmental responses to restoration of rivers used as log floatways: an

interdisciplinary challenge. Ecosystems 8, 779–800. https://doi.org/10.1007/s10021-005-0030-9.
Nyman, P., Box, W.A.C., Stout, J.C., Sheridan, G.J., Keesstra, S.D., Lane, P.N.J., Langhans, C., 2020. Debris-flow-dominated sediment transport through a channel network after wildfire. Earth Surf. Process. Landf. 45, 1155–1167. https://doi.org/10.1002/esp.4785.
Olefeldt, D., Goswami, S., Grosse, G., Hayes, D., Hugelius, G., Kuhry, P., McGuire, A.D., Romanovsky, V.E., Sannel, A.B.K., Schuur, E.A.G., Turetsky, M.R., 2016. Circumpolar distribution and carbon storage of thermokarst landscapes. Nat. Commun. 7, 13043. https://doi.org/10.1038/ncomms13043.
Olson, D.H., Burton, J.I., 2019. Climate associations with headwater streamflow in managed forests over 16 years and projections of future dry headwater stream channels. Forests 10, 968. https://doi.org/10.3390/f10110968.
Opperman, J.J., Meleason, M., Francis, R.A., Davies-Colley, R., 2008. "Livewood": Geomorphic and ecological functions of living trees in river channels. BioScience 58, 1069–1078. https://doi.org/10.1641/B581110.
Parr, T.B., Cronan, C.S., Ohno, T., Findlay, S.E.G., Smith, S.M.C., Simon, K.S., 2015. Urbanization changes the composition and bioavailability of dissolved organic matter in headwater streams. Limnol. Oceanogr. 60, 885–900. https://doi.org/10.1002/lno.10060.
Passalacqua, P., Do Trung, T., Foufoula-Georgiou, E., Sapiro, G., Dietrich, W.E., 2010. A geomorphic framework for channel network extraction from lidar: nonlinear diffusion and geodesic paths. J. Geophys. Res. Earth Surf. 115, F01002. https://doi.org/10.1029/2009JF001254.
Payn, R.A., Gooseff, M.N., McGlynn, B.L., Bencala, K.E., Wondzell, S.M., 2009. Channel water balance and exchange with subsurface flow along a mountain headwater stream in Montana. United States. Water Resour. Res. 45, W11427. https://doi.org/10.1029/2008WR007644.
Pennino, M.J., Kaushal, S.S., Beaulieu, J.J., Mayer, P.M., Arango, C.P., 2014. Effects of urban stream burial on nitrogen uptake and ecosystem metabolism: implications for watershed nitrogen and carbon fluxes. Biogeochemistry 121, 247–269. https://doi.org/10.1007/s10533-014-9958-1.
Perry, D., Harrison, I., Fernandes, S., Burnham, S., Nichols, A., 2021. Global analysis of durable policies for free-flowing river protections. Sustainability 13, 2347. https://doi.org/10.3390/su13042347.
Peterson, D.A., Kampf, S.K., Puntenney-Desmond, K.C., Fairchild, M.P., Zipper, S., Hammond, J.C., Ross, M.R.V., Sears, M.G., 2024. Predicting streamflow duration from crowd-sourced flow observations. Water Resour. Res. 60, e2023WR035093. https://doi.org/10.1029/2023WR035093.
Peterson, D.M., Jones, C.N., Plattner, A.M., Shogren, A.J., Godsey, S.E., 2025. Using hydrogeomorphic features to quantify structural and functional hydrologic connectivity in a coastal plain headwater stream. Water Resour. Res. 61, e2024WR038533. https://doi.org/10.1029/2024WR038533.
Petrin, Z., McKie, B., Buffam, I., Laudon, H., Malmqvist, B., 2007. Landscape-controlled chemistry variation affects communities and ecosystem function in headwater streams. Can. J. Fish. Aquat. Sci. 64, 1563–1572. https://doi.org/10.1139/f07-118.
Pfeiffer, A., Wohl, E., 2018. Where does wood most effectively enhance storage? Network-scale distribution of sediment and organic matter stored by instream wood. Geophys. Res. Lett. 45, 194–200. https://doi.org/10.1002/2017GL076057.
Piatka, D.R., Nanasi, R.L., Mwanake, R.M., Engelsberger, F., Willibald, G., Neidl, F., Kiese, R., 2024. Precipitation fuels dissolved greenhouse gas (CO_2, CH_4, N_2O) dynamics in a peatland-dominated headwater stream: results from a continuous monitoring setup. Front. Water 5, 1321137. https://doi.org/10.3389/frwa.2023.1321137.
Placzkowska, E., Gornik, M., Mocior, E., Peek, B., Potoniec, P., Rzonca, B., Siwek, J., 2015. Spatial distribution of channel heads in the Polish Flysch Carpathians. Catena 127, 240–249. https://doi.org/10.1016/j.catena.2014.12.033.
