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OVERVIEW

Zero or not? Causes and consequences of zero-flow stream gage readings

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Abstract

Streamflow observations can be used to understand, predict, and contextualize hydrologic, ecological, and biogeochemical processes and conditions in streams. Stream gages are point measurements along rivers where streamflow is measured, and are often used to infer upstream watershed-scale processes. When stream gages read zero, this may indicate that the stream has dried at this location; however, zero-flow readings can also be caused by a wide range of other factors. Our ability to identify whether or not a zero-flow gage reading indicates a dry fluvial system has far reaching environmental implications. Incorrect identification and interpretation by the data user can lead to inaccurate hydrologic, ecological, and/or biogeochemical predictions from models and analyses. Here, we describe several causes of zero-flow gage readings: frozen surface water, flow reversals, instrument error, and natural or human-driven upstream source losses or bypass flow. For these examples, we discuss the implications of zero-flow interpretations. We also highlight additional methods for determining flow presence, including direct observations, statistical methods, and hydrologic models, which can be applied to interpret causes of zero-flow gage readings and implications for reach- and watershed-scale dynamics. Such efforts are necessary to improve our ability to understand and predict surface flow activation, cessation, and connectivity across river networks. Developing this integrated understanding of the wide range of possible meanings of zero-flows will only attain greater importance in a more variable and changing hydrologic climate.

This article is categorized under:

Science of Water > Methods
Science of Water > Hydrological Processes
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KEYWORDS

aquatic network, non-perennial, stream gages, streamflow, zero flow

1 | INTRODUCTION

Hydrometric networks are fundamental to predicting and monitoring floods and allocating resources to support human and ecosystem water needs (Ruhi, Messager, & Olden, 2018). It is therefore unsurprising that most streamflow gages are installed on large, perennial streams worldwide (Fekete & Vörösmarty, 2002; Poff, Bledsoe, & Cuhaciyan, 2006). Approximately 3% of the 9,322 US Geological Survey (USGS) gages in the contiguous United States are located on streams with seasonally prolonged zero-flow readings, and 10% have recorded zero-flow for at least 1 day in their period of record (Figure 1b, GAGES-II: Falcone, Carlisle, Wolock, & Meador, 2010). At the global scale, ~20% of the 8,875 gages in the Global Runoff Data Center (GRDC) network (excluding contiguous U.S. coverage) have zero-flow readings in their daily record (Figure 1c). Non-perennial rivers and streams comprise >50% of the global river network (Datry, Bonada, & Boulton, 2017), and are generally underrepresented in-stream gage networks. Despite this under-representation, the presence of zero-flow readings from existing gage networks provides an opportunity to describe and understand the hydrology of both perennial and non-perennial streams.

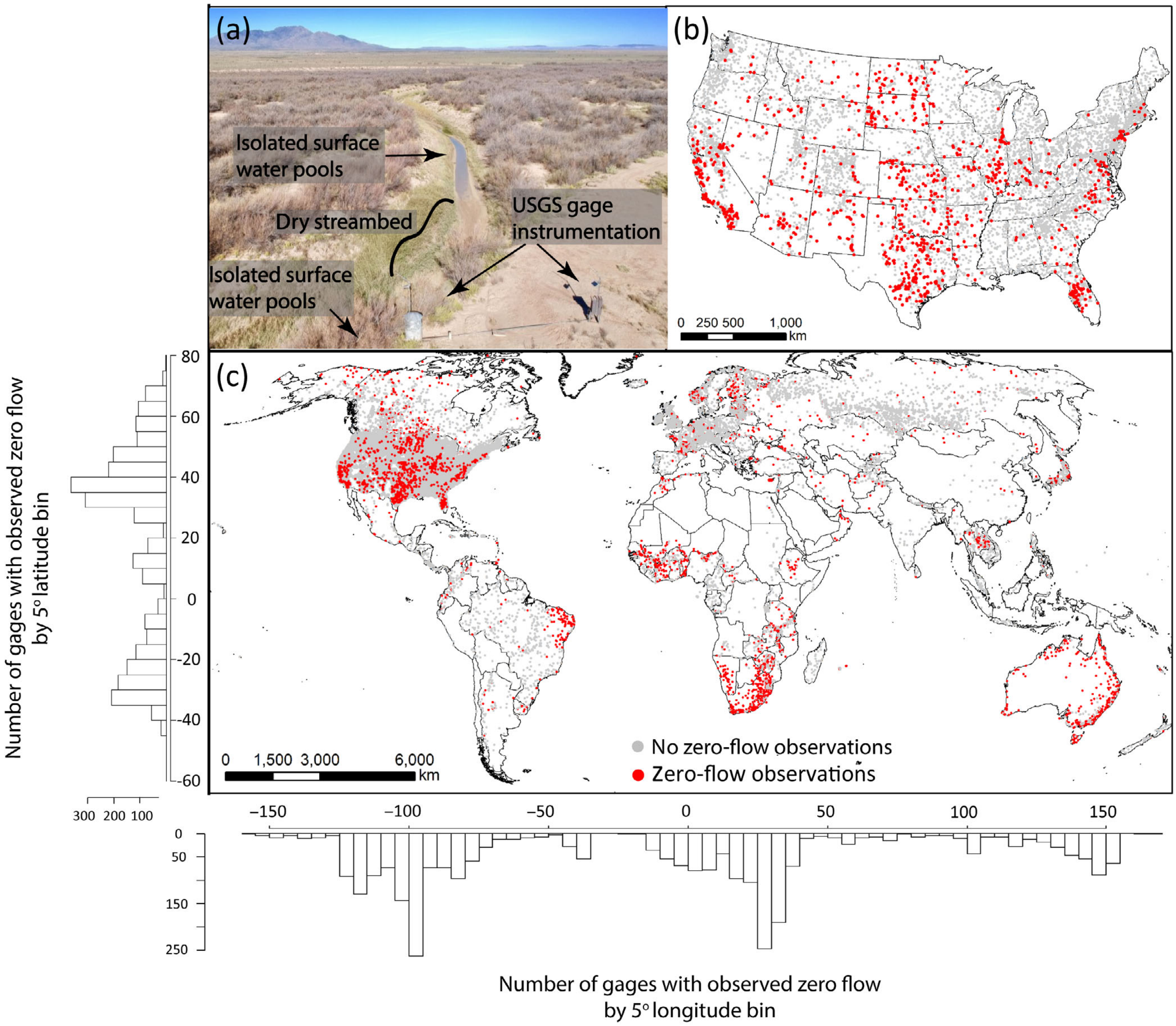


FIGURE 1 (a) An example of a zero-flow gage reading in which isolated surface water pools are present at and around gage instrumentation (USGS site: 08353000), (b) USGS gages with daily flow observations, and (c) All USGS gages plus GRDC (excluding United States where USGS gages are shown) with daily flow observations. Gray circles represent gages with no recorded zero-flow observations and red circles represent gages with at least one recorded zero-flow observation (zero-flow observation defined as 0 daily mean flow at stream gage). Photo credit: DryRivers Research Coordination Network work group, taken September 25, 2019

Zero-flow readings can be caused by multiple scenarios (Figure 2, Table 1); untangling these potential scenarios requires high-quality long-term datasets that incorporate periodic zero-flow readings. Measurement procedures and quality-assurance/quality-control (QA/QC) protocols vary by organization, with the USGS and World Meteorological Organization providing detailed guidance on stream gaging (WMO, 2010), field measurements (Sauer & Turnipseed, 2010), and data QA/QC (e.g., Painter & Loving, 2015; Sauer, 2002). Researchers around the world use USGS data because they are recognized for their high quality due in large part because of the rigorous data review process prior to release. In this study, we leverage examples predominantly from USGS gaging stations to illustrate patterns in zero-flow observations in time series data that may be evident in less strictly reviewed data. In the simplest case, a record of zero-flow at the gage indicates the true lack of flowing water at the gage and, presumably, upstream in the basin (Figure 2, "Natural Drivers"). This is a natural phenomenon across river networks in arid and semiarid landscapes and in low-order streams in humid regions (Buttle et al., 2012; Goodrich, Kepner, Levick, & Wigington, 2018; Jensen, McGuire, McLaughlin, & Scott, 2019), and can occur due to transmission losses and evapotranspiration that result in isolated

