

The significance of small streams

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Abstract Headwaters, defined here as first- and second-order streams, make up 70%–80% of the total channel length of river networks. These small streams exert a critical influence on downstream portions of the river network by: retaining or transmitting sediment and nutrients; providing habitat and refuge for diverse aquatic and riparian organisms; creating migration corridors; and governing connectivity at the watershed-scale. The upstream-most extent of the channel network and the longitudinal continuity and lateral extent of headwaters can be difficult to delineate, however, and people are less likely to recognize the importance of headwaters relative to other portions of a river network. Consequently, headwaters commonly lack the legal protections accorded to other portions of a river network and are more likely to be significantly altered or completely obliterated by land use.

Keywords headwaters, hydrology, water quality, land use, connectivity, resilience

1 Introduction

Headwater streams, defined here as first- and second-order channels (Strahler, 1952), cumulatively constitute the great majority of channel length within a river network (Downing et al., 2012). A substantial body of research on the physical, chemical, and biological functions of headwater streams clearly indicates their importance to the entire river network, yet these relatively small streams are most likely to be ignored by legal protections extended to rivers and to be aggressively altered in connection with diverse land uses. The intent of this paper is to briefly review existing knowledge of headwater streams and to highlight knowledge gaps that are important in terms of fundamental understanding and management of headwater streams.

Beyond their relatively small size, drawing general-

izations about headwater streams is difficult because of their diversity. In high-relief environments, headwater streams can be steep channels narrowly confined between valley walls, with extremely turbulent flow. In low-relief environments, headwater streams can be swales in which a distinct channel alternately appears and then becomes less pronounced in a downstream direction. Headwater streams are likely to have no surface flow for much of the time in drylands or karst regions, but may also be dry for portions of the year even in wet environments (Meyer et al., 2007b). Headwater streams can initiate from a lake or pond, a spring or seep, or from a point at which surface runoff is sufficiently concentrated to erode a persistent channel. Many headwater streams end at the junction with a larger channel, but they can also flow directly into a lake or into the ocean in coastal environments.

2 State of knowledge of headwater streams

This portion of the paper reviews the state of knowledge of headwater streams with respect to eight primary topics. With respect to physical characteristics, this section discusses the point on a landscape at which headwater streams initiate; the movement of water and sediment downstream through headwater channels; the water chemistry of headwaters and the influences of headwater form and process on downstream water quality; and the distinctive characteristics of channel morphology and stability in headwater streams. In the context of ecological characteristics, this section discusses: the unique characteristics of headwaters aquatic and riparian biota and the role of headwaters in sustaining riverine biota in downstream portions of the river network; the importance of diverse forms of connectivity associated with headwater streams; and the cumulative effects of land use and river engineering that may substantially alter or even obliterate significant portions of the total length of headwaters within a river network. Finally, this section highlights issues around public recognition of headwaters as rivers, rather than erosional features that are not fully part of river

networks, as well as the problem of legally protecting portions of the river network that many people may not recognize as rivers.

2.1 The start of the channel network

Streams originate at channel heads or stream heads. A channel head is the upstream-most point of concentrated water flow and sediment transport between definable banks (Montgomery and Dietrich, 1988, 1989). The channel head separates hillslopes or unchanneled hollows from channel networks (Dietrich and Dunne, 1993). The channel head may or may not coincide with the stream head, which is the upstream-most location of perennial flow (Jaeger et al., 2007).

Channel heads within even a small geographic area can have substantially different contributing drainage areas as a result of the multiple factors that influence the surface and subsurface flow paths that result in flow concentration and initiation of a channel. Individual channel heads may reflect primarily surface runoff, preferential subsurface flow (Jones, 1971), or some combination of surface and subsurface flow. The location of a channel head can also vary through time as factors such as land use or wildfire alter runoff, surface erodibility, sediment supply, and hillslope stability (Jefferson and McGee, 2013; Wohl, 2013). Landslides or debris flows, for example, can alter the location of channel heads (Montgomery and Dietrich, 1992).

