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How Low Can You Go?: Widespread Challenges in Measuring Low Stream Discharge and a Path Forward

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How low can you go? Widespread challenges in measuring low stream discharge and a path forward

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Scientific Significance Statement

Low flows pose unique challenges for accurately quantifying streamflow. Current field methods are not optimized to measure these conditions, which in turn, limits research and management. In this essay, we argue that the lack of methods for measuring low streamflow is a fundamental challenge that must be addressed to ensure sustainable water management now and into the future, particularly as climate change shifts more streams to increasingly frequent low flows. We demonstrate the pervasive challenge of measuring low flows, present a decision support tool (DST) for navigating best practices in measuring low flows, and highlight important method developmental needs.

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Data Availability Statement: All data used in this manuscript is publicly available in the USGS National Water Information System and can be accessed using the DataRetrieval Package (De Cicco et al. 2022). All code used to retrieve this data and perform analysis can be found in a public github repository (https://github.com/dry-rivers-rcn/Low_flows), and the code is included as a PDF in the Supporting Information Materials. Copies of the .csv data files and the code can also be found at https://zenodo.org/record/8277960.

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

Measuring discharge at low flows: A challenge of increasing importance

Water resource management is facing mounting challenges associated with water scarcity, including interactive effects of a changing climate and increased water demand (Craig et al. 2017). Climate change is increasing drought severity in many regions (Cook et al. 2020), while demand for limited water supplies depletes water resources (de Graaf et al. 2019). Combined, these stressors result in lower and more variable flows in streams and rivers (Zipper et al. 2021), particularly in arid regions (Hammond et al. 2021). Despite challenges posed by low-flow conditions, the majority of resources (e.g., time, funding) for monitoring streamflow have historically focused on high-water concerns, such as ensuring navigation and predicting floods (Vörösmarty et al. 2001; Ruhi et al. 2018), in larger, perennially-flowing systems (Krabbenhoft et al. 2022).

Low-flow conditions (Mauger et al. 2021), which we define as streams or rivers with little downstream surface water flow caused by small volumes or very low downstream velocities (i.e., slackwater), are increasingly prevalent and thus necessitate greater focus on quantification approaches. Streamflow is the underlying physical template structuring biotic and abiotic processes, biogeochemical cycling, and ecological communities in river systems; thus, inaccurate low-flow measurements can propagate to and hinder diverse analyses requiring accurate low-flow data, ranging from drought characterization (Hammond et al. 2022), environmental flow allocations (Neachell and Petts 2019), ecological function assessments (Leigh and Datry 2017), species conservation plans (Lopez et al. 2022), and streamflow forecasting (Forzieri et al. 2014).

We posit that a lack of low-flow measurement techniques leaves monitoring networks ill-equipped to inform water management, which is a fundamental challenge that must be addressed to ensure sustainable water management in the future. Our objectives are to: (1) demonstrate the widespread challenges in low-flow measurement across an existing monitoring network in the United States, (2) discuss limitations of current streamflow measurement methods in low-flow conditions, (3) present a DST for choosing among existing measurement methods, and (4) highlight important methodological developments needed to improve low-flow measurement and monitoring. Such methodological progress is a prerequisite for understanding how low flows will respond to changing climate and human demands, thereby supporting management and policy actions seeking to avoid or minimize these impacts.

Low flows are widespread and difficult to measure

Point measurements of streamflow are essential for short- and long-term studies and monitoring, and can be made using many different methods (Turnipseed and Sauer 2010). If conducted over a range of flow conditions, discrete streamflow measurements can be used to develop a rating curve which relates stage and discharge, allowing for long-term, continuous quantification of discharge via stage sensors (Turnipseed and Sauer 2010). We focus our analysis and discussion on methods for point measurements of streamflow, but emphasize that limitations in these approaches have implications for the accuracy of longer-term streamflow monitoring via rating curve development.

To quantify the prevalence of substandard low-flow measurements, we examined manual point measurements of streamflow from 8008 U.S. Geological Survey (USGS) gages across the continental United States in the GAGES II dataset (Falcone 2011), which is a dataset of sites with either 20+ years of discharge since 1950 or that were operational as of 2009 (Appendix S1). For each manual streamflow measurement, we collected the quality code assigned by USGS hydrographers immediately after making the discharge measurement: "Poor" quality is assigned when uncertainty in the discharge measurement is estimated to be above 8%, "fair" when uncertainty is estimated to be less than 8%, good when uncertainty is estimated to be less than 5%, and excellent when uncertainty is estimated to be less than 2% (Turnipseed and Sauer 2010). These quality codes are a qualitative method for estimating the accuracy of individual discharge measurements based on suitability of the channel cross-section, flow state, and other flow conditions (Turnipseed and Sauer 2010).