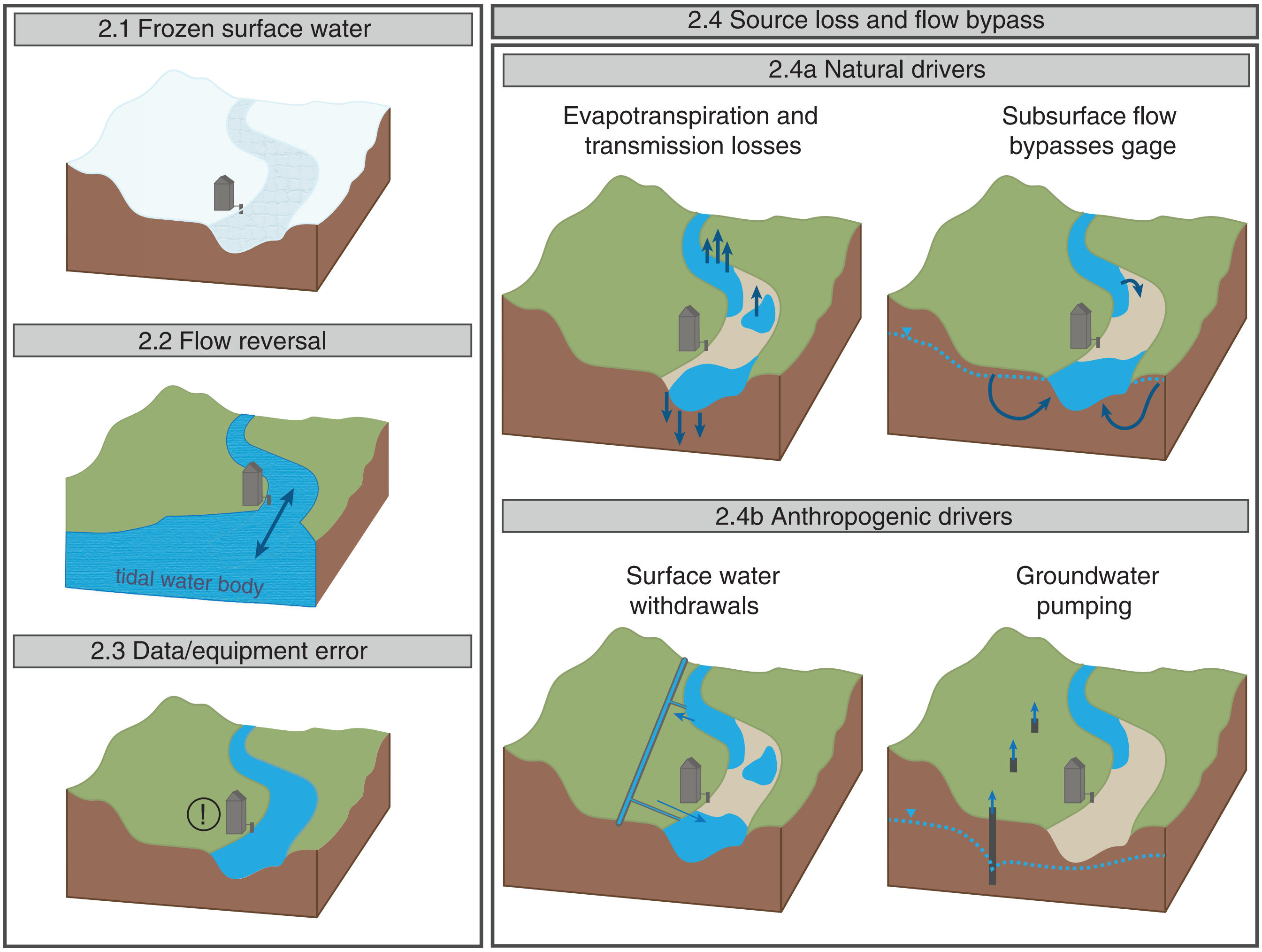


FIGURE 2 Common scenarios of zero-flow readings at gages, as outlined in Section 2. Scenarios 2.1–2.3 (left panel) can produce a zero-flow reading despite the presence of water; Scenarios 2.4a and b (right panel) produce zero-flow readings, but have variable drivers and implications for local and network-scale stream ecosystems and hydrology. Figure order does not imply prevalence on the landscape

surface water and subsurface flow bypass. Anthropogenic influences such as surface and groundwater abstraction can also cause zero-flow (Figure 2 "Anthropogenic Drivers"). However, zero-flow readings when there is water flowing at the gage can also occur due to frozen surface water, flow reversals, and equipment uncertainty and error (Figure 2). It is often challenging to reconcile these different causes from flow observations alone.

Identifying the causes of zero-flow readings may help end users of these data improve their interpretations of hydrologic, biogeochemical, and ecological conditions of rivers. Different causes of zero-flow have different consequences for ecological processes during zero-flow periods and once flow resumes. For example, after periods with no surface flow, flow resumption can export large pulses of inorganic and organic nutrients and carbon (Shumilova et al., 2019) and produce a pulse of organic matter processing and CO_2 emissions from a rewetted river (Datry et al., 2018). In cases where upstream sources of organic matter and other resources are drained by non-perennial streams, the pulse may continue for the entire flow duration (Hosen, Armstrong, & Palmer, 2018). Thus, the concentrations and forms of those materials will vary depending on the duration and nature of low- or zero-flow conditions. The impact of zero-flow on biological communities also depends on the drivers of zero-flow. The presence of remnant surface water pools, hyporheic zones, or nearby perennial water bodies can provide refugia for aquatic taxa, facilitating community recovery after surface flow resumes (Adams & Warren, 2005; Bogan et al., 2017; Vorste, Corti, Sagouis, & Datry, 2016). Therefore, distinguishing causes of zero-flow events is critical to accurately understand and manage water resources and associated ecosystems (Table 1).

Here, we posit that our ability to accurately interpret gage-measured surface flow has important consequences for how we understand, model, and describe related hydrologic, biogeochemical, and ecological processes in intermittent

TABLE 1 Types of zero-flow readings at gages illustrated in Figure 2 as well as indicators and contextual data that can be used to identify causes and consequences of these zero-flow readings

Type	Scenario	Cause	Indicators/contextual data	Consequences
Zero-flow gage readings not related to channel drying	Frozen surface water	Equipment is embedded in ice while flow persists	Temperature, temperature profiles, photography, video, and post facto flood pulse at ice break-up	End user interpretation of zero-flow may alter interpretation of water chemistry, sediment loads, basin water yields, and organism dispersal
	Flow reversal	Tidal system, seiche	Velocity profiles, lunar data, weather data (e.g., wind), and stage height	
		Land use change	Land cover GIS, digital elevation models (DEMs)	
		Inter-basin transfers	Withdrawal data (management agencies)	
	Data/equipment error and uncertainty	Sensor fouling and drift	Time-series analysis, calibration comparisons	
		Platform failure	Instrument reports error, power loss, and loss of telemetry	
Surface flow in network but not at gage due to natural processes	Isolated surface water pools	Hyporheic flow between surface water pools persists, but gage reads zero when located out of pools	Remote sensing, DEMs, and geomorphological surveys	Spatial extent of zero flow and surface water unknown, which can lead to difficulty in assessment of implications for organismal distributions and connectivity, biogeochemical processes, and fluxes
	Flow bypasses gage	Flow persists, but reads zero due to position along channel or channel migration	Hydrography datasets, DEMs, and geomorphological surveys	
Surface flow in network but not at gage due to anthropogenic processes	Surface water diversion	Flow persists upstream and downstream but water has been withdrawn, or diverted around the gage site	Remote sensing, agency data for water abstraction, proximity to water storage and transmission infrastructure, and land use/land cover data	
	Groundwater pumping	Flow may persist upstream and/or downstream of the gage site, but groundwater pumping has eliminated groundwater contributions to flow at the gage site, causing a stream to dry	Agency data for water abstraction, groundwater wells/piezometers, and land use/land cover data	

and perennial streams. First, we present the potential causes of zero-flow gage readings (Section 2). Next, we explore the importance and hydrologic, ecological, and biogeochemical implications and consequences of these zero-flow observations (Section 3). Finally, we discuss methods for determining streamflow presence (Section 4), including direct observation (Section 4.1), statistical methods (Section 4.2), and hydrologic models (Section 4.3). Flow measurements provide a critical source of data for hydrologists, ecologists, water managers, and policy makers; this article aims to enhance our understanding of the significant portion of global waterways that flow intermittently, but are perennially important.

2 | CAUSES AND INDICATORS OF ZERO-FLOW STREAM GAGE READINGS

We present scenarios in which factors other than complete channel drying cause zero-flow gage readings (Sections 2.1–2.3) as well as scenarios in which loss of surface flow at a specific gaging station may not reflect upstream or network-scale conditions (Section 2.4). For these scenarios, we provide examples from USGS gage stations, U.S. field research stations, and international gaging networks. We also highlight possible catchment or aquatic system indicators that can be used in conjunction with flow observations to determine causes of zero-flow readings.