A channel initiation threshold, C , is most commonly expressed in the form of

$$AS^a \geq C, \quad (1)$$

where A is contributing catchment area and S is hillslope gradient (Dietrich et al., 1992, 1993; Prosser and Abernethy, 1996). Studies from diverse regions indicate substantial variability in A and S both within a region and between regions (Montgomery and Fournelle-Georgiou, 1993; Prosser and Dietrich, 1995; Istanbuloglu et al., 2002; Yetemen et al., 2010). Local variations in hillslope gradient and erodibility strongly influence the location of individual channel heads (Henkle et al., 2011; Julian et al., 2012).

Commonly used maps of river networks (e.g., developed from 10 m DEMs) do not adequately represent channel heads and first-order channels, which are typically not visible in aerial imagery and are difficult and time-consuming to map in the field. Consequently, many investigators assume that channel heads lie near reversals or inflections in averaged hillslope profiles (e.g., Tarboton et al., 1991; Ijjasz-Vasquez and Bras, 1995; Heine et al., 2004), although this can lead to significant over- or under-estimation of contributing area (Tarolli and Dalla Fontana, 2009; Henkle et al., 2011).

The uncertainty associated with remote prediction of the

locations of channel heads and the difficulty in actually mapping channel head locations in most regions result in limited mapping and quantification of first-order channels in many river networks. This in turn makes it difficult to understand or predict the implications of activities such as: upland mining that obliterates entire headwater streams (Palmer et al., 2010; Bernhardt and Palmer, 2011); changes in legal protection and regulation of small streams (Nadeau and Rains, 2007); land uses such as urbanization that increase water yield to streams (Paul and Meyer, 2001) or agriculture or timber harvest that increase sediment yield to streams (Campbell and Doeg, 1989); or loss of spawning or nursery habitat in headwaters (Freeman et al., 2007).

2.2 Hydrology, hydraulics, and sediment transport

Headwater streams are commonly regarded as source regions for water, solutes, mineral sediment, and particulate organic matter (Schumm, 1977; Alexander et al., 2007; MacDonald and Coe, 2007; McClain and Naiman, 2008). Small streams are closely coupled to upland sources of these materials and tend to lack surface and subsurface storage zones in the form of broad valley bottoms and floodplains or extensive alluvial aquifers and hyporheic zones (McGlynn et al., 2004).

Across diverse hydroclimatic regions, headwater streams tend to exhibit more spatial and temporal hydrologic variability than larger channels as a result of: smaller contributing areas; shorter surface and subsurface flow paths from uplands to channels; and less surface (floodplain, secondary channels) and subsurface (alluvial aquifer, hyporheic zone) storage of water (Gomi et al., 2002; Richardson and Danehy, 2007). Headwater streams also tend to be more strongly influenced by relatively localized disturbances such as convective storms, wildfires, and debris flows or landslides, which can affect the entire contributing area of a first- or second-order stream. Consequently, regional relations between drainage area and either peak or base flow may not accurately describe the headwater portions of a river network. Flow in headwater streams is also less likely to be systematically measured by stream gages, which further limits ability to characterize flow regime in headwater streams.

Among the most hydrologically variable headwater streams are those which are ephemeral or intermittent. Ephemeral streams flow only during and soon after precipitation inputs, and have no ground water inputs or base flow (USACE, 2012). Intermittent streams flow continuously only at certain times of the year when the water table intersects the surface along the channel course, such as when the stream receives water from a spring or from a surface source such as melting snow (Osterkamp, 2008). During periods of low flow, dry segments alternating with flowing segments create longitudinally discontinuous flow (Reynolds et al., 2015). Intermittent

streams are also sometimes called temporary rivers because of the lack of flow at some points in space and time along the stream course (Arthington et al., 2014). Most ephemeral and intermittent streams are poorly characterized, or uncharacterized, with respect to the spatial extent, magnitude, frequency, and duration of surface flow under current conditions, although these headwaters are likely to be especially prone to hydrologic changes under a changing climate (Jaeger et al., 2014).