Pokhrel, P., Attal, M., Sinclair, H.D., Mudd, S.M., Naylor, M., 2024. Downstream rounding rate of pebbles in the Himalaya. Earth Surface Dyn. 12, 515–536. https://doi.org/10.5194/esurf-12-515-2024.
Porcal, P., Dillon, P.J., Molot, L.A., 2015. Temperature dependence of photodegradation of dissolved organic matter to dissolved inorganic carbon and particulate organic carbon. PLoS One 10, e0128884. https://doi.org/10.1371/journal.pone.0128884.
Qiu, Z., Hall, C., Drewes, D., Messinger, G., Prato, T., Hale, K., Van Abs, D., 2013. Hydrologically sensitive areas, land use controls, and protection of healthy watersheds. J. Water Resour. Plan. Manag. 140. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000376.
Raymond, P.A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., et al., 2013. Global carbon dioxide emissions from inland waters. Nature 503, 355–359. https://doi.org/10.1038/nature12760.
Reidy, M., Berggren, M., Lupon, A., Laudon, H., Sponseller, R.A., 2025a. Riparian zone heterogeneity influences the amount and fate of biodegradable dissolved organic carbon at the land-water interface. J. Geophys. Res. Biogeosci. 130, e2024JG008471. https://doi.org/10.1029/2024JG008471.
Reidy, M., Buckley, S., Jamtgard, S., Laudon, H., Sponseller, R.A., 2025b. Biogeochemical patterns vary with hydrogeomorphology in riparian soils along a boreal headwater stream. Freshwater Sci. 44, 61–75. https://doi.org/10.1086/734546.
Rengers, F.K., McGuire, L.A., Ebel, B.A., Tucker, G.E., 2018. The evolution of a colluvial hollow to a fluvial channel with periodic steps following two transformational disturbances: A wildfire and a historic flood. Geomorphology 309, 121–130. https://doi.org/10.1016/j.geomorph.2018.01.003.
Rengers, F.K., Stoker, J.M., Kostelnik, J., Kean, J.W., Wohl, E.E., Barnhart, K.R., Guido, L. E., 2026. Channel morphology and large wood control postfire debris-flow erosion and deposition. Earth Surf. Process. Landf. 51, e70287. https://doi.org/10.1002/esp.70287.
Renwick, W.H., Smith, S.V., Bartley, J.D., Buddemeier, R.W., 2005. The role of impoundments in the sediment budget of the conterminous United States. Geomorphology 71, 99–111. https://doi.org/10.1016/j.geomorph.2004.01.010.
Reynolds, J.B., Simmons, R.C., Burkholder, A.R., 1989. Effects of placer mining discharge on health and food of Arctic grayling. J. Am. Water Resour. Assoc. 25, 625–635. https://doi.org/10.1111/j.1752-1688.1989.tb03100.x.
Rice, J.S., Anderson, W.P., Thaxton, C.S., 2011. Urbanization influences on stream temperature behavior within low-discharge headwater streams. Hydrol. Res. Lett. 5, 27–31. https://doi.org/10.3178/hrl.5.27.
Richardson, J.S., 2019a. Biological diversity in headwater streams. Water 11, 366. https://doi.org/10.3390/w11020366.
Richardson, J.S., 2019b. Headwater streams. In: Goldstein, M.I., DellaSala, D.A. (Eds.), Encyclopedia of the World's Biomes. Elsevier, pp. 271–378. https://doi.org/10.1016/B978-0-12-409548-9.11957-8.
Richardson, J.S., Naiman, R.J., Swanson, F.J., Hibbs, D.E., 2005. Riparian communities associated with Pacific Northwest headwater streams: Assemblages, processes, and uniqueness. J. Am. Water Resour. Assoc. 41, 935–947. https://doi.org/10.1111/j.1752-1688.2005.tb03778.x.
Riley, R.H., Townsend, C.R., Niyogi, D.K., Arbuckle, C.A., Peacock, K.A., 2003. Headwater stream response to grassland agricultural development in New Zealand. N. Z. J. Mar. Freshw. Res. 37, 389–403. https://doi.org/10.1080/00288330.2003.9517175.
Roa-Garcia, M.C., Brown, S., Schreier, H., Lavkulich, L.M., 2011. The role of land use and soils in regulating water flow in small headwater catchments of the Andes. Water Resour. Res. 47, W05510. https://doi.org/10.1029/2010WR009582.
Roberts, M.T., Geris, J., Hallett, P.D., Wilkinson, M.E., 2023. Mitigating floods and attenuating surface runoff with temporary storage areas in headwaters. WIREs Water 10, e1634. https://doi.org/10.1002/wat2.1634.