For each gage, we identified the minimum streamflow value associated with a "good" manual flow measurement and calculated the percent of each gage's daily streamflow record below the minimum "good" threshold. To ensure our results were not overly sensitive to the value of the minimum "good" threshold, we also compared the percentage of each gage's streamflow record below two additional thresholds: (1) streamflow value corresponding to the minimum "fair" measurement, and (2) average of minimum "fair" and minimum "good" thresholds (*see* Table S1 for details), and obtained comparable results. The "minimum good" metric provides a conservative estimate of the duration of flow measurements with high uncertainty for each site; it only considers uncertainty related to manual measurements and does not account for additional uncertainty in stage measurements stemming from low-flow conditions. We interrogated the USGS network because it represents a high standard that many individual investigators use as a benchmark, and because it provided a large dataset relating manual streamflow measurements with qualitative assessments of quality/uncertainty. We performed all analyses in R version 4.2.1 (R Core Team 2022) and obtained USGS data from the National Water Information System using the DataRetrieval Package (De Cicco et al. 2022).

Across the GAGES II network, the average percentage of flow records below the minimum good measurement was 8.4%, indicating high overall quality of the streamflow measurements. However, we found that 393 gages ($\sim$ 5.5%) had at least 50% of flow records below the minimum good flow value, 68 of which had over 95% of flow records below the minimum good flow threshold (Fig. 1A). Sites with a high percentage of streamflow below the minimum "good" threshold are widely distributed across diverse climatic zones, land uses, and hydrologic settings, although the greatest density of high uncertainty records are concentrated in the arid southwestern United States where low flows and water management issues linked to scarcity are pervasive (Brown et al. 2019).

To provide an example of the difficulties in making low-flow measurements, we focused on the gage for Kings Creek near Manhattan KS (USGS Gage 06879650), a well-studied, grassland stream with a long continuous record (1979–present). Only 73 of the 238 manual flow measurements (∼ 31%) were considered "good" or "excellent" (Fig. 1B). The relatively low incidence of "good" manual flow measurements at Kings Creek resulted in over 58.6% of the