The distribution of hydraulic forces in headwater streams is commonly not adequately described by standard formulas and assumptions such as the semi-log vertical velocity profile because of the relatively shallow flow and hydraulically rough boundaries of headwater channels (Ferguson, 2007; Wohl, 2010). Headwater streams in high-relief regions also exhibit substantial longitudinal variation in channel geometry as a result of external controls such as differences in bedrock erodibility and tectonic activity (Adams and Spotila, 2005; Wohl, 2010). Consequently, applications of sediment transport formulae developed for larger channels typically over-predict bedload transport in small streams, particularly in headwater streams of high-relief environments, which tend to have very coarse-grained substrate that limits entrainment of underlying finer sediment (Gomez and Church, 1989; Wohl, 2010). In coarse-grained channels, non-fluvial processes such as debris flows may create episodic evacuation of stored materials at intervals of years to decades (Wohl and Pearthree, 1991; Benda et al., 2005). Limited ability to accurately predict or measure sediment transport in headwaters can create substantial uncertainties in predicting sediment yield for the entire river network, because headwaters tend to be source regions for sediment. Limited ability to quantify sediment transport also creates substantial uncertainty in predicting the cumulative effects of land uses that alter sediment yields to headwaters.

2.3 Water chemistry

The water chemistry of headwater streams is important for at least two reasons. First, headwater stream chemistry is highly influenced by upland flow paths and the chemistry of incoming surface and ground waters. Upland flow paths to headwaters tend to be relatively short and consequently strongly influenced by atmospheric inputs, bedrock geology, and soil characteristics (Wohl, 2010). Lacking the buffering mechanisms of downstream portions of a river network, headwaters can react rapidly and significantly to changes in land use or atmospheric inputs.

Second, headwaters are the first line of defense against potential contaminants such as excess fine sediment or nutrients and the first receiving point for organic matter. Consequently, the characteristics of the riparian zone and the bankfull channel strongly influence the degree to which sediment and nutrients are retained and biochemically processed or passed directly downstream (Alexander et al.,

2007). A continent-wide study of headwaters in North America, for example, revealed that the most rapid uptake and transformation of inorganic nitrogen occurs in the smallest streams (Peterson et al., 2001), although the study lacked data from larger rivers for comparison. Another study indicated that basic water chemistry parameters (e.g., dissolved O, total N, total P) in downstream reaches of a river network in eastern Kansas correlated most closely with riparian land cover adjacent to first-order streams (Dodds and Oakes, 2008).

Organic matter (OM) and nutrients enter headwater streams via litter fall from riparian plants, overland flow, and subsurface movement (Wipfli et al., 2007). Dissolved OM enters primarily with ground water, whereas particulate OM transported by overland flow enters primarily during runoff from snowmelt or rainfall. OM entering a headwater stream can be retained and biochemically processed through consumption, or can be transported downstream (Webster et al., 1999; Richardson et al., 2005). Retention versus transport depends strongly on flow (much of the transport occurs during periods of higher flow) and on the physical complexity of the channel. Physical complexity associated with bedforms, hyporheic exchange, transient storage in flow separation zones associated with features such as bank irregularities or instream large wood, and variations in cross-sectional or planform geometry (e.g., secondary channels and over-bank areas) enhances retention (Speaker et al., 1984; Grimm et al., 2005; Gooseff et al., 2007). Increased retention of solutes and particulate matter by even minutes to hours can facilitate uptake by microbial and invertebrate stream organisms (Battin et al., 2008).

2.4 Channel form and stability

At least two aspects of channel morphology can be distinctive in headwater streams relative to larger channels in a river network. First, headwater channels can be physically difficult to delineate in terms of their upstream and lateral extent. Headwater channels in low-relief environments are particularly likely to be longitudinally discontinuous with respect to clearly definable bed and banks because the stream flows through wetlands or ponds as it continues downstream. Lack of longitudinally continuous channel form can also be common along headwater streams in drylands or karst regions. These downstream discontinuities in channel development can lead to questions as to what does and does not constitute a channel, particularly in a regulatory context (Mersel and Lichvar, 2014).

Second, the geometry of headwater streams is likely to change substantially over timescales of 10^0 – 10^1 years in response to changes in water and sediment inputs associated with intense precipitation, debris flows, wild-fires, and other upland disturbances because of the lack of buffering in the form of downstream attenuation by

floodplains and secondary channels. This can lead to questions as to whether a headwater stream is stable in the context of stream management and channel engineering. Designating a river as stable or unstable always depends on the time period being considered, but the influence of time period is particularly strong when assessing stability of headwater streams.