Robison, A.L., Wollheim, W.M., Perryman, C.R., Cotter, A.R., Mackay, J.E., Varner, R.K., Clarizia, P., Emakovich, J.G., 2022. Dominance of diffusive methane emissions from lowland headwater streams promotes oxidation and isotopic enrichment. Front. Environ. Sci. 9, 791305. https://doi.org/10.3389/fenvs.2021.791305.
Rocher-Ros, G., Stanley, E.H., Loken, L.C., Casson, N.J., Raymond, P.A., Liu, S., et al., 2023. Global methane emissions from rivers and streams. Nature 621, 530–535. https://doi.org/10.1038/s41586-023-06344-6.
Roy, A.H., Dybas, A.L., Fritz, K.M., Lubbers, H.R., 2009. Urbanization affects the extent and hydrologic permanence of headwater streams in a Midwestern US metropolitan area. J. N. Am. Benthol. Soc. 28, 911–928. https://doi.org/10.1899/08-178.1.
Roy, J.W., Bickerton, G., 2011. Toxic groundwater contaminants: an overlooked contributor to urban stream syndrome? Environ. Sci. Technol. 46, 729–736. https://doi.org/10.1021/es2034137.
Roy, S., Sahu, A.S., 2018. Road-stream crossing an in-stream intervention to alter channel morphology of headwater streams: case study. Int. J. River Manag. 16, 1–19. https://doi.org/10.1080/15715124.2017.1365721.
Rubio-Rios, J., Hayden, B., Nakamoto, B.J., Casas, J.J., 2025. Black alder may enhance riparian buffer mitigation of pine-plantation effects on macroinvertebrate food webs in headwater streams. Ecol. Indic. 176, 113637. https://doi.org/10.1016/j.ecolind.2025.113637.
Ruhe, R.V., 1952. Topographic discontinuities of the Des Moines Lobe. Am. J. Sci. 250, 46–56.
Russell, P.P., Gale, S.M., Munoz, B., Dorney, J.R., Rubino, M.J., 2015. A spatially explicit model for mapping headwater streams. J. Am. Water Resour. Assoc. 51, 226–239. https://doi.org/10.1111/jawr.12250.
Ryan, S.E., Porth, L.S., Troendle, C.A., 2002. Defining phases of bedload transport using piecewise regression. Earth Surf. Process. Landf. 27, 971–990. https://doi.org/10.1002/esp.387.
Ryan, S.E., Porth, L.S., Troendle, C.A., 2005. Coarse sediment transport in mountain streams in Colorado and Wyoming, USA. Earth Surf. Process. Landf. 30, 269–288. https://doi.org/10.1002/esp.1128.
Ryan, S.E., Bishop, E.L., Daniels, J.M., 2014. Influence of large wood on channel morphology and sediment storage in headwater mountain streams, Fraser Experimental Forest, Colorado. Geomorphology 217, 73–88. https://doi.org/10.1016/j.geomorph.2014.03.046.
Salinas, M.J., Casas, J.J., Rubio-Rios, J., Lopez-Carrique, E., Ramos-Miras, J.J., Gil, C., 2018. Climate-driven changes of riparian plant functional types in permanent headwater streams: implications for stream food webs. PLoS One 13, e0199898. https://doi.org/10.1371/journal.pone.0199898.
Sangireddy, H., Stark, C.P., Kladzyk, A., Passalacqua, P., 2016. GeoNet: an open source software for the automatic and objective extraction of channel heads, channel network, and channel morphology from high resolution topography. Environ. Model Softw. 83, 58–73. https://doi.org/10.1016/j.envsoft.2016.04.026.
Sawakuchi, H.O., Neu, V., Ward, N.D., Barros, M.L.C., Valerio, A.M., Gagne-Maynard, W., Cunha, A.C., et al., 2017. Carbon dioxide emissions along the lower Amazon River. Front. Mar. Sci. 4, 76. https://doi.org/10.3389/fmars.2017.00076.
Schade, J.D., Bailio, J., McDowell, W.H., 2016. Greenhouse gas flux from headwater streams in New Hampshire, USA: Patterns and drivers. Limnol. Oceanogr. 61, S165–S174. https://doi.org/10.1002/lno.10337.
Scheller, M., van Meerveld, I., Seibert, J., 2024. How well can people observe the flow state of temporary streams? Front. Environ. Sci. 12, 1352697. https://doi.org/10.3389/fenvs.2024.1352697.
Schmadel, N.M., Ward, A.S., Wondzell, S.M., 2017. Hydrologic controls on hyporheic exchange in a headwater mountain stream. Water Resour. Res. 53, 6260–6278. https://doi.org/10.1002/2017WR020576.