2.1 | Frozen surface water

Ice typically forms first at the water surface, blocking the water-atmosphere interface, but often allowing flow to continue beneath the frozen surface (Figure 2a; Beltaos & Prowse, 2009). Below-ice discharge is difficult to measure, and therefore determining flow conditions, including whether flows have dried or completely frozen, can be challenging (Melcher & Walker, 1992). If flow cannot be safely or accurately measured, flows are typically estimated (Fulton et al., 2018; Melcher & Walker, 1992; Hamilton & Moore, 2012; Sauer & Turnipseed, 2010), and especially in very cold regions, long periods of inferred zero flow may be reported after the river profile has been observed to completely freeze (Figure 3a). A zero-flow reading is likely due to disruption of equipment by ice or because of fully frozen, no-flow conditions or when downstream ice-jams cause upstream backwater effects (Beltaos & Prowse, 2009; Spencer, 1910). In this section, we discuss USGS measurements and related documentation because of their high quality measurements, derived data products, and QA/QC protocols, as well as studies that assess associated uncertainties. For example, USGS reports the uncertainties associated with data quality codes (e.g., "poor" quality represents >8% measurement error, "fair" as 8%, good as 5%, and excellent as 2%). Other data products without similarly rigorous procedures likely have larger errors and uncertainties associated with their reported discharge values.

Ice is a prevalent feature in our global river networks; for example, more than half of USGS gaging stations are affected by ice during a portion of the winter months (Melcher & Walker, 1992), and thus data users should interpret such readings with care. Detection of ice presence is typically based on direct observation, including drone use, or indirectly detected based on temperature readings. The USGS typically flags ice-affected flow measurements using the USGS

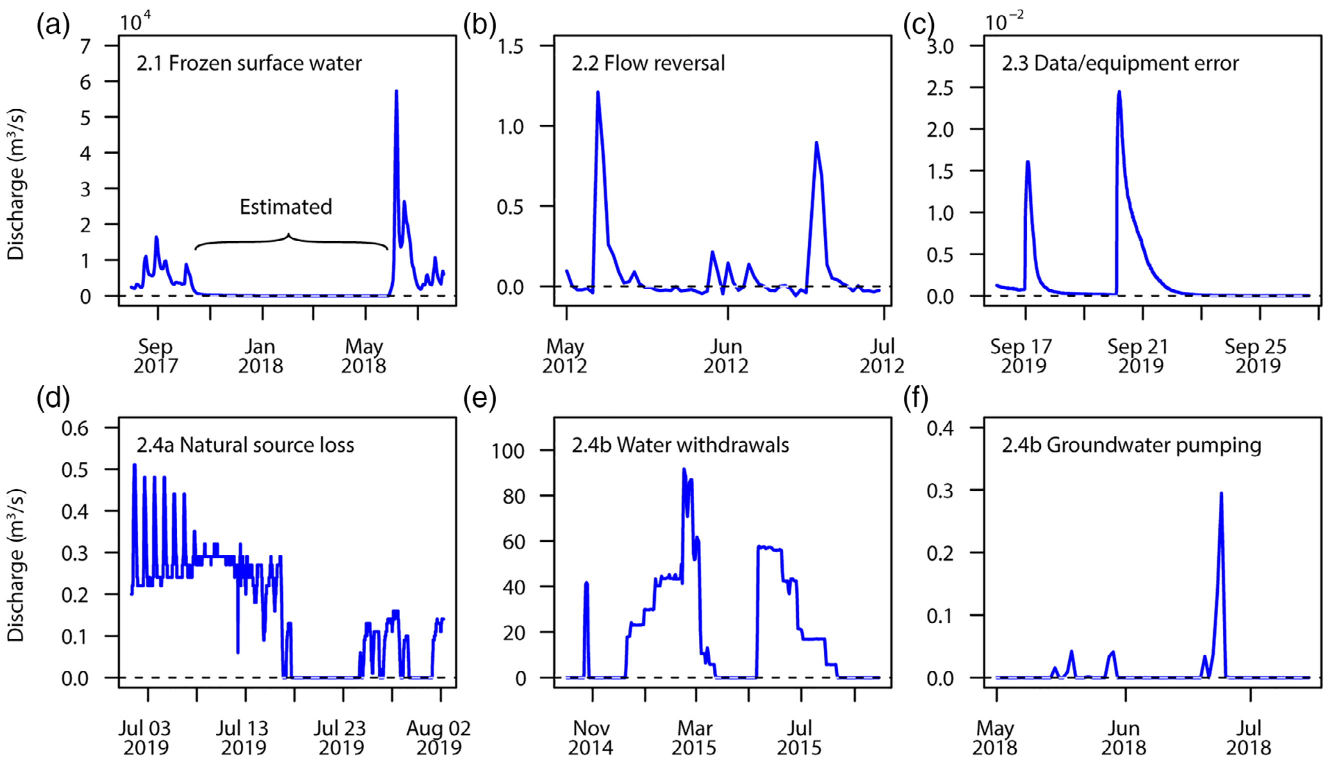


FIGURE 3 Examples of daily hydrographs displaying zero-flow readings. (a) Kuparuk River, near Deadhorse, AK (USGS site: 15896000), (b) Berger Ditch near Oregon, OH (USGS site: 04194085), (c) Rio Puerco near Bernardo, NM (USGS site: 08353000, provisional data downloaded September 26, 2019), (d) Agua Fria River Near Mayer, AZ (USGS site: 09512500, provisional data downloaded Sep. 26, 2019), (e) Snake River near Milner Dam, ID (non-USGS gage), and (f) Arkansas River at Garden City, KS (USGS site: 07139000). Subplot subtitles indicate the associated zero-flow scenarios as illustrated in Figure 2. Data source: U.S. Geological Survey, 2019

Quality Code of "Ice" and rates the accuracy classification as "poor" (Fulton et al., 2018). Ice break-up is generally easier to identify than ice freeze-up due to a characteristic spike in the hydrograph (Figure 3a); post hoc corrections of ice-affected flow conditions can be useful. When ice is present, USGS gage records typically do not report stage measurements, and flow data are either unreported, estimated by the gage operator, or directly measured. Direct measurement of sub-ice flow involves drilling through surface ice at specified intervals and measuring sub-ice flow velocity and geometry to calculate flow. If site access is possible, USGS protocols suggest monthly to bimonthly sub-ice measurements (Boning, 1994). USGS flow measurements that are ice-affected may also contain the USGS Quality Code of "Provisional" and should be carefully interpreted by the user. For example, the field measurement that occurred during the flow conditions in Figure 3a was rated as poor with uncertainty of >8%. Direct communication with technicians who are operating gaging stations may help determine the accuracy of reported zero-flow conditions.

Seasonally frozen rivers and streams are widespread at high latitudes and elevations (Bennett & Prowse, 2009). Ice can impact a range of important hydrologic, geomorphic, ecologic, biogeochemical, and socioeconomic functions of rivers (Prowse, 2001a, 2001b). River and stream ice can be studied using climate and land surface models (e.g., Brooks, Prowse, & O'Connell, 2013; Park et al., 2016), optical and microwave remote sensing (Brakenridge, Nghiem, Anderson, & Mic, 2007; Yang, Pavelsky, & Allen, 2020), and in situ observations, including stream gage records (Rokaya, Budhathoki, & Lindenschmidt, 2018). Sources of publicly available, in situ ice occurrence data include USGS and Water Survey of Canada stream gage records and the United States National Weather Service direct ice observation records. Ice presence and thickness indicators are usually based on air temperature and other factors, including latitude, precipitation, elevation, and waterbody size (Brooks et al., 2013; Park et al., 2016). However, there has not been a focus on quantifying the accuracy of zero-flow readings associated with ice over large regions. Uncertainty in flow estimates typically increases during ice conditions, but can be reduced by established approaches (e.g., Fulton et al., 2018; Melcher & Walker, 1992; Sauer & Turnipseed, 2010), including measuring temperature profiles from the ice surface to the channel bed or direct measurement of sub-ice flows, if present.

2.2 | Flow reversals

Rivers are typically viewed as systems with unidirectional flow; however, flow reversals can occur naturally in estuarine and lacustrine environments, which can lead to possible misinterpretation of zero-flow readings at nearby gages as dry channel conditions (Table 1; Figure 2b). For instance, tributaries to large inland lakes can produce zero-flow observations during seiche events when downstream flow is equally countered by upstream flowing water from the lake. Strong winds and rapid changes in atmospheric pressure push water across the lake during seiches. After the wind stops, the water continues to oscillate back and forth for hours to days depending upon the magnitude of the initiating winds, dampening from the basin, and/or opposing meteorological forces (Korgen, 1995). Because of their large sizes, seiche effects on tributaries have received much attention on the Laurentian Great Lakes, particularly in Lake Erie and its eastern and western tributaries where large water level changes can occur there due to the shallowness and orientation of the lake relative to the direction of prevailing winds (Bedford, 1992; Mortimer, 1987). For example, Berger Ditch is a channelized perennial tributary (~40 km^2) with its gage positioned 1.6 km upstream of Lake Erie near Oregon, Ohio. Over a representative 2-month period (61 days), flow frequently oscillated between above 0 m^3/s (30 days) and below 0 m^3/s (31 days; Figure 3b).