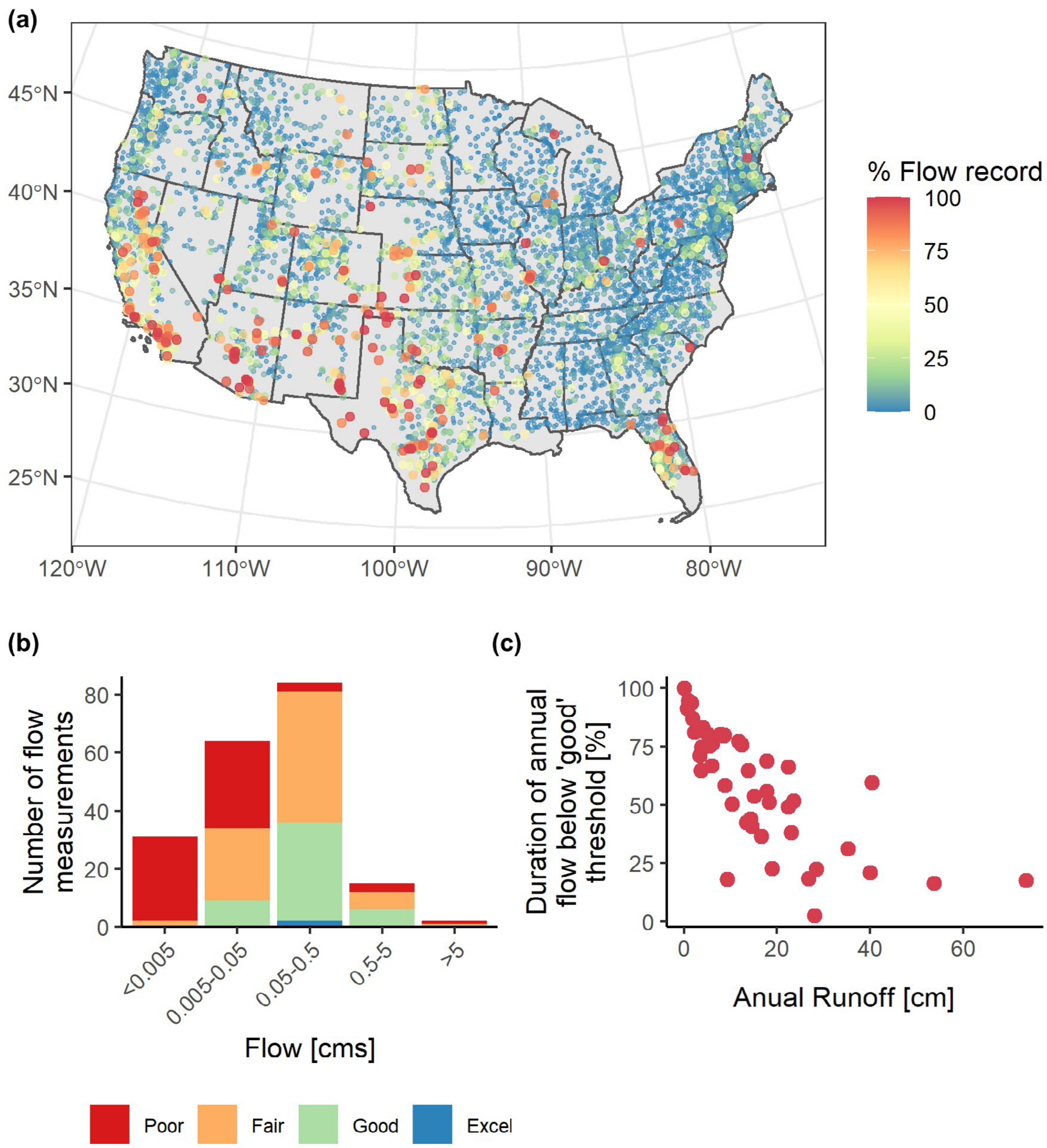

Fig. 1. (**A**) Map of USGS gage locations with the symbol color and size reflecting the percent of each streamflow record where discharge falls below the lowest manual flow measurement rated as "good" as defined by the USGS (*see* explanation in text). Symbol size is inversely proportional to the duration of record below "good," where larger circles represent gages with longer durations below the minimum "good" threshold. (**B**) Distribution of poor (red), fair (orange), good (green), and excellent (blue) manual flow measurements at the Kings Creek (USGS Gage 06879650) near the Konza Prairie Biological Station, Kansas, US. (**C**) Relationship between annual runoff from Kings Creek and the duration of the year spent below the lowest "good" manual flow measurement from 1980 to 2021. Up to 100% of the flow record in years with low cumulative runoff falls below the lowest "good" manual measurement, highlighting the potential for high uncertainty during these years.

daily flow record (from 1980 to 2021) being below the lowest "good" flow measurement, with the proportion below that threshold in a given water year ranging from 2.5% to 100%. This underscores that even for a given site, the relative importance of accurate low-flow measurements will vary from year-to-year, with greatest impact during dry years (Fig. 1C). Furthermore, uncertainties in low-flow measurements may propagate into subsequent estimates of nutrient export, which may lead to some annual load estimates to be much less certain than others. Systems with frequent low flows and flashy high flows may also face highly uncertain streamflow measurements at the high flow end of the rating curve, leading to additional sources of uncertainty. While a sensitivity analysis of uncertainty propagation in streamflow is beyond the scope of this paper, our analysis highlights many areas in the United States where current methods are poorly suited to capture low-flow conditions.

Methodological challenges and crowd-sourced recommendations for measuring streamflow in low-flow conditions

Three general categories of methods comprise the toolbox available to most practitioners. These include: (1) velocity-area methods; (2) tracer-based methods using salt or dye; and (3) measuring stage at a known streambed geometry (e.g., flume or weir) or capturing flow at a channel constriction (WMO 2010). Most methods tend to be inaccurate or unusable under low-flow conditions (Hamilton 2008) for three reasons: (1) low water velocities and/or shallow water depths (Fig. 2A,B), (2) mobile streambeds and/or irregular channels (Fig. 2D,E), and (3) high proportions of flow in the subsurface (Fig. 2C–E).

