How can we improve our understanding of headwater systems worldwide and positively impact protection levels?

Advancing the science of headwater streamflow for global water protection

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What level of understanding do we have of headwater streams? How can we improve both our understanding and our management? Headwater streams are often overlooked components of watersheds globally and are generally unprotected. Headwater streamflow is variable, covers broad areas, and may be seasonal, intermittent, or ephemeral. The authors argue that creating a global understanding of headwater systems and flow regimes across space and time will support better management. They propose uniform definitions for headwater systems, summarize their regulatory status, synthesize the ways data and modelling are used to characterized headwater streamflow across space and time, and suggest new approaches for understanding and describing headwaters.

How can we define a headwater stream and a headwater system?

- The authors define headwaters as the surface-water catchment areas and groundwater zones contributing water, material, and energy to a stream.
- The upper extents of headwater streams are where distinct channels with water flow and sediment transport emerge from diffuse up-basin processes. The lower extent of headwater streams are where the contributions of local water, material, and energy are less than the contributions from upstream.
- For modelling purposes, the authors propose defining the downstream extent of headwaters as the lowest point of a 1:24,000 or similar scale stream network map that includes 1 and 2 order streams. With additional data the lower extent can be defined based on physical attributes, such as the relationship between channel width and stream order.

What protections do headwaters currently have in the United States?

- The main protection for headwater systems and streams is the Clean Water Act. A 2023 US Supreme Court ruling limited protections to streams and rivers that are relatively permanent, thereby excluding intermittent, non-perennial streams from protected status.
- The first step to improve protection of headwaters is to increase our understanding of headwater systems broadly by more fully characterizing functions and extents of headwaters and integrating this knowledge across landscapes and regions.

How can observational and modelling approaches be used to understand headwater systems and streams?

- Researchers have used modified temperature, light, and electrical conductivity sensors with field cameras to gather data on frequency, duration, and timing of surface water presence.

These techniques can be used to describe headwater wetting and drying patterns, spatially and temporally.

- Areas of future progress include using fine-scale remote-sensed data for characterizing headwater flow regimes, and creating comprehensive headwater flow databases at regional, continental, and global scales.

How has modelling increased our understanding of headwater hydrology? What further work is needed?

- Field observations are not always available and hydrologic models are needed to cover gaps spatially and temporally. Further work is needed to refine runoff generation models for small headwater streams, especially given that precipitation and temperature data are generally available at courser resolutions.
- We can improve the connections between our understanding of watershed processes and models simulating headwater system dynamics. Additionally, combining the hillslope and watershed boundary modelling approach with the headwater stream network and associated riparian system approach will increase our ability to model headwater systems in a more holistic way.

How can we use measuring and mapping to improve the way we study headwater hydrology?

- Headwater streams and systems should be mapped, including spatial and temporal variation, nationally and globally using a variety of criteria to define headwaters. Different maps could be utilized by researchers or managers, depending on their question of interest.
- To understand headwater flow propagation and control and to increase our ability to infer headwater hydrology from downstream gauges, researchers must amass additional headwater streamflow data and investigate headwater dynamics within watersheds.

How can we use data synthesis to improve our understanding and classification of headwater systems?

- In order to use hydrology data to identify, characterize, and understand headwater systems and their spatial and temporal variation, we should create a headwater hydrology benchmark dataset, which would include gauged and observational streamflow data and be located and synthesized in large-scale databases and online platforms.
- A headwater classification system using physical attributes, processes, and hydrological signatures would support management decisions based on headwater system type. A classification system would require improved understanding of how headwater streams differ across physiographic, climatic, and hydrological regimes.

Research Approach/Methods

- The authors describe gaps in understanding of function, climate response, flow propagation, and permanence of headwater streams.
- They then discuss ways to address these deficiencies through adoption of standard definitions, increased data collection, increased mapping, improved modelling, and large-scale synthesis.

Keywords headwater stream, headwater classification, watershed resiliency, headwater definition, headwater protection