2.5 Aquatic and riparian biota

Headwater streams can provide unique aquatic and riparian habitats not present elsewhere in a river network. These habitats may be used by permanently resident species or by migrant species that travel to headwaters during particular seasons or life stages in search of a refuge from temperature or flow extremes, competitors, predators, or introduced species (Schlosser, 1995; Meyer et al., 2007a). Headwater streams can serve as a source of colonists to downstream regions (Pond et al., 2016) and as a source of emerging and drifting insects (Griffith, 1998). Headwaters can provide spawning and rearing areas (Montgomery et al., 1999), sources of food (Wipfli and Gregovich, 2002), and migration corridors throughout a landscape (McClain and Naiman, 2008) (Fig. 1). Even ephemeral or intermittent headwaters can support rich and distinctive biological communities (Meyer et al., 2007a).

Headwater streams are particularly closely coupled with adjacent riparian and terrestrial environments because of the higher ratio of aquatic-riparian interface relative to larger rivers. Organic matter from litter fall and recruitment of large wood, as well as terrestrial invertebrates, create important food subsidies for headwater streams (Nakano and Murakami, 2001; Wipfli et al., 2007). Similarly, emergent aquatic insects create important food sources for riparian predators such as spiders and birds (Baxter et al., 2005).

Despite these diverse ecological functions and biota, as of 2007 a complete species list did not exist for any headwater stream in the United States (Meyer et al., 2007a). Such a list would likely include hundreds to thousands of species. The 1-m-wide Breitenbach, a first-order stream in Germany, for example, has 1004 invertebrate taxa (Allan, 1995).

2.6 The importance of connectivity

Connectivity here refers to fluxes of water, sediment, organic matter, and solutes, and movements of organisms, between distinct portions of a drainage basin (Fig. 2). Connectivity can be described for six dimensions and with respect to magnitude, frequency, duration, and spatial extent. The characteristics of diverse forms of connectivity can be temporally and spatially variable in headwater streams and therefore difficult to quantify or predict, not least because both direct, systematic measurements (e.g., water discharge, sediment discharge, water quality para-

meters) and indirect estimates from remote imagery are less likely to be available for headwaters than for larger rivers. The details of connectivity are nonetheless likely to be of vital importance to headwater biotic communities and to downstream portions of the river network. Longitudinal disconnectivity in the form of waterfalls, for example, may limit upstream migration of exotic species and preserve populations of indigenous organisms (Adams et al., 2001). Lateral connectivity between channel and floodplain promoted by beaver dams or logjams can sustain riparian wetlands that store fine sediment and organic matter and enhance downstream water quality (Polvi and Wohl, 2013). Vertical connectivity between the channel and hyporheic zone promoted by well-developed bedforms such as pools and riffles can create interstitial habitat for macroinvertebrates that support fish populations (Stanford and Ward, 1988; Smock et al., 1992), as well as thermal stability (Sawyer et al., 2012) and nitrogen uptake (Nihlgard et al., 1994).

Because flow in headwater streams can be very shallow and aquatic organisms inhabiting these streams can be small-bodied or weak swimmers or jumpers, even very small structures such as culverts, irrigation intakes, or grade-controls can effectively disconnect portions of the channel upstream of the structure from the rest of the network (FSSSWG, 2008). Groundwater withdrawal that lowers the alluvial water table or surface-water diversions can also significantly limit longitudinal and/or lateral (channel-floodplain) connectivity of headwaters (Falke et al., 2011).

2.7 Cumulative effects of land use and river engineering

Headwaters are arguably the most endangered river ecosystems because of the cumulative alteration and complete loss of headwater streams through land uses and river engineering (Meyer and Wallace, 2001). Among those activities that disproportionately affect headwaters are: upland mining (Palmer et al., 2010; Bernhardt and Palmer, 2011); burial in urban and agricultural areas (Elmore and Kaushal, 2008); plowing over, draining, or channelizing small streams in agricultural areas (Petersen et al., 1987); groundwater withdrawal that lowers regional and alluvial water tables (Falke et al., 2011); and longitudinal disconnection associated with small structures such as road culverts (FSSSWG, 2008). Headwaters are also affected by: dams that block access of organisms from downstream reaches or alter the water and sediment regimes of headwaters (Beasley and Hightower, 2000); removal or alteration of riparian ecosystems (Sweeney et al., 2004); increased nutrient and sediment yields from point and non-point sources (Alexander et al., 2007); and introduction of exotic aquatic and riparian species (Adams et al., 2001).