Schumm, S.A., 1973. Geomorphic thresholds and complex response of drainage systems. In: Morisawa, M. (Ed.), Fluvial Geomorphology. State University of New York, Binghamton, NY, pp. 299–310.

Schumm, S.A., 1977. The Fluvial System. Wiley, New York.
Scordo, E.B., Moore, R.D., 2009. Transient storage processes in a steep headwater stream. Hydrol. Process. 23, 2671–2685. https://doi.org/10.1002/hyp.7345.
Segura, C., 2021. Snow drought reduces water transit times in headwater streams. Hydrol. Process. 35, e14437. https://doi.org/10.1002/hyp.14437.
Seibert, J., Grabs, T., Kohler, S., Laudon, H., Winterdahl, M., Bishop, K., 2009. Linking soil- and stream-water chemistry based on a riparian flow-concentration integration model. Hydrol. Earth Syst. Sci. 13, 2287–2297. https://doi.org/10.5194/hess-13-2287-2009.
Shavers, E., Stanislawski, L.V., 2020. Channel cross-section analysis for automated stream head identification. Environ. Model Softw. 132, 104809. https://doi.org/10.1016/j.envsoft.2020.104809.
Shaw, S.B., 2016. Investigating the linkage between streamflow recession rates and channel network contraction in a mesoscale catchment in New York State. Hydrol. Process. 30, 479–492. https://doi.org/10.1002/hyp.10626.
Shobe, C.M., Bower, S.J., Maxwell, A.E., Glade, R.C., Samassi, N.M., 2024. The uncertain future of mountaintop-removal-mined landscapes1: How mining changes erosion processes and variables. Geomorphology 445, 108984. https://doi.org/10.1016/j.geomorph.2023.108984.
Sidle, R.C., Tsuboyama, Y., Noguchi, S., Hosoda, I., Fujieda, M., Shimizu, T., 2000. Stormflow generation in steep forested headwaters: a linked hydrogeomorphic paradigm. Hydrol. Process. 14, 369–385. https://doi.org/10.1002/(SICI)1099-1085(20000228)14:3%3C369::AID-HYP943%3E3.0.CO;2-P.
Simon, N., Bour, O., Faucheux, M., Lavenant, N., Le Lay, H., Fovet, O., Thomas, Z., Longuevergue, L., 2022. Combining passive and active distributed temperature sensing measurements to locate and quantify groundwater discharge variability into a headwater stream. Hydrol. Earth Syst. Sci. 26, 1459–1479. https://doi.org/10.5194/hess-26-1459-2022.
Simpson, G., Castelltort, S., 2006. Coupled model of surface water flow, sediment transport and morphological evolution. Comput. Geosci. 32, 1600–1614. https://doi.org/10.1016/j.cageo.2006.02.020.
Sjöberg, Y., Jan, A., Painter, S.L., Coon, E.T., Carey, M.P., O'Donnell, J.A., Koch, J.C., 2022. Permafrost promotes shallow groundwater flow and warmer headwater streams. Water Resour. Res. 57, e2020WR027463. https://doi.org/10.1029/2020WR027463.
Smiley, P.C., King, K.W., Fausey, N.R., 2010. Public health perspectives of channelized and unchannelized headwater streams in central Ohio: a case study. J. Water Health 8, 577–592. https://doi.org/10.2166/wh.2010.160.
Smiley, P.C., King, D.W., Fausey, N.R., 2011. Influence of herbaceous riparian buffers on physical habitat, water chemistry, and stream communities within channelized agricultural headwater streams. Ecol. Eng. 37, 1314–1323. https://doi.org/10.1016/j.ecoleng.2011.03.020.
Smith, T.R., 2010. A theory for the emergence of channelized drainage. J. Geophys. Res. Earth Surf. 115, F02023. https://doi.org/10.1029/2008JF001114.
Smock, L.A., Metzler, G.M., Gladden, J.E., 1989. Role of debris dams in the structure and functioning of low-gradient headwater streams. Ecology 70, 764–775. https://doi.org/10.2307/1940226.
Smolders, A.J.P., Lock, R.A.C., Van der Velde, G., Medina Hoyos, R.I., Roelofs, J.G.M., 2003. Effects of mining activities on heavy metal concentrations in water, sediment, and macroinvertebrates in different reaches of the Pilcomayo River, South America. Arch. Environ. Contam. Toxicol. 44, 314–323. https://doi.org/10.1007/s00244-002-2042-1.
Snyder, C.G., Hitt, N.P., Young, J.A., 2015. Accounting for groundwater in stream fish thermal habitat responses to climate change. Ecol. Appl. 25, 1397–1419. https://doi.org/10.1890/14-1354.1.