Many streams transition from visible surface water flow to very slow or imperceptible movement of water, which is sometimes spatially discontinuous or pooled. Low velocities can lead to poor tracer mixing and recovery when using dilution gaging methods (Fig. 2A). High channel width-to-depth ratios (i.e., very wide channels with shallow water) can also lead to poor tracer mixing and the inability to fully submerge velocimeters (Fig. 2E). Furthermore, highly variable bed elevations (e.g., rocks and boulders) or emergent vegetation can further reduce the accuracy of velocity measurements and even render them impossible (Fig. 2D). Finally, estimates of discharge based on velocity-area methods only measure surface-water flow and therefore are not directly comparable to tracer-based estimates, which capture some subsurface flow. This is particularly relevant in low-flow conditions which often exhibit a greater proportion of hyporheic flow. These general problems are not mutually exclusive; indeed, multiple issues can arise in low-flow settings, leaving practitioners unsure about which method to use and leading to considerable uncertainty in low-flow measurements.

Given these challenges, we present a DST that reflects our collective experience working in low-flow systems, and describes how we approach applying existing discharge methods given the complicating factors that dominate low-flow systems (Fig. 3). The aim of the DST is to offer guidance on a systematic way to apply consistent methods to complex systems. This tool assumes the chosen location is the best available site (i.e., there are no better sites within a reasonable distance upstream or downstream) and highlights what conditions should be avoided in site selection. The DST is not intended to be a data-driven study on the optimal way to measure low flows, rather it is offering informed opinions on what methods tend to work best in specific contexts from experts who frequently attempt flow measurements under non-ideal conditions. In compiling the DST, we also highlight conditions where method development should be prioritized, which we hope catalyzes further discussion and method advances within the water resource community.

The initial bifurcation in this DST separates sites by whether water is visibly flowing or not (Fig. 3). We define visible flow as whether material in the water (e.g., leaves) can be observed moving downstream. If there is no visible movement, fewer options exist to measure flow. If streamflow is visible, the DST prompts a series of questions regarding channel cross-section and water depth to help practitioners identify the most suitable flow measurement for their site (Fig. 3). We acknowledge that the pathways and nodes are not equally likely to be encountered. For example, very few locations have natural constriction points for which the bucket method is suitable (Fig. 2F), even though it appears twice (Fig. 3). Furthermore, three nodes terminate in "no widely used methods." In our experience, the majority of sites where we work (numbering in the dozens, examples in Fig. 2) fall into nodes characterized by "no widely used method" for at least part of the year, leaving us unable to accurately measure hydrologic fluxes and limiting subsequent analyses like long-term nutrient flux estimates. While this DST can be used to help practitioners identify the best possible methods, we acknowledge that under many low-flow conditions, even a recommended method can lead to suboptimal discharge measurements with relatively high error.

Selecting a method to measure discharge requires practitioners to identify the degree of precision needed for their study and consider trade-offs between precision and resource costs. For some studies, hydrologic parameters that are easier to measure—like depth, wetted width/area, or approximate flow state—may be sufficient (Jaeger et al. 2023). In contrast, biogeochemistry studies for which water movement is a key variable for calculating nutrient loads (Gómez-Gener et al. 2021) may require greater precision than studies focused on aquatic habitat. Other trade-offs, including personnel costs, measurement frequency, and available time to conduct a measurement may outweigh the scientific considerations given in Fig. 3. At low but visible flows, dilution gaging can be

Fig. 2. Photos of different low-flow conditions that lead to difficulty implementing established discharge methods. The colors outlining each photo corresponds to a box in the decision support tool. (**A**) Slackwater with no visible flow, Blue River headwaters, Oklahoma, photo: Amy Burgin. (**B**) Stage less than 10 cm deep, South Fork of King's Creek headwaters (subwatershed N02B), Kansas, photo: Amy Burgin. (**C**) A channel that can be modified to use a portable flume, Bohner Creek, McMurdo Dry Valleys, Antarctica, photo: Anna Wright (**D**) Large substrate leading to bed elevation variability greater than 50% of channel depth, tributary to Wolverine Creek, Alaska, photo: Hannah Richardson. (**E**) Threaded channels, Hassayampa River, Arizona, photo: Raphael Mazor. (**F**) A natural constriction in a channel suitable for using a bucket method, Dry Creek, Idaho, photo: Mac Beers.

used but may take hours to days, rather than minutes to an hour required at moderate to high flow conditions. In addition, dilution gaging at low flows often results in non-optimal breakthrough curves from incomplete mixing that are not suitable for discharge estimates. Portable flumes/weirs are faster to implement but require modifying the channel, for example manually creating berms to concentrate flow through a flume (Fig. 2C), which may not be possible for many reasons. While the DST provides recommendations for general categories of measurement methods, further modifications of each method can help accommodate specific flow conditions (e.g., different variations on the application of dilution gaging; Table S1). We provide suggestions for situations where modifications of standard methods may be desirable, and further challenges in applying those modifications in Table S1.