Headwater streams are in some respects disproportionately affected by these activities because such streams are

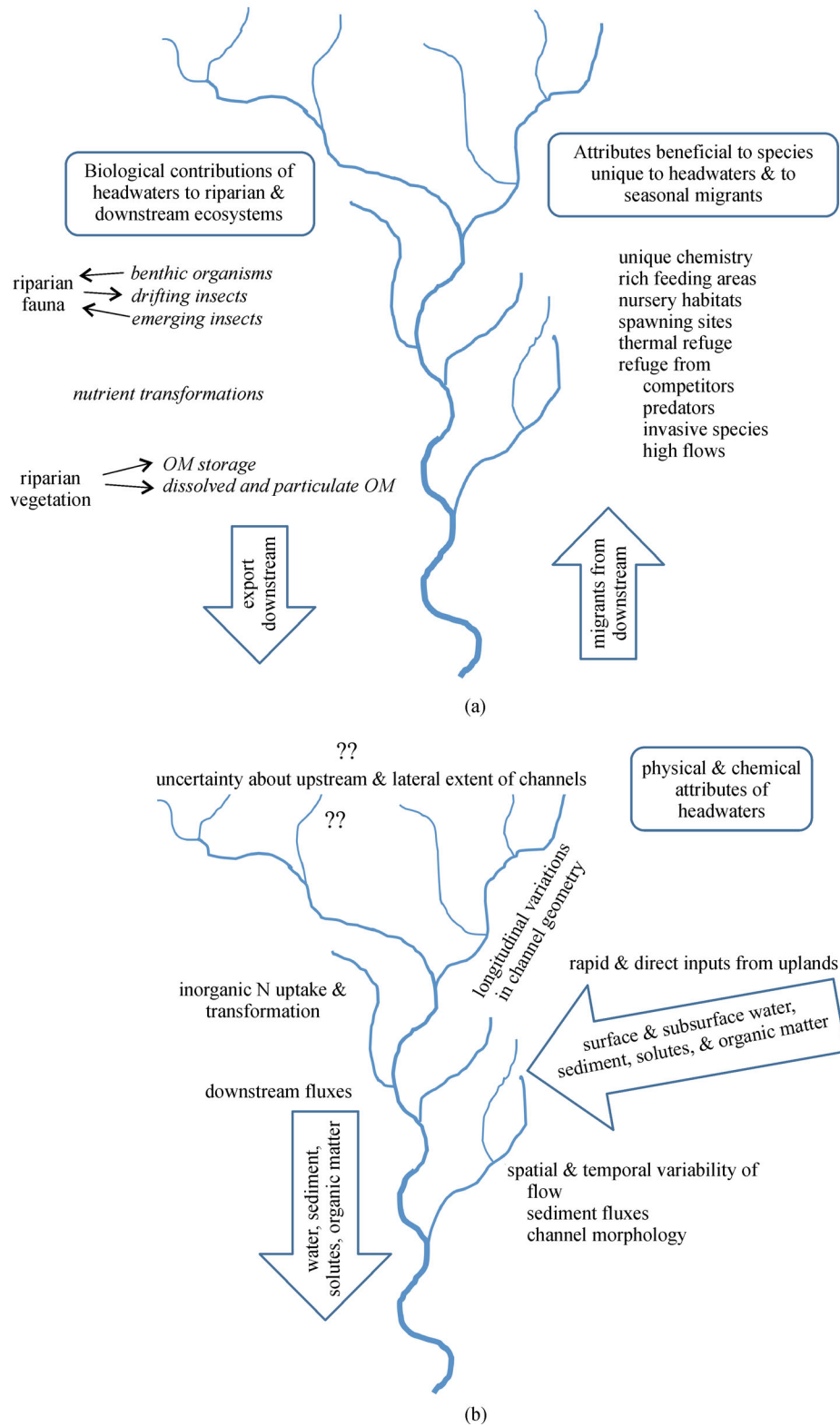


Fig. 1 Schematic illustration of (a) biotic contributions of headwaters and (b) physical characteristics of headwaters.