Stammler, K.L., Yates, A.G., Bailey, R.C., 2013. Buried streams: Uncovering a potential threat to aquatic ecosystems. Landsc. Urban Plan. 114, 37–41. https://doi.org/10.1016/j.landurbplan.2013.02.008.
Stanfield, L.W., Jackson, D.A., 2011. Understanding the factors that influence headwater stream flows in response to storm events. J. Am. Water Resour. Assoc. 47, 315–336. https://doi.org/10.1111/j.1752-1688.2010.00518.x.
Stepchinski, L.M., Rains, M.C., Lee, L.C., Lis, R.A., Nutter, W.L., Rains, K.C., Stewart, S.R., 2023. Hydrologic connectivity and flow generation from California vernal pool, swale, and headwater stream complexes to downstream waters. Wetlands 43, 34. https://doi.org/10.1007/s13157-023-01678-3.
Steward, A.L., Datry, T., Langhans, S.D., 2022. The terrestrial and semi-aquatic invertebrates of intermittent rivers and ephemeral streams. Biol. Rev. 97, 1408–1425. https://doi.org/10.1111/brv.12848.
Stewart, B., Shanley, J.B., Kirchner, J.W., Norris, D., Adler, T., Bristol, C., Harpold, A.A., Perdrial, J.N., Rizzo, D.M., et al., 2022. Streams as mirrors: reading subsurface water chemistry from stream chemistry. Water Resour. Res. 58, e2021WR029931. https://doi.org/10.1029/2021WR029931.
Stock, J., Dietrich, W.E., 2003. Valley incision by debris flows: evidence of a topographic signature. Water Resour. Res. 39, 1089. https://doi.org/10.1029/2001WR001057.
Stout, B.M., Benfield, E.F., Webster, J.R., 1993. Effects of a forest disturbance on shredder production in southern Appalachian headwater streams. Freshw. Biol. 29, 59–69. https://doi.org/10.1111/j.1365-2427.1993.tb00744.x.
Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. In: EOS, Trans. American Geophysical Union, 38, pp. 913–920. https://doi.org/10.1029/TR038i006p00913.
Stubblefield, A., Chandra, S., Eagan, S., Tuvshinjargal, D., Davaadorzh, G., Gilroy, D., Sampson, J., Thorne, J., Allen, B., Hogan, Z., 2005. Impacts of gold mining and land use alterations on the water quality of central Mongolian rivers. Integr. Environ. Assess. Manag. 1, 365–373. https://doi.org/10.1002/ieam.5630010406.
Sullivan, S.M.P., Hughes, R.M., Vadas, R.L., Davies, G.T., Shirey, P.D., Colvin, S.A.R., Infante, D.M., Danehy, R.J., Sanchez, N.K., Keast, R.B., 2025. Waterbody connectivity: linking science and policy for improved waterbody protection. BioScience 75, 68–91. https://doi.org/10.1093/biosci/biae117.
Surenkhorloo, P., Buyanaa, C., Dolgorjav, S., Bazarsad, C.O., Zamba, B., Bayarsaikhan, S., Heiner, M., 2021. Identifying riparian areas of free flowing rivers for legal protection: model region Mongolia. Sustainability 13, 551. https://doi.org/10.3390/su13020551.
Taillardat, P., Bodmer, P., Deblois, C.P., Poncot, A., Prijac, A., Riahi, K., Gandois, L., del Giorgio, P.A., Bourgault, M.A., Tremblay, A., Garneau, M., 2022. Carbon dioxide and methane dynamics in a peatland headwater stream: Origins, processes, and implications. J. Geophys. Res. Biogeosci. 127, e2022JG006855. https://doi.org/10.1029/2022JG006855.
Takahashi, N.O., Ishimura, D., Yamada, K., Ohta, R.J., Arai, Y., Yamane, Y., 2025. Shape evolution of bulk sediment in headwater streams: effects of rock type and particle size. Earth Surface Dyn. 13, 959–980. https://doi.org/10.5194/esurf-13-959-2025.
Talling, P.J., Sowter, M.J., 1999. Drainage density on progressively tilted surfaces with different gradients, Wheeler Ridge, California. Earth Surf. Process. Landf. 24, 809–824. https://doi.org/10.1002/(SICI)1096-9837(199908)24:9%3C809::AID-ESP13%3E3.0.CO;2-R.
Tao, J., Barros, A.P., 2014. Coupled prediction of flood response and debris flow initiation during warm- and cold-season events in the Southern Appalachians, USA. Hydrol. Earth Syst. Sci. 18, 367–388. www.hydrol-earth-syst-sci.net/18/367/2014/.
Tarboton, D.G., Bras, R.L., Rodriguez-Iturbe, I., 1991. On the extraction of channel networks from digital elevation data. Hydrol. Process. 5, 81–100. https://doi.org/10.1002/hyp.3360050107.