In most cases, stage height, if the gage datum is known, can differentiate flow reversals from dry channel conditions. Negative flow values will also indicate the occurrence of flow reversals where velocity meters are used to measure flow (Gotvald & Oberg, 2008; Ruhl & Simpson, 2005). Zero-flow readings that occur briefly between positive and negative flow can be inferred as periods of slack water. Other sources of information useful to confirm flow reversal include coinciding data for water level, tide timing, or any water physicochemical (e.g., specific conductivity and salinity) data reported at the gage (Table 1).

2.3 | Data/equipment uncertainty

Streamflow can be quantified using a range of methods (e.g., volumetric, velocity-area method, slope-area method, and tracer-dilution method), which vary in suitability for different environments and purposes. Additionally, there are different methods for characterizing the duration, frequency, and timing of flow (Bhamjee & Lindsay, 2011; Kaplan, Sohrt, Blume, & Weiler, 2019). However, most of these measurements require information on water stage, open channel flow velocities, and the relationship between water level and streamflow (i.e., rating curves). Errors or lack of information in these three components may lead to uncertainty in low- and zero-flow gage readings. In this section, similar to previous sections, we discuss USGS measurements and related documentation.

Pressure transducers are a widely used instrument for measuring water stage at gages, but they have uncertainties related to internal temperature compensation (Sorensen & Butcher, 2011), exposure to sunlight (Cain, Davis, Loheide, & Butler, 2004), measurement and clock drift (Post, Banks, & Brunke, 2018; Rau et al., 2019; Sorensen & Butcher, 2011), and large changes in salinity (Post et al., 2018). Another potential source of error is calibration drift through periods of wetting and drying, issues with barometric pressure correction for non-vented pressure transducers, or from interference when affected by algae and vegetation at the intake to stilling wells. In addition to these sources of equipment error, stage measurements can suffer from error due to the location of gaging infrastructure. For example, the gage datum is often designated at an elevation below the streambed surface to avoid negative values (Sauer & Turnipseed, 2010), which can add uncertainty to using stage as an indicator of zero-flow conditions. While some gage locations may be driven by cooperating agencies' interests in particular locations (e.g., USGS cooperating state or local agencies who provide funding for station maintenance), many gaging stations are placed on straight, incised, single-threaded channels, and positioned to minimize the influence of channel bed changes (Juracek & Fitzpatrick, 2009). This may introduce spatial biases in the representation of zero-flow when different geomorphic conditions are present in the reaches upstream or downstream of the gage. It should also be noted that the location of gages can change due to a wide variety of reasons and is a widespread issue when working with long time-series datasets. For example, an estimated 33–50% of USGS gages have changed their datum and/or location over their period of record (Wilby et al., 2017), which can introduce temporal bias into zero-flow gage readings. As a result, the spatial representation of gage data can vary over time and must be taken into account by end users of such data.

According to USGS standards (Sauer & Turnipseed, 2010), open channel flow in natural channels should be measured using the velocity-area method every 6–8 weeks as well as during extremely high and low flows when possible. Velocity measurements are typically conducted with current meters (e.g., acoustic Doppler current profiler), but these measurements are hampered by low water depths as flow approaches zero (Soupir, Mostaghimi, & Mitchem, 2009). Uncertainty using the velocity-area method also increases in narrow channels because fewer subsections are measurable, or where water levels in streams are rapidly changing (Tillery, Phillips, & Capesius, 2001). Velocity measurements, like water level measurements, can also be affected by interference from vegetation and algae.

Rating curve uncertainty can be substantial (>10%) for streams that typically have near-zero flows and/or in those where stage height is less sensitive to variation in discharge (wide, shallow channels) than those with deep and narrow channels (Horner et al., 2018). In a review of hydrologic uncertainties, the confidence bounds ranged from ±50 to 100% for low flows, ±10 to 20% for medium-high in-bank flows, and ±40% for out-of-bank flows (McMillan, Krueger, & Freer, 2012). This is primarily a result of two factors; first is the frequency of manual observations. Streams that dry frequently or for long periods are likely to be visited on numerous occasions when flow is zero, in contrast to sites that are infrequently dry. In the latter situation, extrapolation outside the rating curve may be used to define zero flow, resulting in higher uncertainty in differentiating low flow versus zero flow. Second, daily flow values may misrepresent temporal flow averages. For example, the minimum daily reported value for flow at USGS gages is 0.0003 m^3/s (0.01 ft^3/s; Sauer, 2002), so very brief periods of flow can result in a daily value >0.0003 m^3/s (specified as 0.01 ft^3/s). That is, a single 15-min reading of 0.03 m^3/s (1 ft^3/s) over a day that otherwise had zero flow has a mean value of 0.0003 m^3/s.

QA/QC processes are put in place by agencies and individuals to ensure data are collected using consistent methods and have comparable quality across space and time (e.g., Painter & Loving, 2015; Sauer, 2002). Automatic arithmetic and logic checks through data processing software and documentation of QA/QC findings and data revisions are imbedded within the steps used by agencies to produce flow records for gaging stations. Because flow estimations at the lower extremes are particularly susceptible to uncertainty, it is important for measurements in these systems to adopt and adhere to strict QA/QC methodologies (e.g., Painter & Loving, 2015). While it is often preferable or necessary to use recent available data from gaging stations, care should be taken when using provisional data, as zero-flow readings may be updated based on field measurements. For example, provisional data retrieved from the Rio Puerco, New Mexico, United States gaging station indicated flow (Figure 3c), while visual inspection during the same period identified lack of connected surface flow on September 25th, 2019 (Figure 1a). Because isolated pools existed above and below the gaging station in this particular scenario, additional information such as where technicians take discharge measurements relative to the gaging station can help end users determine the site-specific context of zero-flow readings.

2.4 | Source losses

Flow in streams can be activated or sustained by contributions from snowmelt, direct precipitation, both shallow and deep subsurface flowpaths, as well as from human inputs (Dunne & Black, 1970; Nadeau & Rains, 2007). Under natural conditions, surface flow reductions can be generalized into source losses due to seasonal or supraseasonal contribution losses (summer drying and drought), longitudinal flow loss (transmission loss and bypass flow), and diel transpiration losses. Under human-impacted conditions, surface water extraction or groundwater pumping can reduce surface flow. Flow reductions along portions of stream channels challenge the ability to construct accurate water balances of non-perennial stream systems (Shanafield & Cook, 2014; Figure 4). As a result of the spatiotemporal variability of surface flow across fluvial networks, point-scale measurements of flow conditions may not be representative of upstream conditions. Here, we describe zero-flow gage reading scenarios that highlight why understanding spatially variable surface flow reductions across river networks is important when interpreting zero-flow readings at individual gages.

2.4.1 | Natural upstream source loss or flow bypass

In minimally disturbed or natural systems in arid and semiarid climates, source losses are common in catchments that have seasonal precipitation, such as in monsoonal desert systems (Allen et al., 2019) and snowmelt-driven streams (Sando & Blasch, 2015). For example, in the southwest and central United States, non-perennial surface flow can activate in response to rain events (Costigan et al., 2015) and riparian vegetation can quickly transpire in response and drawdown surface flows (Bauer, Held, Zimmermann, Linn, & Kinzelbach, 2006). Streams in the central United State, such as Kansas, Minnesota, and North Dakota, tend to dry in the fall because they are located in basins that have insufficient snowpack to provide meltwater-generated baseflow year round (Buttle et al., 2012; Eng, Wolock, & Dettinger, 2016).

Flow magnitudes can decrease or cease downstream, such as in distributary streams, which are prevalent in arid and semi-arid landscapes (Slatyer, 1969). In some source loss scenarios, surface water lost to downward transmission reemerges as surface flow downstream (Costigan et al., 2015); this is termed bypass flow (Figure 2.4a). For example, Kings Creek (Kansas, United States) has significant natural bypass flow due to subsurface stratigraphy, leading to conditions where the upstream gage may read flow when the downstream gage does not, and vice versa (Figure 4; Costigan et al., 2015).