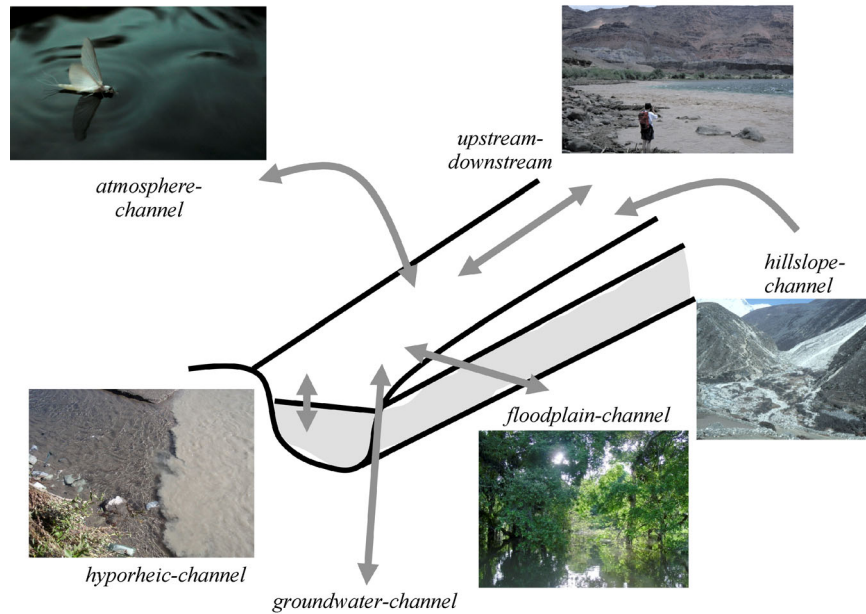


Fig. 2 The six dimensions of connectivity. The segment of channel shown here is connected to: upstream and downstream portions of the river network; adjacent uplands; the floodplain; ground water; the hyporheic zone (gray); and the atmosphere. The photograph for upstream-downstream connection was taken during a flood on the Paria River, a tributary of the Colorado River that enters just downstream from Glen Canyon Dam in Arizona, USA. In this view, the Paria is turbid with suspended sediment whereas the Colorado, which is released from the base of the dam, is clear. The photograph for the hillslope-channel connection shows a large landslide entering the Dudh Khosi River in Nepal. The photograph for the floodplain-channel connection was taken along the Rio Jutai, a blackwater tributary of the Amazon River, during the annual flood in early June. In this view the ‘flooded forest’ is submerged by several meters of water. The photograph for hyporheic-channel connection shows a mixing zone between hyporheic return flow (clear water at left) and turbid surface flow along a braided section of the Duke River in Canada. The photograph for atmosphere-channel connection shows a mayfly emerging from the river prior to entering the atmosphere as a winged adult (image courtesy of Jeremy Monroe, Freshwaters Illustrated). (After Wohl, 2014, Figure 1.1)

less likely to be regarded as legitimate rivers that require legal protection and because headwaters are so widely distributed and have such a large cumulative length. Multiple studies have called attention to the large-scale consequences of cumulative headwater alteration, including: flashier hydrographs (Meyer and Wallace, 2001); downstream eutrophication and coastal hypoxia (Howarth, 2008); lower secondary productivity of river ecosystems as a result of reduced trophic subsidies to downstream river segments (Freeman et al., 2007); and reduced viability of freshwater biota, which are among the most endangered groups of organisms in the world (Ricciardi and Rasmussen, 1999).

2.8 Public recognition and legal protection

As reviewed in Nadeau and Rains (2007), the U.S. Supreme Court in its 2001 *SWANCC* decision ruled that the U.S. Army Corps of Engineers had exceeded its statutory authority by asserting Clean Water Act jurisdiction over non-navigable, isolated, intrastate waters based solely on their use by migratory birds. Prior to 2001, any tributary to a navigable water and virtually all delineated

wetlands were regarded as jurisdictional, or considered a water of the United States under the Clean Water Act, because of their potential to serve as migratory bird habitat (Leibowitz et al., 2008). The *SWANCC* decision stripped most headwater streams of protection under the Clean Water Act and continues to be the focus of intense legal and policy debate. As emphasized in many studies, the physical, chemical, and biological integrity of floodplains and downstream portions of a river network depend on at least episodic connectivity with headwaters (Ward and Stanford, 1995; Tockner et al., 2000), so that lack of legal protection of quantity and quality of downstream flows, as well as the presence and habitat and biotic diversity of headwater stream ecosystems, affects entire river networks.