Tarolli, P., Dalla Fontana, G., 2009. Hillslope-to-valley transition morphology: new opportunities from high resolution DTMs. Geomorphology 113, 47–56. https://doi.org/10.1016/j.geomorph.2009.02.006.
Thomas, E.L., Peretto, G.T., 2016. Hydrogeomorphic connectivity on road crossings in rural headwaters and its effect on stream dynamics. Sci. Total Environ. 550, 547–555. https://doi.org/10.1016/j.scitotenv.2016.01.100.
Thornes, J.B., 1970. The hydraulic geometry of stream channels in the Xingu-Araguaia headwaters. Geogr. J. 136, 376–382. https://doi.org/10.2307/1795188.
Törnlund, E., Östlund, L., 2002. Floating timber in northern Sweden: the construction of floatways and transformation of rivers. Environ. Hist. 8, 85–106. https://doi.org/10.3197/096734002129342611.
Triantafillou, S., Wohl, E., 2024. Geomorphic characteristics influencing post-fire river response in mountain streams. Geomorphology 466, 109446. https://doi.org/10.1016/j.geomorph.2024.109446.
Tsujimura, M., Onda, Y., Ito, J., 2001. Stream water chemistry in a steep headwater basin with high relief. Hydrol. Process. 15, 1847–1858. https://doi.org/10.1002/hyp.243.
Turunen, J., Elbrecht, V., Steinke, D., Aroviita, J., 2021. Riparian forests can mitigate warming and ecological degradation of agricultural headwater streams. Freshw. Biol. 66, 785–798. https://doi.org/10.1111/fwb.13678.
Utz, R.M., Hilderbrand, R.H., 2011. Interregional variation in urbanization-induced geomorphic change and macroinvertebrate habitat colonization in headwater streams. J. N. Am. Benthol. Soc. 30, 25–37. https://www.journals.uchicago.edu/doi/10.1899/10-007.1.
Valett, H.M., Morrice, J.A., Dahm, C.N., Campana, M.E., 1996. Parent lithology, surface-groundwater exchange, and nitrate retention in headwater streams. Limnol. Oceanogr. 41, 333–345. https://doi.org/10.4319/lo.1996.41.2.0333.
Van Dine, D.F., 1985. Debris flows and debris torrents in the Southern Canadian Cordillera. Can. Geotech. J. 22, 44–68. https://doi.org/10.1139/t85-006.
Vautier, C., Abherve, R., Labasque, T., Laverman, A.M., Guillou, A., Chatton, E., Dupont, P., Aquilina, L., de Dreuzy, J.R., 2020. Mapping gas exchanges in headwater streams with membrane inlet mass spectrometry. J. Hydrol. 581, 124398. https://doi.org/10.1016/j.jhydrol.2019.124398.
Vidon, P., Serchan, S., 2016. Landscape geomorphic characteristic impacts on greenhouse gas fluxes in exposed stream and riparian sediments. Environ Sci Process Impacts 18, 844. https://doi.org/10.1039/C6EM00162A.
Walker, C.M., King, R.S., Whigham, D.F., Baird, S.J., 2012. Landscape and wetland influence on headwater stream chemistry in the Kenai Lowlands, Alaska. Wetlands 32, 301–310. https://doi.org/10.1007/s13157-011-0260-x.
Wallace, J.B., Vogel, D.S., Cuffney, T.F., 1986. Recovery of a headwater stream from an insecticide-induced community disturbance. J. N. Am. Benthol. Soc. 5, 115–126. https://doi.org/10.2307/1467866.
Wallace, J.B., Webster, J.R., Eggert, S.L., Meyer, J.L., Siler, E.R., 2001. Large woody debris in a headwater stream: long-term legacies of forest disturbance. Int. Rev. Hydrobiol. 86, 501–513. https://doi.org/10.1002/1522-2632(200107)86:4/5%3C501::AID-IROH501%3E3.0.CO;2-8.
Walsh, R., Ward, A.S., 2022. An overview of the evolving jurisdictional scope of the U.S. Clean Water Act for hydrologists. WIREs Water 9, e1603. https://doi.org/10.1002/wat2.1603.
Ward, A.S., Fitzgerald, M., Gooseff, M.N., Voltz, T.J., Binley, A.M., Singha, K., 2012. Hydrologic and geomorphic controls on hyporheic exchange during base flow recession in a headwater mountain stream. Water Resour. Res. 48, W04513. https://doi.org/10.1029/2011WR011461.
Ward, A.S., Schmadel, N.M., Wondzell, S.M., 2018. Simulation of dynamic expansion, contraction, and connectivity in a mountain stream network. Adv. Water Resour. 114, 64–82. https://doi.org/10.1016/j.advwatres.2018.01.018.