Zero flow can also be observed on a diel basis, driven by evapotranspiration losses in small streams with low flows (Graham, Barnard, Kavanagh, & McNamara, 2013). For example, at the Agua Fria River near Mayer, Arizona, flow

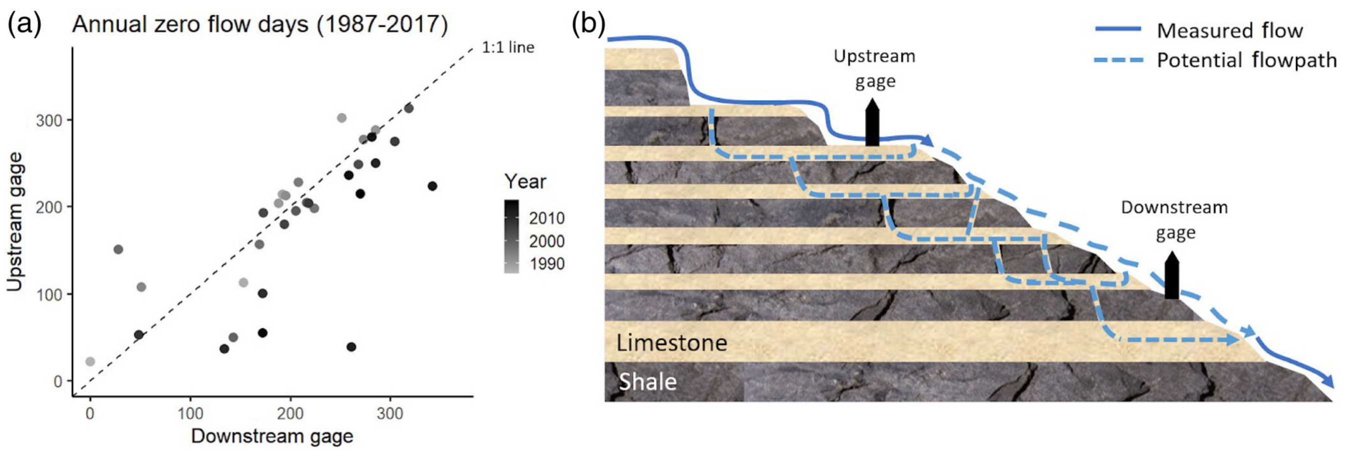


FIGURE 4 Kings Creek, Konza Prairie, Kansas represents a stream where the upstream gage may read flow when the downstream gage does not, and vice versa. (a) Comparison of the number of zero-flow days per year at an upstream gage (watershed N04D) and a downstream gage (USGS gage 06879650) demonstrates some years where the downstream gage has more zero-flow days than the upstream gage, as indicated by the points below the dashed 1:1 line. (b) Conceptualization of the landscape with alternating limestone (more porous) and shale (less porous) subsurface stratigraphy that can route upstream springfed flow around the downstream gage at times. Data in (a) courtesy of the USGS and Konza Prairie Long Term Ecological Research station and (b) is reprinted with permission from Costigan, Daniels, and Dodds (2015)

appears at night when transpiration from riparian cottonwoods decreases, and disappears when cottonwoods take up water during the day (Figure 3d). This diel variation in observed flow might mask the presence of surface flow-disconnected pools that may persist along the channel (sensu Figure 1a). Similarly, a USGS gage on Kiamichi River at Big Cedar, Oklahoma (USGS gage 07335700) reads zero flow frequently in late summer in most years, but stage height still fluctuates during those times, which suggests there is still surface water that might be present in the form of disconnected surface water pools.

While climate and geomorphic indicators can help in identifying bypass flow (e.g., parafluvial flows) or evaporative losses, these indicators are not yet fully characterized across systems. For example, streams with highly transmissive streambeds, subsurface preferential flow paths (e.g., limestone), and/or those in water-limited regions are the most likely to have zero-flow readings (Figure 4; Larned, Datry, Arscott, & Tockner, 2010; Meyer & Meyer, 2000). In alluvial rivers, the longitudinal organization of regional-scale surface water-groundwater interactions can lead to discontinuous surface flow patterns (Capderrey, Datry, Foulquier, Claret, & Malard, 2013; Vander Vorste, Mermillod-Blondin, et al., 2016). In such cases, large amounts of alluvial deposits or other substrate that promote infiltration across river segments could be indicators of natural flow bypass. In addition, diel patterns in flow magnitudes could indicate that in-stream or near-stream vegetation are causing flow loss. Therefore, there are many cases in which streams may naturally lose water upstream or by flow bypass, making network context particularly important when interpreting local gage data.

2.4.2 | Anthropogenically driven upstream source loss or flow bypass

Zero-flow gage readings can also result from upstream human activities that reduce or deplete surface water at the gage (Figures 2.4b and 3e,f). These activities can include direct surface water withdrawals (Deitch, Kondolf, & Merenlender, 2009; Rader & Belish, 1999), withdrawals from interconnected groundwater systems (Barlow & Leake, 2012; Dodds, Gido, Whiles, Fritz, & Matthews, 2004), dam management that results in periods with no flow (Cooney & Kwak, 2013; Steward, von Schiller, Tockner, Marshall, & Bunn, 2012), subsurface or adjacent mining practices that lead to subsidence or sinkhole formation (Landis, 2017; Newman, Agioutantis, & Boede Jimenez Leon, 2017; Starnes & Gasper, 1996), or intra- or inter-basin water transfers that cause some or all flow to bypass the gaging station and even reverse flows (Davies, Thoms, & Meador, 1992). Both irrigation diversions and water transfers can also increase flow magnitudes and durations (Henszey, Skinner, & Wesche, 1991; Laurenson & Hocutt, 1986); though important, this phenomenon is out of the scope of our review.

Direct surface water withdrawals for irrigation and other uses, such as oil and gas development (Maloney et al., 2018), can impact surface flows in both small and large streams and rivers, depending on the size, centrality, and water demand of irrigation projects (Deitch et al., 2009). For example, in 1979, the Idaho State Water Plan formally separated water administration above and below Milner Dam on the Snake River, establishing a "protected" flow of zero at the dam (Idaho State Water Plan, 2012). Although the State Water Plan recognized that zero-flow conditions might not be desirable, it legally allowed for consumptive uses to reduce the river to zero flow above the dam. Contributions from tributary springs and irrigation return flows reconstitute the Snake River downstream of the dam. This produces a flow bypass scenario in which a section of the drainage network was dry, but upstream and downstream sections have surface flow (e.g., Figure 2.4b).

Another prominent example of anthropogenically driven upstream source loss is widespread surface flow depletion caused by groundwater pumping (Barlow & Leake, 2012; Condon & Maxwell, 2019). Groundwater pumping-induced flow depletion is widespread globally, but it is challenging to quantify because it occurs slowly, with reductions in surface flow potentially occurring months to years after the onset of pumping (Gleeson & Richter, 2018; McCallum, Andersen, Giambastiani, Kelly, & Ian Acworth, 2013). In western Kansas, widespread irrigation from the High Plains aquifer since the mid-20th century has resulted in a lower regional water table such that many formerly perennial rivers and streams have transitioned from gaining and perennial to losing and non-perennial (Figure 5; Kustu, Fan, & Robock, 2010).

Indicators of anthropogenic stream drying could include proximity to water infrastructure (e.g., dams and canals), presence of water management organizations or irrigation districts in charge of delivery and regulation of irrigation water, or the amount of irrigated acreage or number of irrigation wells upstream of a gaging station (Table 1). When available, groundwater and surface water withdrawal data are particularly valuable (e.g., USGS National Water Information System database; U.S. Geological Survey, 2019. https://waterdata.usgs.gov/nwis) for step-change and trend

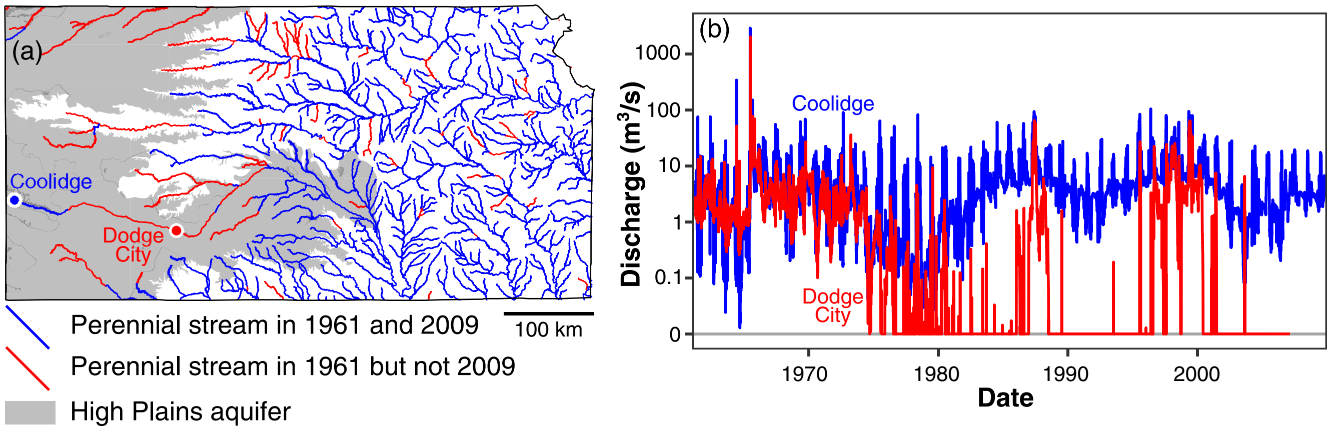


FIGURE 5 (a) Map of Kansas (United States) showing regional transitions from perennial to non-perennial flow between 1961 and 2009 resulting from groundwater pumping from the High Plains aquifer. (b) Time series of discharge (1961–2009) from Arkansas River at Coolidge, KS (USGS gage 07137500) and Arkansas River at Dodge City, KS (USGS gage 07139500) showing increase in zero-flow occurrences through time associated with groundwater depletion between Coolidge and Dodge City. Points in (a) indicate locations of gaging stations plotted in (b). Perennial/non-perennial stream map modified from data used in Kansas High Plains Atlas (http://www.kgs.ku.edu/HighPlains/HPA_Atlas/index.html) and based on data collected and interpreted from Kansas Surface Water Register (Kansas Department of Health and Environment, 2013)

analysis (Kustu et al., 2010). Numerous statistical and numerical modeling approaches could also be used to identify when changes in zero-flow readings are unrelated to changes in climate, indicating a potential anthropogenic driver (Ahn & Merwade, 2014; Khazaei et al., 2019; Zipper, Motew, Booth, Chen, et al., 2018).