Where do we go from here?

In streams and rivers, streamflow is the underlying physical template structuring biotic and abiotic processes, biogeochemical cycling, and ecological communities. Discharge is used to assess the degree of connectivity between tributaries and quantify movement of solutes through a stream network.

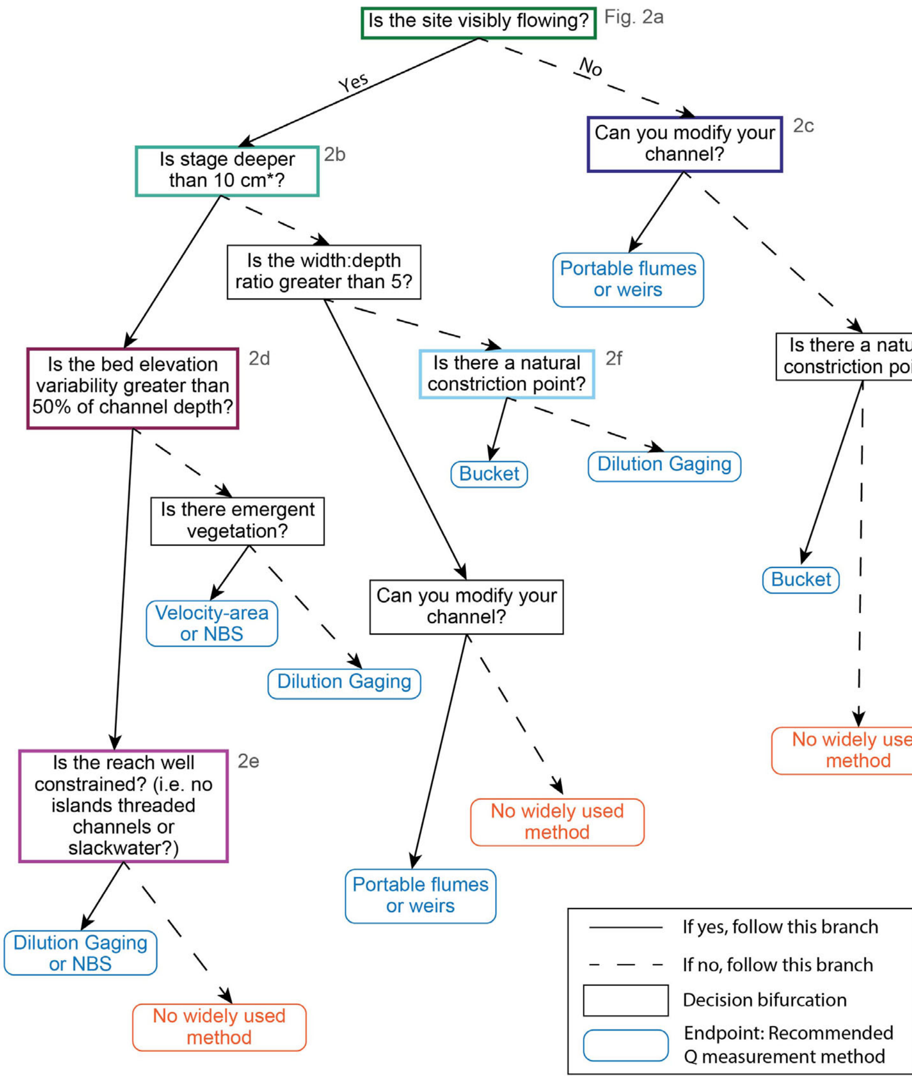

Fig. 3. Decision support tool for identifying a method of streamflow measurement in challenging low-flow conditions. This assumes the user has identified the best available site. Each box asks a question to characterize the site and narrow down available methods. Boxes outlined in light and dark green, blue, and maroon correspond to the color-coding on example photos in Fig. 2 and are labeled with the corresponding panel letter from Fig. 2. Rounded blue boxes are endpoints of the tool, suggesting a discharge measurement method: dilution gaging, neutrally buoyant spheres (NBS), velocity–area, portable flumes, and filling a bucket or other vessel. Rounded red boxes are endpoints of the tool where conditions are such that the authors believe there is no suitable widely used method of measuring streamflow. The asterisk (*) indicates a point of clarification: we provide an approximate numerical threshold of 10 cm for this note; this roughly corresponds to three times the vertical resolution of most acoustic doppler velocimeters, and as such the minimum depth that can accurately measure using the 0.6 × depth method (Turnipseed and Sauer 2010).