Warix, S.R., Godsey, S.E., Lohse, K.A., Hale, R.L., 2021. Influence of groundwater and topography on stream drying in semi-arid headwater streams. Hydrol. Process. 35, e14185. https://doi.org/10.1002/hyp.14185.
Weitzell, R.E., Kaushal, S.S., Lynch, L.M., Guinn, S.M., Elmore, A.J., 2016. Extent of stream burial and relationships to watershed area, topography, and impervious surface area. Water 8, 538. https://doi.org/10.3390/w8110538.

Welcomme, R.L., 1976. Some general and theoretical considerations on the fish yield of African rivers. J. Fish Biol. 8, 351–364. https://doi.org/10.1111/j.1095-8649.1976.tb03964.x.
White, W.R., Crisman, T.L., 2016. Headwater streams of Florida: types, distribution and a framework for conservation. River Res. Appl. 32, 452–461. https://doi.org/10.1002/rra.2845.
Whiting, P.J., Stamm, J.F., Moog, D.B., Orndorff, R.L., 1999. Sediment-transporting flows in headwater streams. Geol. Soc. Am. Bull. 111, 450–466. https://doi.org/10.1130/0016-7606(1999)111%3C0450:STFIHS%3E2.3.CO;2.
Williams, M.R., Filoso, S., 2023. Changes in hydrology and pollutant loads from stream restoration in an urban headwater catchment. J. Hydrol. 618, 129164. https://doi.org/10.1016/j.jhydrol.2023.129164.
Wohl, E., 2004. Limits of downstream hydraulic geometry. Geology 32, 897–900. https://doi.org/10.1130/G20738.1.
Wohl, E., 2006. Human impacts to mountain streams. Geomorphology 79, 217–248. https://doi.org/10.1016/j.geomorph.2006.06.020.
Wohl, E., 2013. Migration of channel heads following wildfire in the Colorado Front Range, USA. Earth Surf. Process. Landf. 38, 1049–1053. https://doi.org/10.1002/esp.3429.
Wohl, E., 2014. A legacy of absence: Wood removal in US rivers. Prog. Phys. Geogr. 38, 637–663. https://doi.org/10.1177/0309133314548091.
Wohl, E., 2015. Legacy effects on sediment in river corridors. Earth Sci. Rev. 147, 30–53. https://doi.org/10.1016/j.earscirev.2015.05.001.
Wohl, E., 2018. The challenges of channel heads. Earth Sci. Rev. 185, 649–664. https://doi.org/10.1016/j.earscirev.2018.07.008.
Wohl, E., 2021. An integrative conceptualization of floodplain storage. Rev. Geophys. 59, e2020RG000724. https://doi.org/10.1029/2020RG000724.
Wohl, E., Goode, J.R., 2008. Wood dynamics in headwater streams of the Colorado Rocky Mountains. Water Resour. Res. 44, W09429. https://doi.org/10.1029/2007WR006522.
Wohl, E., Inamdar, S., 2025. Beaver versus human: the big differences in small dams. WIREs Water 12, e70019. https://doi.org/10.1002/wat2.70019.
Wohl, E., Jaeger, K., 2009. A conceptual model for the longitudinal distribution of wood in mountain streams. Earth Surf. Process. Landf. 34, 329–344. https://doi.org/10.1002/esp.1722.
Wohl, E., Scott, D., 2017. Transience of channel head locations following disturbance. Earth Surf. Process. Landf. 42, 1132–1139. https://doi.org/10.1002/esp.4124.
Wohl, E., Kuzma, J.N., Brown, N.E., 2004. Reach-scale channel geometry of a mountain river. Earth Surf. Process. Landf. 29, 969–981. https://doi.org/10.1002/esp.1078.
Wohl, E., Hall, R.O., Lininger, K.B., Sutfin, N.A., Walters, D.M., 2017. Carbon dynamics of river corridors and the effects of human alterations. Ecol. Monogr. 87, 379–409. https://doi.org/10.1002/ecm.1261.
Wohl, E., Scamardo, J., Morrison, R.R., 2025a. James Buttle Review: Bed, banks and beyond: River flood dynamics. Hydrol. Process. 39, e70131. https://doi.org/10.1002/hyp.70131.
Wohl, E., Clark, M., Li, L., Soulsby, C., Tetzlaff, D., 2025b. Knots in the strings: Do small-scale river features shape catchment-scale fluxes? WIREs Water 12, e70036. https://doi.org/10.1002/wat2.70036.
Wohl, E.E., Pearthree, P.A., 1991. Debris flows as geomorphic agents in the Huachuca Mountains of southeastern Arizona. Geomorphology 4, 273–292. https://doi.org/10.1016/0169-555X(91)90010-8.