3 | BIOGEOCHEMICAL AND ECOLOGICAL CONSEQUENCES OF ZERO-FLOW STREAM GAGE READINGS

Flow dynamics in streams and rivers that exhibit zero-flow gage readings challenge our assumptions of the causes and consequences of hydrologic, biogeochemical, and ecological processes in watersheds. The existence of terrestrial-aquatic interfaces within stream channels that expand and contract vertically, longitudinally, and laterally through time during no flow events calls for a greater integration of knowledge across disciplines to address possible misinterpretations of zero-flow gage readings (e.g., soil science, Arce et al., 2019; meteorology, Costigan, Jaeger, Goss, Fritz, & Goebel, 2016; and geomorphology, Poff, Olden, Pepin, & Bledsoe, 2006). Given that non-perennial streams are estimated to account for at least half of the global river network length (Datry et al., 2017), assessments of hydrologic conditions (e.g., Larned et al., 2011), biogeochemical cycles (e.g., Gómez-Gener et al., 2015, 2016), and ecological functions (e.g., Larned et al., 2010; Leigh, Stewart-Koster, Sheldon, & Burford, 2012) that are sensitive to cycles of wetting and drying should carefully consider potential scenarios of zero-flow conditions. Imperative to this effort is the ability to accurately and objectively identify zero-flow conditions. Below, we identify potential consequences of misinterpretation of zero-flow gage data for ecological and biogeochemical understanding.

3.1 | Frozen surface water

When the entire water column and hyporheic zone of streams freezes and there is no surface flow, gages will record zero-flow readings. These cases often cause dramatic biogeochemical and ecological effects. Biogeochemical process rates in frozen streams are assumed to slow to a near halt when freezing temperatures reduce microbial activity and there is limited hydrologic transport of substrates (Contosta et al., 2017). Many aquatic taxa perish when frozen, but several taxa have strategies to cope with freezing that are comparable to those developed by taxa exposed to drying (Tolonen et al., 2019). For example, communities in Antarctic streams are dominated by taxa adapted to severe freezing, including cyanophytes such as *Phormidium*, *Oscillatoria*, *Nostoc*, and *Gloeocapsa*; chlorophytes such as *Binuclearia*, *Prasiola*, and *Tribonema*; and the pennate diatoms *Navicula* and *Hantzschia* (Howard Williams, Vincent, Broady, &

Vincent, 1986). However, there are instances when streams may not be entirely frozen, despite gage readings of zero-flow (Beltaos & Prowse, 2009). In these cases, ice formation on the surface of streams may interfere with instruments, leading to a zero-flow estimate even though there is flow beneath the ice. Some gage networks provide quality control to ensure accurate readings when ice is present. The USGS, for example, will either take flow measurements directly or leave data unreported. However, in the case of ice formation, provisional data may represent zeros, which if not properly evaluated by the data user can lead to imprecise estimation of the biogeochemical and ecological implications of ice formation (also thereby underscoring the need for caution in using provisional data). For example, dissolved oxygen levels in water flowing under surface ice will decline over time (Prowse, 2001b), a biogeochemical change that may not be anticipated if zero flow is recorded. In addition, surface ice can prevent gas evasion (e.g., carbon dioxide flux to the atmosphere), leading to the accumulation of biogenic gases in stream water (Campeau, Lapierre, Vachon, & del Giorgio, 2014) and introducing uncertainty in annual gas flux estimates. Surface ice formation can also induce higher fluxes into the hyporheic zone, potentially enhancing surface water-groundwater exchange (Weber, Booth, & Loheide, 2013). With incomplete understanding of the extent of ice formation and amount of flow during periods of zero-flow gage readings, the role of ice as a driver of biogeochemical and ecological processes may be misrepresented.

A misinterpretation of zero-flow due to incomplete stream freezing may also have implications for our understanding of whether ice formation has impacted local stream biodiversity across wide geographical gradients where in-person validation is not possible. Surface-ice formation can cause direct mortality of aquatic invertebrates and trigger mass dispersal of fish and invertebrates away from freezing fronts (Irons, Miller, & Oswood, 1993; Prowse, 2001b; Tolonen et al., 2019). Many aquatic taxa can survive surface-ice formation, at least in the short term, by moving to unfrozen refugia, including nearby springs where water generally remains ice-free and water temperatures are more stable due to the thermal influence of groundwater, or by burrowing into streambed sediments (Tolonen et al., 2019). Thus, the precise ecological and biogeochemical implications of zero-flow readings in colder climates that can be influenced by ice formation are context dependent.

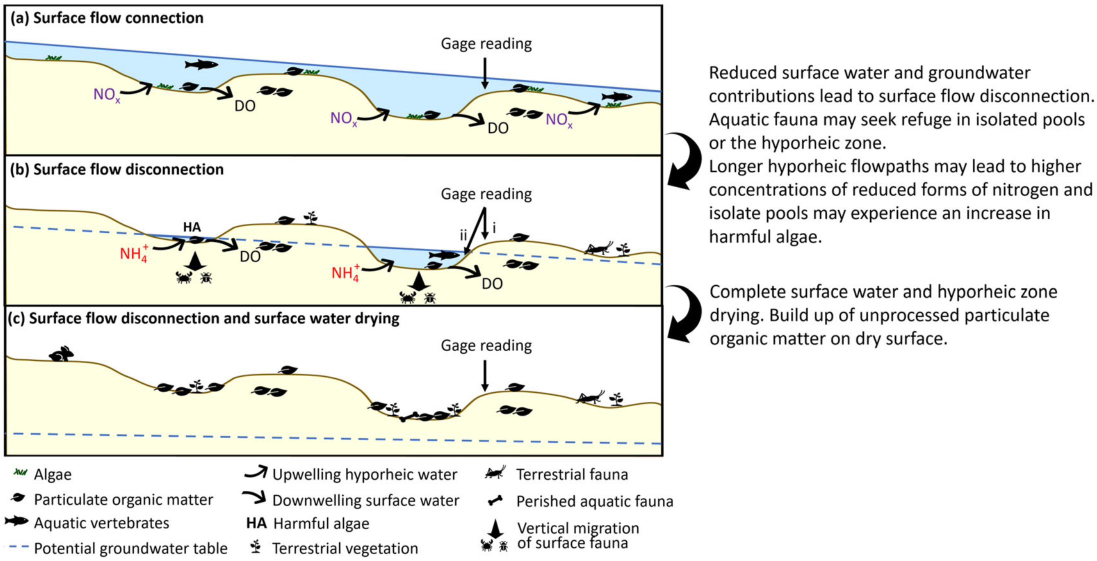
3.2 | Flow reversals

When stream gages are located at or near the boundary of lakes or oceans, short-term zero-flow readings can occur when water reverses flow direction from downstream to upstream due to winds or tides. In this case, zero-flow is not associated with drying. Nonetheless, misinterpretation of readings can misconstrue the underlying reasons behind large, albeit often temporary, biogeochemical and ecological changes. For example, flow reversal events can affect water quality gradients, drive physicochemical mixing of water, and alter suspended sediment dynamics (Linares, Wu, Anderson, & Chu, 2018; Rueda & Cowen, 2005; Uncles, Stephens, & Smith, 2002). Physicochemical effects of flow reversal are especially pronounced in tidal regions, where plumes of high salinity water can move upstream into fresh waters. Saline intrusion during flow reversal events is important ecologically because the distribution, abundance, and growth of both freshwater and marine organisms are controlled by salinity gradients (e.g., Chadwick & Feminella, 2001; DeMarco, Couvillion, Brown, & La Peyre, 2018; Glover, DeVries, & Wright, 2013). However, the biogeochemical and ecological impacts of flow reversal events are generally short-lived, as these zero-flow events tend to be brief relative to periods of downstream or upstream flow.