Images

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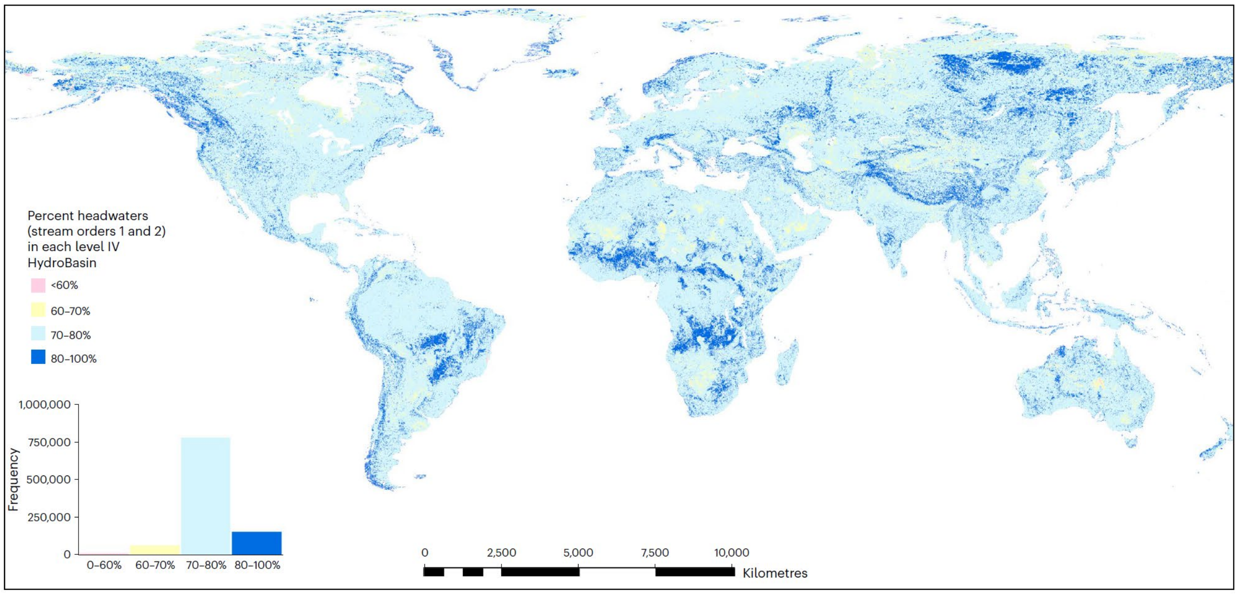

Figure 1 in Golden et al. 2025. Percentage of headwater streams by length in level 4 HydroBASINS across the globe using the MERIT Hydro-based stream network (with a 5 ha drainage threshold) as used in the Hydrography90m global hydrography dataset. Headwater streams are operationally defined here as Strahler stream orders 1 and 2. For level 4 HydroBASINs data and the Hydrography90m global hydrography dataset, see ref. 116 and ref. 103, respectively.

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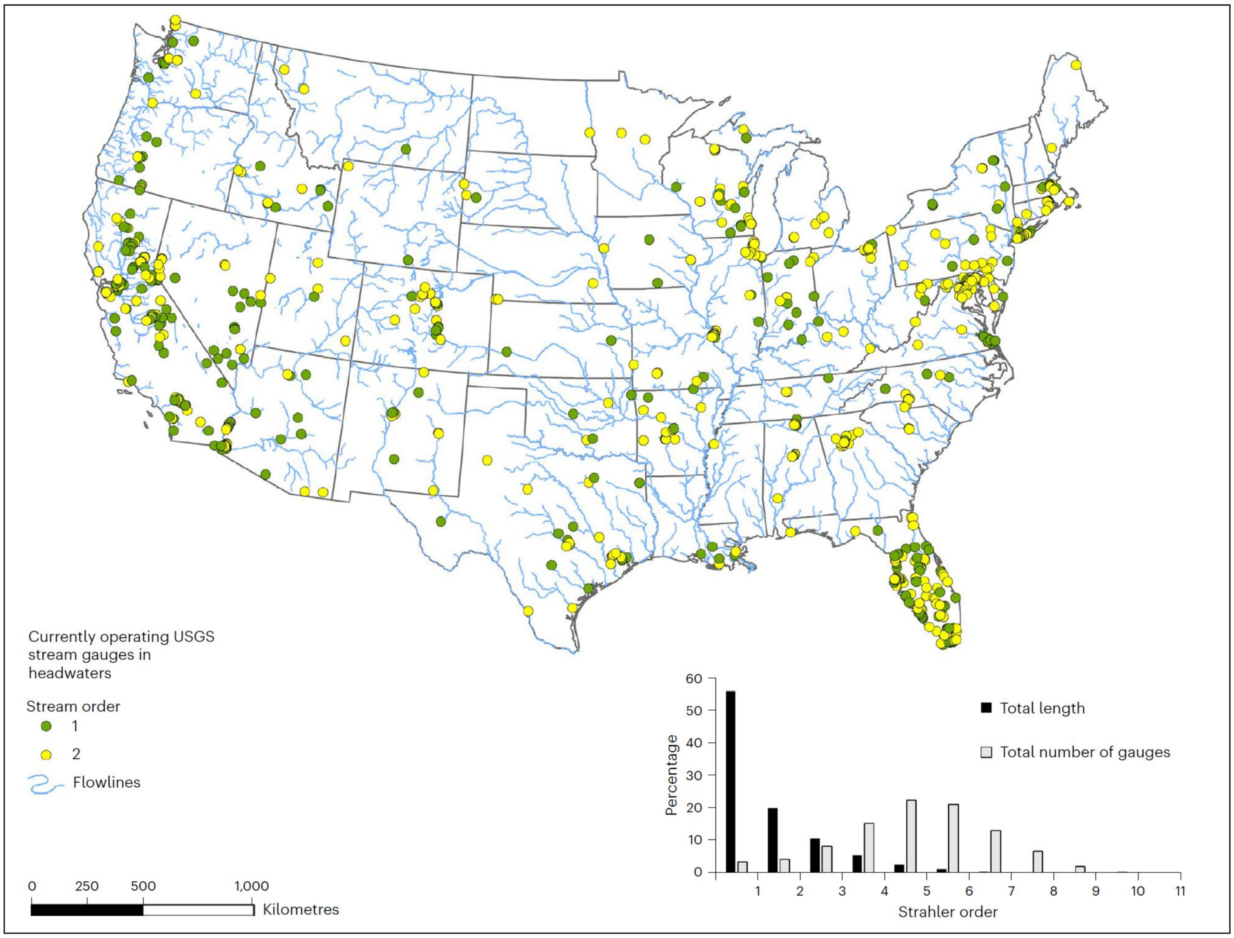