Wollheim, W.M., Bernal, S., Burns, D.A., Czuba, J.A., Driscoll, C.T., Hansen, A.T., Hensley, R.T., Hosen, J.D., Inamdar, S., Kaushal, S.S., Koenig, L.E., Lu, Y.H., Marzadri, A., et al., 2018. River network saturation concept: factors influencing the balance of biogeochemical supply and demand of river networks. Biogeochemistry 141, 503–521. https://doi.org/10.1007/s10533-018-0488-0.
Wondzell, S.M., 2011. The role of the hyporheic zone across stream networks. Hydrol. Process. 25, 3525–3532. https://doi.org/10.1002/hyp.8119.
Wood, D.M., Welsh, A.B., Petty, J.T., 2018. Genetic assignment of brook trout reveals rapid success of culvert restoration in headwater streams. N. Am. J. Fish Manag. 38, 991–1003. https://doi.org/10.1002/nafm.10185.
Wood, E.F., Sivapalan, M., Beven, K., Band, L., 1988. Effects of spatial variability and scale with implications to hydrologic modeling. J. Hydrol. 102, 29–47. https://doi.org/10.1016/0022-1694(88)90090-X.
Wood, P.J., Gunn, J., Smith, H., Abas-Kutty, A., 2005. Flow permanence and macroinvertebrate community diversity within groundwater dominated headwater streams and springs. Hydrobiologia 54, 55–64. https://doi.org/10.1007/s10750-005-2213-y.
Woodhurst, G.D., de Scally, F.A., 2017. Sediment loading of alpine debris-flow channels by snow avalanches, Canadian Rocky Mountains. Geografiska Annaler A 100, 4–26. https://doi.org/10.1080/04353676.2017.1366830.
Woodrow, R.L., White, S.A., Conrad, S.R., Wadnerkar, P.D., Rocher-Ros, G., Sanders, C. J., Holloway, C.J., Santos, I.R., 2024. Enhanced stream greenhouse gas emissions at night and during flood events. Limnol. Oceanogr. Lett. 9, 276–285. https://doi.org/10.1002/lol2.10374.
Woods, R., Sivapalan, M., Duncan, M., 1995. Investigating the representative elementary area concept: An approach based on field data. Hydrol. Process. 9, 291–312. https://doi.org/10.1002/hyp.3360090306.
Wu, J., Liu, H., Wang, Z., Ye, L., Li, M., Peng, Y., Zhang, C., Zhou, H., 2021. Channel head extraction based on fuzzy unsupervised machine learning method. Geomorphology 391, 107888. https://doi.org/10.1016/j.geomorph.2021.107888.
Wu, J.Y., Thompson, J.R., Kolka, R.K., Franz, K.J., Stewart, T.W., 2013. Using the Storm Water Management Model to predict urban headwater stream hydrological response to climate and land cover change. Hydrol. Earth Syst. Sci. 17, 4743–4758. www.hydrol-earth-syst-sci.net/17/4743/2013/.
Xu, Z.X., Zhao, F.F., Li, J.Y., 2009. Response of streamflow to climate change in the headwater catchment of the Yellow River basin. Quat. Int. 208, 62–75. https://doi.org/10.1016/j.quaint.2008.09.001.
Yifru, B.A., Chung, I.M., Kim, M.G., Chang, S.W., 2022. Augmenting freshwater availability in mountain headwater streams: assessing the sustainability under baseline and future climate change scenarios. Int. Soil Water Conserv. Res. 10, 293–307. https://doi.org/10.1016/j.iswcr.2021.08.002.
Zarnetske, J.P., Gooseff, M.N., Bowden, W.B., Greenwald, M.J., Brosten, T.R., Bradford, J.H., McNamara, J.P., 2008. Influence of morphology and permafrost dynamics on hyporheic exchange in arctic headwater streams under warming climate conditions. Geophys. Res. Lett. 35, L02501. https://doi.org/10.1029/2007GL032049.
Zhao, S., Cheng, S., Ruan, Y., Xu, Y.J., Sun, H., Ye, C., Liu, W., Li, S., 2026. Urban development elevates methane and carbon dioxide emission in headwater streams. Water Res. 289, 124876. https://doi.org/10.1016/j.watres.2025.124876.
Zimmerman, R.C., Goodlett, J.C., Comer, G.H., 1967. The influence of vegetation on channel form of small streams. In: *Symposium on River Morphology, 75*, 255-275. General Assembly of Bern, Switzerland.
Zipper, S.C., Hammond, J.C., Shanafield, M., Zimmer, M., Datry, T., Jones, C.N., et al., 2021. Pervasive changes in stream intermittency across the United States. Environ. Res. Lett. 16, 084033. https://doi.org/10.1088/1748-9326/ac14ec.