3.3 | Upstream source loss, flow bypass, and stream drying

Gages most often provide zero-flow readings when flow actually ceases (Box 1). Cessation of flow can be due to loss of upstream source flow, flow bypass, or complete stream drying (Figure 2). These drivers can have different consequences for interpretation of data linking zero-flow readings to stream biota community composition and ecosystem process rate estimation. For instance, bypass flow, including inter-basin transfers, not only alters the amount of water measured at the watershed outlet and included in export calculations, but alternate flow paths (e.g., hyporheic and groundwater flow paths) may carry different concentrations of materials out of watersheds (Alexander, Elliott, Shankar, & McBride, 2002). Understanding the causes of zero-flow readings can improve our estimates of the potential for transformation and remobilization of solutes, breakdown of organic matter in non-perennial streams, and distribution of aquatic organisms (Datry, Larned, & Tockner, 2014). For this reason, analyses based on gages with periods of zero flow require

BOX 1 POTENTIAL REACH-SCALE ECOLOGICAL AND BIOGEOCHEMICAL CONSEQUENCES OF FLOW REDUCTION OR LOSS IN RELATION TO GAGE READINGS AT SEVERAL LOCATIONS ALONG A STREAM CHANNEL



(a) Gage readings indicate positive flow at times when adjacent stream reaches are connected by surface flow. Downwelling surface water delivers oxic water to the hyporheic zone and relatively short hyporheic flowpaths cause upwelling of oxidized forms of inorganic nitrogen. Microbial and invertebrate activity degrades dissolved and particulate organic matter in both surface and hyporheic environments. Organisms without drying-tolerant adaptations persist, and surface flow connections facilitate movement of organisms limited to in-channel dispersal.

(b) Interpretation of gage readings can mislead by either (i) recording zero flow where surface waters persist but have become disconnected or (ii) recording positive surface flow in stagnant pools. In pools, dissolved oxygen decreases and harmful algae, such as cyanobacteria, may become established. Hyporheic flowpaths may become longer and lead to upwelling of more reduced forms of inorganic nitrogen (i.e., NH_4^+). The processing of dissolved and particulate organic matter may be largely constrained to saturated sediments in the hyporheic zone. Surface water invertebrates may seek refuge in the saturated hyporheic zone or enter dormant life history phases; aquatic organisms without drying-tolerant adaptations may seek refuge in residual pools or perennial reaches. In dry reaches, particulate organic matter may accumulate and terrestrial invertebrates may colonize the dry stream channel. Terrestrial vegetation may grow on dry stream surfaces, increasing stored quantities of particulate organic matter.

(c) The flow gage correctly records surface flow disconnection and complete surface water drying. Lowering of the shallow groundwater table may cause desaturation of the hyporheic zone. Surface and hyporheic ecosystem processes largely cease and organic matter continues to accumulate.

Note: Reprinted with permission from Figure 3 in Andersen et al. (2016).

consideration of alternate drivers of flow cessation and may require complementing gage measurements with additional point measurements throughout the stream network.

When gages capture non-zero flow, surface water connectivity enables a suite of measurements of hydrologic, biogeochemical, and biological processes associated with lotic environments (Box 1a). When streams begin to dry, they often fragment to form isolated pools (Box 1b), and the interpretation of zero-flow gage readings are varied and complex. In evaporating pools, habitat contracts, temperature swings intensify, and other physicochemical conditions become more variable (Lake, 2000), increasing the spatial variability of primary production and respiration (Busch & Fisher, 1981). A wide range of biogeochemical processes have been observed within isolated surface water pools, including evapoconcentration of solutes and the development of hypoxic conditions (Acuña et al., 2014; Skoulikidis, Vardakas, Amaxidis, & Michalopoulos, 2017). Stagnant pools can become hypoxic where photosynthesis is limited by canopy shading (Blaszczak, Delesantro, Urban, Doyle, & Bernhardt, 2019) or high concentrations of optically dense dissolved organic matter, which stimulate anaerobic microbial activity (Briée, Moreira, & López-García, 2007), and create conditions inhospitable to many aquatic organisms (Boulton, 2003; Stanley, Buschman, Boulton, Grimm, & Fisher, 1994).

The distribution and connectivity of remnant surface water pools (Box 1b) can vary substantially along a continuum and consequences can include reduced or extirpated populations (Bogan, Boersma, & Lytle, 2015) and altered patterns of population and community structure and connectivity (Boulton, Rolls, Jaeger, & Datry, 2017; Perkin, Gido, Costigan, Daniels, & Johnson, 2015). Although stream drying can be detrimental to many aquatic species (Datry et al., 2014), some taxa have evolved adaptive traits in response to hydrologic extremes, such as flooding and drought (Lytle & Poff, 2004). Many organisms respond to loss of connectivity by seeking refuge in permanent pools or sections with permanent surface flow (Albanese, Angermeier, & Dorai-Raj, 2004; Fey, 1983; Momot, 1966; Walker, Adams, & Adams, 2013). Aquatic macroinvertebrates may migrate vertically to the hyporheic zone (Stubbington, 2012; Vander Vorste, Malard, & Datry, 2016) and aquatic fauna density may increase in residual aquatic environments (Krabbenhoft, Burdett, & Turner, 2017). Consequences for vertebrates, such as amphibians, vary from habitat loss for tolerant species to extirpation for species with lower desiccation tolerance or longer larval durations (Mims, Phillipsen, Lytle, Kirk, & Olden, 2015).

When surface pools dry completely (Box 1c), hyporheic flow can maintain microbial functioning (Burrows et al., 2017) and influence ecological community composition (Vander Vorste, Corti, Sagouis, & Datry, 2016). Physiological adaptations to withstand loss of surface water include biological mechanisms that extend tolerance to anoxia (Milton, 2003), prevent cell rupture during freezing (Frisbie & Lee, 1997), increase tolerance to varying water physicochemistry (Chadwick, Hunter, Feminella, & Henry, 2002; Luo et al., 2014), and protect cells and tissues from desiccation (Watanabe, 2006). Behavioral adaptations also enable survival in absence of surface flow, such as cocoon building by chironomids (Danks & Jones, 1978; Frouz, Matena, & Ali, 2003) and synchronized stream exodus before complete drying occurs (Smith, 1973). Some organisms can even withstand complete drying via aestivation or diapause and reemerge from dormancy when water returns (Bogan et al., 2017).

When attempting to attribute the many biological and biogeochemical consequences of zero-flow gage readings, users of gage data need to be cognizant of the potential for misinterpretation of zero-flow readings. In cases where information is used to interpret large spatial and temporal scales, extrapolating gage (point) data to hydrologic networks could propagate inaccuracies of flow across the network or misrepresentation of an accurate zero-flow reading when system connectivity is of interest (e.g., potential refugia from drying, Dodds et al., 2004). True zero-flow observations at a gage cannot necessarily be extrapolated to upstream or downstream conditions without additional information (Sivakumar, Singh, Berndtsson, & Khan, 2015). For example, zero-flow conditions at a particular gage do not exclude the possibility of isolated surface pools (Pease, Justine Davis, Edwards, & Turner, 2006) or hyporheic flow (Wood, Boulton, Little, & Stubbington, 2010) that will correspondingly affect stream biota and biogeochemical processes. If total water or material flux downstream is of interest, a zero-flow reading may also cause incorrect interpretations. For example, bypass flow or groundwater pumping may influence the calculation of hydrologic or nutrient budgets for a watershed, such that information derived solely from gaging stations presents a biased characterization of the total flux (i.e., zero-flow at the gage may not correspond to zero-flow up or down stream). This bias could impact various management and conservation efforts including dam releases (Harman & Stewardson, 2005), budgeting for municipal water use and water rights allocations (Wurbs, 2005), and endangered species salvage projects (Archdeacon, 2016). Furthermore, the use of zero-flow data in the context of hydrologic modeling efforts, statistical analysis of hydrologic networks, and identifying sample locations can be hindered by overreaching interpretation of zero-flow observations. Given this uncertainty, we suggest caution in interpretation of gage data, particularly where zero-flow events are a common occurrence.

4 | WHAT OTHER APPROACHES CAN PROVIDE CONTEXT FOR INTERPRETING ZERO-FLOW OBSERVATIONS?

As highlighted in previous sections, a more complete understanding of the causes of zero-flow readings can aid in interpreting the hydrologic, ecological, and biogeochemical conditions of aquatic systems. This section addresses whether existing observation and modeling frameworks can help data users determine causes of zero-flow observations. Here, we detail relative strengths and limitations of approaches for interpreting zero-flow observations including (a) empirical observations, (b) statistical approaches, and (c) mechanistic hydrologic models.

4.1 | Observations of flow status of rivers and streams

Ground-truthing is the ultimate test of whether or not a stream has surface flow, but is potentially time and labor intensive. Visual observations of flow presence or absence along the stream network yield spatially distributed information on which locations have zero surface flow (Barefoot, Pavelsky, Allen, Zimmer, & McGlynn, 2019; Godsey & Kirchner, 2014; Zimmer & McGlynn, 2017). Citizen science has recently enabled more widespread observations of flow conditions in streams (Allen et al., 2019; Datry, Pella, Leigh, Bonada, & Hugueny, 2016; Kampf et al., 2018). In-person observations are discrete in time; however, this may not be sufficient to characterize systems that expand and contract rapidly in response to storm events or diurnal fluctuations in evapotranspiration (Ward, Schmadel, & Wondzell, 2018). Further, these observations have potential for error if the observer does not see water covered by vegetation/ice or inaccurately georeferences observations.