Figure 4 in Golden et al. 2025. Percentage of US Geological Survey (USGS) stream gauges across the conterminous United States with at least 5 years of recent data (2018–2023) that are considered headwaters, as operationally defined by Strahler stream orders 1 and 2, based on the NHDPlus High Resolution (V2) dataset. The stream gauge locations were derived from the National Water Information System121. The flowlines in the figure are from NHDPlus High Resolution data and are from stream orders ≥7 for graphical purposes. The state boundaries were derived from the US Census Bureau120. The NHDPlus High Resolution (V2) dataset can be found at ref. 33. The currently operating USGS stream gauges in this figure all have an end date after 2019 with at least 5 years of data.

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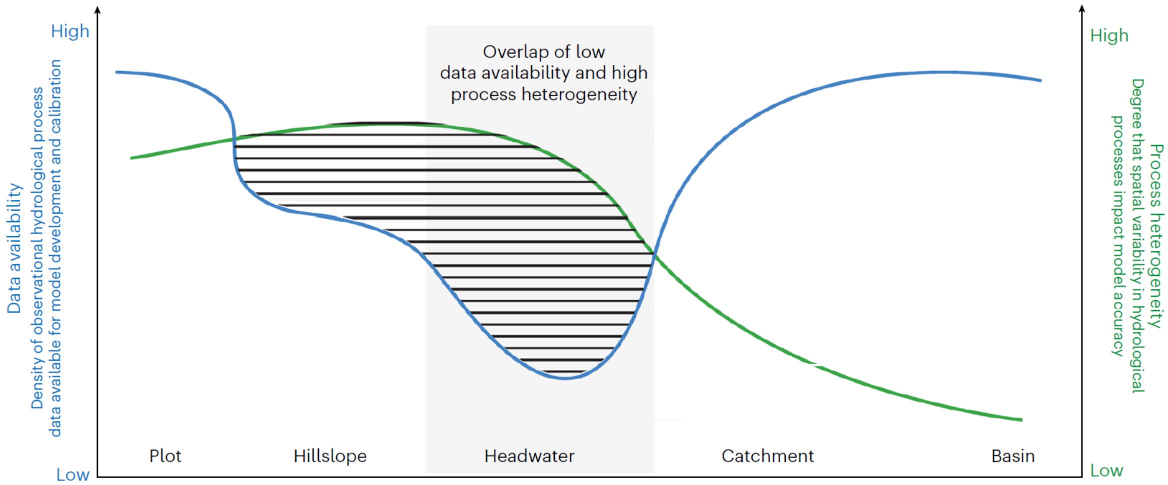

Figure 5 in Golden et al. 2025. Simple conceptualization of data availability balanced against hydrological process heterogeneity at different scales of flow regime modelling. We are required to capture a relatively dense level of process heterogeneity (compared with catchment- and basin-scale models) to get an accurate headwater flow regime model, yet the spatial density of data required to do this is limited–except for a handful of highly instrumented headwaters, nationally and around the globe. For our purposes, plots are small, highly instrumented parts of the landscape unrelated to drainage areas; hillslopes are sloped areas of the land draining to streams; headwaters are defined herein; catchments are small-to-medium drainage areas or watersheds (~1–1,000 km2); and basins are large drainage areas >1,000 km2).