In the 2006 *Rapanos* decision, the U.S. Supreme Court extended protection to waters that possess a ‘significant nexus’ as a result of being able “either alone or in combination with similarly situated lands in the region, [to] significantly affect the chemical, physical, and biological integrity of other covered waters more readily understood as ‘navigable’”. This decision places the burden of proof regarding significant affects (nexus) on regulatory agencies

Table 1 Research needs for headwater streams

Research need	Description
Mapping	We are unable to predict the location of first-order channels in particular, which limits ability to define their spatial distribution and cumulative length or area. This in turn limits understanding of their physical or ecological function, as well as the extent of direct or indirect human alteration of these smallest channels in a river network
Resistance & resilience	We cannot adequately characterize or predict either physical or ecological resistance or resilience of many headwater streams. We need additional case studies of headwaters response to natural and human-induced disturbances in order to develop a sufficient body of literature to support generalizations and predictions. We also need metrics to characterize resistance and resilience of headwater streams, which are likely to have greater magnitude and frequency of disturbances than higher-order channels
Human alterations	We need more site-specific case studies and watershed- to regional-scale assessments of how land use and climate change affect the distribution, form, and function of headwaters
Biota	Complete species inventories do not exist for the great majority of headwater streams, which limits our ability to understand and predict the contribution of headwaters to biodiversity and the ecological resilience of these streams to natural and human disturbances
Hydrology	There is a need for both techniques to measure the spatial and temporal extent of surface flow in streams that are ephemeral or intermittent, and datasets of such measurements. We also need more quantitative measurements of hydrologic variability and metrics that characterize hydrologic variability
Hydraulics and sediment regime	Headwaters are predominantly sediment transfer zones, but we need more case studies of the magnitude and episodicity of sediment inputs and downstream transfer, including the hydraulic thresholds that facilitate such transfer
Connectivity	As with hydrologic variability, we need more measurement techniques, metrics, and datasets of diverse forms of connectivity in headwaters

such as the U.S. Corps of Engineers and the U.S. Environmental Protection Agency. As a result, there is an urgent need for methods to evaluate the hydrological permanence, connectivity (magnitude, duration, frequency) of downstream fluxes, and ecological integrity of headwater streams (Leibowitz et al., 2008). As an example of a metric that can be used to assess hydrological permanence, Leibowitz et al. (2008) proposed the maximum duration of continuous flow for a stream segment, which in turn requires instrumentation to document or quantify the presence of surface flow (Jaeger and Olden, 2012).

The key point that this discussion of United States policy is intended to illustrate is that headwaters are commonly not adequately recognized as a portion of a river network by those who are not river scientists. Consequently, headwaters are particularly likely to lack legal protection under the legislation protecting water quality and stream flow within a region or country (Meyer et al., 2007b).

3 Moving forward

Regardless of the geographic region considered, first- and second-order channels make up 70%–80% of the total channel length of river networks (Downing et al., 2012). The abundance of headwater channels and their numerous ecosystem functions underlie the need to enhance our understanding of this portion of river networks. Enhanced understanding can be considered in two contexts: research gaps and needs for education and outreach.

Table 1 lists some of the basic areas in which research

targeted at headwater channels would be particularly useful. Each of the topics briefly discussed in sections 2.1 through 2.7 requires additional research targeted at headwater streams. Section 2.8 relates to the need for additional education and outreach. Because headwater streams are so widespread and can be difficult to recognize, people outside the community of river scientists are less likely to consider these small channels worthy of protection or to be actively hostile to the idea of extending regulatory authority to headwater streams. There is an urgent need to increase public awareness of the vital ecosystem services provided by headwater streams and of the integral role of these small streams in whole river networks. As one of my colleagues has expressed it, you would not expect a forest to remain healthy if you removed all of the leaves from every tree. So we cannot expect our freshwater resources to remain vital if we destroy much of the functioning of headwater streams.

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