Low-cost sensors can complement field observations, allowing continuous-in-time but discrete-in-space characterization of flow status. For example, commercial electric resistance, temperature, and light sensors have been modified to observe the presence of surface flow at discrete locations (Chapin, Todd, & Zeigler, 2014; Jensen et al., 2019). However, these sensor readings may be noisy, and their output does not distinguish standing and flowing water. Surface water state loggers provide a more easily interpreted alternative to temperature and conductance-based measurements (Epting et al., 2018). Assendelft and van Meerveld (2019) designed a multi-sensor system, which include electrical resistance, temperature, float switch, and flow sensors, to more accurately monitor hydrological states of streams. Time-lapse cameras installed at stream gages can also help determine when water or ice is present, whether water is flowing or stagnant at the gage, and the connectivity of surface water presence along the channel (Costigan et al., 2017). Uncertainties from camera images are related to shadowing, glare, or other features that obstruct the view of the surface water.

Sensors can also be employed to track longitudinal patterns of surface flow. For example, several studies included longitudinal arrays of pressure transducers (e.g., Schmadel, Ward, & Wondzell, 2017; Ward et al., 2018) or electrical conductivity and temperature sensors (Blasch et al., 2004; Constantz, Stonestorm, Stewart, Niswonger, & Smith, 2001; Jaeger & Olden, 2012). Temperature-based methods require conditions in which the temperature variability differs between conditions with and without surface water. For rivers without dense canopy cover, remotely sensed data may be used to classify the presence or absence of flow in non-perennial streams (Allen et al., 2019; Dugdale, Kelleher, Malcolm, Caldwell, & Hannah, 2019; Spence & Mengistu, 2016). This works best for large streams with limited view obstruction paired with fine resolution image data. These examples only provide information about flow conditions on the surface, but they can be combined with well or piezometer observations to examine connectivity between surface and subsurface flow (sensu Peirce & Lindsay, 2015).

Given the possibility of misinterpreting zero-flow conditions from gage readings alone, it is important for data users to review associated data from open-channel field measurements (e.g., visual observations of flow status) and associated metadata to help confirm zero-flow or interpret conditions that are associated with zero-flow records. Further, given potential third-party data users who are interested in zero-flow data, it is critical for managers of such data to be cognizant and consistent in reporting different conditions (e.g., isolated surface water pools, no surface water, and frozen water column) associated with zero-flow measurements.

4.2 | Statistical approaches to predicting patterns of zero-flow conditions

Statistical approaches are being used to infer flow status at both reach and network scales to compensate for limited gages on non-perennial streams, particularly in headwaters or in landscapes dominated by non-perennial river networks (González-Ferreras & Barquín, 2017; Yu, Bond, Bunn, Xu, & Kennard, 2018). These approaches are particularly useful for large areas, and they have the flexibility to incorporate a range of data sources (Cigizoglu, 2005; Kisi, Nia, Gosheh, Tajabadi, & Ahmadi, 2012). For example, researchers have made continual advances in low flow stream statistics to better characterize extreme low and no flow periods (Bhatti, Kroll, & Vogel, 2019). Yet, many of these models do not represent processes, so they may not capture the influence of changing flow drivers over time.

Several statistical models have been developed for network scale predictions of flow status. For example, using the national monitoring network of flow status observation in France, Beaufort, Lamouroux, Pella, Datry, and Sauquet (2018) applied multiple regression models to infer the risk of drying at the catchment scale, defined as the daily probability of drying. In the Pacific Northwest region of the United States, the probability of streamflow permanence model (PROSPER) uses random forests to identify the drivers of surface flow intermittency (Jaeger et al., 2019). This method uses publicly available geospatial data, and a combination of flow observations from several government agencies (McShane & Sando, 2017). PROSPER was calibrated to subregions to account for the spatial variability of drivers, and the resulting stream network maps represent the probability of a stream reach going dry in a given year over the modeling period (2004–2016). While using multiple data forms, these approaches may be subject to the same misinterpretations as described above.

In addition to network-scale statistical approaches, assessing flow within a reach can be particularly valuable given the distance between gaging stations. The empirical longitudinal flow model (ELFMOD) is a statistical tool for estimating flows at multiple points along a fluvial network subject to surface water and groundwater exchanges, using both flow measurements and observations of flow presence or absence at selected sites as well as other predictor variables, such as rainfall and groundwater levels (Larned et al., 2011; Rupp, Larned, Arscott, & Schmidt, 2008). The ELFMOD generates time series of flows and confidence at user-defined points from statistical relationships between gaging stations. This method has been applied at a variety of locations including the Selwyn River in New Zealand, the Albarine River in France, and the Methow River in Washington, United States.

4.3 | Process-based hydrologic modeling to provide context for interpretation

Process-based hydrologic models that simulate flow dynamics can also provide context for interpreting zero-flow observations at stream gages. However, an open question is whether existing process-based representations are adequate to capture expansion, contraction, connection, and disconnection in the surface flow network. Process-based models fall along several continua, including model complexity and spatial scale (Golden et al., 2017).

Process representation ranges from relatively simple lumped parameter approaches ("bucket" models) to highly resolved and parameterized, physically based simulations. Most models route water along a stream channel, and sometimes to that channel (Fread, 1993), typically conserving mass and momentum along the way. At the simplest end of the spectrum, "fill-and-spill" or "bucket" models have been used to forecast stream intermittency or network connectivity (Rassam, Fellows, Hayr, Hunter, & Bloesch, 2006). Other models include increased parameterization and process representation, but are still highly idealized, reduced complexity models (van Meerveld, Kirchner, Vis, Assendelft, & Seibert, 2019; Ward et al., 2018). However, even models that focus on a limited subset of processes, such as the United States Army Corp of Engineers HEC-RAS model (Brunner, 2010), may not be able to simulate discontinuities along non-perennial streams because they assume continuity along the channel (Salas et al., 2018). Some of the most advanced physically based models can effectively represent non-perennial flows, but they require substantial data and computational resources (Batlle-Aguilar, Xie, & Cook, 2015; Kollet & Maxwell, 2006).

Simulating dynamic, discontinuous stream networks requires a trade-off between model fidelity and computational/data resources (Golden et al., 2017). To represent flow discontinuities effectively, fine-scale topographic and substrate data may be needed to parameterize simulations (Fleckenstein, Niswonger, & Fogg, 2006), leading to high computational demand. This level of detail may not be feasible for modeling large watershed areas and is better suited for simulating flow presence or absence in small (<1 km^2) and heavily instrumented areas, for example, to model instream refuges for aquatic species at the reach scale. Moreover, capturing water balance terms such as evapotranspiration and loss to perched and regional aquifers along the length of the channel is notoriously difficult (Shanafield & Cook, 2014), which can make it especially hard to accurately capture the magnitude of flow along non-perennial rivers. Recent reduced-complexity models may provide a trade-off between accuracy and complexity by representing downvalley subsurface flow occurring in parallel with surface flow, allowing dynamic activation, and cessation of surface flow (Ward et al., 2018).

Zero-flow conditions can be modeled at multiple spatial scales ranging from reach to watershed to continental and global scales. We hypothesize that reach- to watershed-scale models (e.g., Ward et al., 2018) might best match observations of no-flow conditions because they are more likely to include all three dimensions of lateral, longitudinal and vertical hydrologic connections (e.g., Boulton & Stokes, 2018). Nonetheless, state and national governments often make policy decisions at regional or national scales (e.g., Alexander, 2015), and therefore models at these scales may provide critical information (e.g., Lin et al., 2019). Notably, while most of these models simulate processes at the reach- to watershed-scale, those processes are often not finely resolved enough to make local management decisions (Irving et al., 2018).

5 | CONCLUSION

Existing stream gage networks can include substantial zero-flow readings even though many are designed to capture hydrologic conditions of perennial streams. This provides an opportunity to characterize properties of non-perennial streams through examining the local- to network-scale causes and consequences of zero-flow readings, which include frozen surface water, flow reversals, data/equipment errors, and natural or anthropogenic source loss and flow bypass. Our ability to make inferences from these gages is limited by difficult-to-discern zero-flow readings, as well as readings that may not represent flow conditions beyond the gage location. We present options for additional data sources and tools that can help identify causes of zero-flow readings. Linking point-scale gage data with network-scale streamflow information to understand the implications of zero-flow readings in network contexts will better inform management and policy decisions. A network context is essential for making inferences about the ecology and biogeochemistry of stream drying. Addressing these challenges will be critical with anticipated increases in the prevalence of streamflow intermittence, with likely changes in the underlying causes and consequences of zero-flow readings.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

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