Time series of discharge are key inputs for models of aquatic ecosystem function and biogeochemical cycling, and the desired output of hydrologic models identifying factors driving streamflow and predicting responses to anthropogenic change. All of these applications require accurate discharge measurements across the full range of flow variability.

While there is no universal answer to the question of "what percent error is acceptable when measuring low flows," we argue the general need for a high degree of accuracy is clear. Although absolute changes in streamflow in low-flow systems may be small (e.g., changes from 0.01 to 0.02 m^3/s), this represents a large relative change within the system (100%). Small changes in discharge at low flows can have substantial consequences for habitat extent and suitability (Rolls et al. 2012). Detection of long-term trends is hampered by imprecise or uncertain data, which may cause trends in vulnerable low-flow systems to go unquantified (Whitfield and Hendrata 2006). Environmental flow regulations require precise data for enforcement (Neachell and Petts 2019), and uncertain low-flow data can complicate implementation and enforcement. Finally, there are many systems ranging from large, arid rivers to small streams where difficult-to-measure low-flow conditions are the norm and thus prevent accurate streamflow measurements across the flow-duration curve, leaving sites with minimal data for research and management purposes. Although low flows may represent a smaller component of annual water or solute fluxes than high flows in many systems, they are critical for understanding and predicting hydrological, ecological, and biogeochemical dynamics in river systems. This is not possible without robust low-flow discharge measurements.

In addition to providing guidance for systematically deciding which methods to employ in determining low-flow discharge, our DST (Fig. 3) highlights areas of critical need for method development and uncertainty assessment. In some cases, further modification and optimization of existing methods may be sufficient (e.g., Table S1). However, there are conditions for which entirely new methods need to be developed or refined, such as: (1) slackwater pools (Fig. 2A); (2) wide, shallow, irregular, or threaded channels (Fig. 2E), particularly in locations with no opportunity for channel modification; (3) reaches with dense emergent vegetation; and (4) reaches where wind strongly affects water surface velocities. These conditions are commonly found in freshwaters but share similarities with coastal settings, opening up the potential for method transfer to/from coastal hydrology (e.g., Birgand et al. 2022).

There are promising recent technological advances including micro velocity sensors (Osorno et al. 2018), time-lapse imagery analysis from trail cameras and videos (Birgand et al. 2022; Chapman et al. 2022; Dolcetti et al. 2022) or radar altimetry (Bandini et al. 2020), and presence/absence sensors for measuring water surface extent (Chapin et al. 2014;). Emerging tools like time-lapse imagery analysis and water presence/absence sensors may improve our understanding of the spatiotemporal variation in the hydrologic state of low-flow systems by providing an assessment of surface water presence at the time of streamflow measurements, or in the absence of suitable discharge measurement approaches. However, more work must be done to advance these methods because as of now they only estimate stage or water presence/absence, leaving the difficulties of estimating discharge unresolved. Finally, there may be settings in which modeling or mathematical relationship development may be the best option (Gao et al. 2021). We suggest a concentrated effort on uncertainty assessment and method development is urgently needed, as there are numerous settings for which there is no current viable method for measuring streamflow.

Methods development for accurate low-flow measurements will be critical as environmental change accelerates, leading to increased hydrologic variability and shifts to low flows around the world. To better manage future trade-offs among water uses, managers will require accurate data on streamflow under low-flow conditions. To achieve this, we need methodological flexibility to capture extreme flow conditions, including at low flows. Without improvements, we will not be able to sustain existing long-term streamflow records that can help us predict the continuing trajectories of environmental change. Understanding and managing shifts in water resources will be critical for ensuring habitat integrity, promoting good water quality, and safeguarding sustainable water access. The first step is ensuring consistent high-quality flow measurements in these vulnerable systems.

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