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Monitoring Streamflow Pulses

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Abstract

At a time when the floods are globally increasing in magnitude, intensity, and frequency there is pressing need to capture and thoroughly understand the dependencies among flow variables during flood wave propagation cycles using real-time measurements acquired in-situ. Taking advantage of the capabilities of the new generation of instruments, the real-time unassisted acquisition of multiple flow variables with high-temporal resolution is now increasingly possible in streams and rivers of various sizes. This paper proposes a new measurement system for estimation of the streamflow gradual variation (pulses) in real time through assimilation of direct measurements in canonical channel flow governing relationships, such as Saint-Venant equations for unsteady open-channels flows. The proposed measurement system innovatively combines the proven capabilities of the index-velocity method with those of the continuous slope-area method to document the complex and often-missed hysteresis effects that are developing during flood wave propagation at a myriad of observation stations located in lowland streams. While the new method is still under development, this paper presents its concept, configuration, and preliminary results obtained with method's sub-components through proof-of-concept experiments and exploratory data-driven analyses. It is hoped that the new streamflow monitoring method will advance modern practices in hydrometry and will enable new discoveries in hydrologic sciences that eventually can improve streamflow data accuracy and usefully support model- and data-driven predictions.

Keywords: Hysteresis, Unsteady open-channel flows, Streamflow monitoring, Index-velocity method, Slope-area method

1. INTRODUCTION

Monitoring and forecasting streamflow are at the core of the decision making for critical socio-economic areas. These data are also used as benchmarks for scientific studies on water cycle, ecological patterns, and climate trends. Given their importance, complexity, and costs, streamflow measurements are acquired by specialized agencies using protocols that were continuously revised through century-long incremental developments (USGS, 1994). Most of these developments have considered river flows as quasi-stationary, i.e., fluctuating within an unchanging envelope of variability (Jain & Lall, 2000). This assumption coupled with limitations of the past monitoring technologies have given rise to empirical- or semi-empirical streamflow monitoring protocols based on ratings established with statistical analyses applied to long records of historical data under the assumption that flows are quasi-steady at any time. The most-often used relationship for monitoring streamflow is the stage-discharge rating (WMO, 2010). Since 1980s, an emerging alternative approach is the index-velocity method that is recommended for measurements in unsteady flows and in areas affected by backwater (Levesque & Oberg, 2012). Both methods combine direct measurements of flow variables (stage for stage-discharge method and stage and index-velocity for index-velocity method, respectively) acquired in one cross section in conjunction with pre-established one-to-one ratings that are uniformly applied for steady and unsteady flows.

It is, however, well documented theoretically that the mechanisms of the flow during the rising and falling stages of the flood wave propagation are different from those of steady flows (Graf &Qu, 2004). Consequently, the discharge ratings during flood wave propagation are inherently multi-valued (a.k.a. looped) pending of the interplay between the flow depth (a geometric descriptor of the flow) and the changes in flow velocity, water-surface slope, cross-sectional area along the channel, and of the flow variables in time (Schmidt, 2002; Henderson, 1966). The looped discharge ratings are in fact manifestation of the hysteresis in the flow mechanisms. Hysteresis, also encountered in other engineering areas, is the property of a process whereby the state of a system at a given time depends on the direction of the change to reach that state (e.g., Prowse, 1984). While the terms loop and hysteresis are acknowledged in monitoring practice, they are only taken into consideration at few stage-discharge stations located in flood-prone area where streamflow forecasts are issued (Holmes, 2016). For those sites, corrections are applied to the streamflow estimates after the data is collected using empirical (Schmidt & Garcia, 2003) or analytical (Fenton, 2018; Di Baldassare & Montanari, 2009; Fenton & Keller, 2001) adjustments applied to the “steady” ratings. The majority of the stage-discharge ratings are used without corrections despite that Holmes (2016) found that hysteresis affects more than 65% of the US stage-discharge stations. The index-velocity method is used without corrections as it deemed that it is in better suited for unsteady flows (Morlock et al, 2002).

To the best of our knowledge, currently there are no systematic studies for uniformly assessing the hysteresis impacts on the streamflow estimates nor for validating the methods used to correct the performance of the ratings during unsteady flows. Accomplishing these overlooked tasks is hindered in the first place by the lack of a widely- recognized method to directly measure streamflow. Besides this impediment, there are other reasons invoked for this status quo, that are argued in the present paper with experimental evidence (Muste & Kim, 2020). First, there is a perception in the hydrometric community that the transitory processes cannot be distinguished from instrument uncertainty (Holmes, 2016). This perception is in contrast with the few available field observations, where considerable differences between measured and actual streamflow data are found for both cyclical processes, i.e., up to 40% due to time-dependent flood wave dynamics (Muste & Kim, 2020; Dottori et al., 2009; Fenton & Keller, 2001). These differences considerably exceed the 5% threshold widely accepted for uncertainty in measurements (Oberg & Mueller, 2007). The second reason, and the most often invoked, is related to the limited capabilities to continuously capture these processes in natural streams. While such a reasoning could have been justified in the past, the substantial advancements produced by the adoption of non-intrusive technologies (e.g., acoustic-, radar-, ultrasound-, and image-based), new deployment technologies (remote- and close-range sensing), and data communication means (cellular networks) in the last four decades have dramatically transformed our in-situ measurement capabilities.

To date, the available instruments enable acquiring data in natural streams with spatio-temporal resolution on par with those obtained in laboratory conditions (Muste et al., 2012). This progress in instrumentation has not been mirrored by similar advancements in streamflow measurement protocols. Specifically, the monitoring protocols continue to apply statistical analysis to the quasi-randomly and discreetly acquired data rather than exploring more physical-based measurement approaches that take advantage of the capabilities of the new generation of instruments. A notable feature of the new generation of instruments is their non-intrusive nature which reduces the installation and operational costs. As a result, there is a need to identify monitoring approaches capable of accurately tracking flow variables in real time in steady and unsteady flows.

The present paper attempts to illustrate how the new monitoring method can track cyclical changes of the flow variables (called herein pulses). The variable pulse as defined herein is a series of consecutive data points in the flow stream variables cycling from a lower (base) value to a peak and then returning at the initial position. These pulses are generated by the initiation of a rainfall event or changes in the rainfall intensity and/or its spatial distribution over the station’s drainage area. We introduce herein the term “pulse” to enable the distinction between a single- and multi-pulse hydrograph associated with the propagation of a flood waves. The proposed method ingests directly measured flow variables and their gradients into canonical equations for unsteady flows (also valid in steady flows) applied to gaging sites where the best practices for site selection are strictly followed (Rantz et al. 1982b). The monitoring method’s innovation consists in: a) the adoption of a reach-scale approach; and b) capturing changes of all flow variables in real time over the full duration of the flood wave propagation without making recourse to rating curves. The paper presents the fundamentals of the proposed measurement concept and provide possible configurations and deployments for the measurement system. Selected results from prior work with components of the proposed system are reported in this paper to illustrate the possibility to monitor unsteady flows pulse by pulse. The work is currently in progress, with more results expected by the time of the conference.

2. MEASUREMENT CONCEPT AND IMPLEMENTATION

2.1 Measurement Concept

We build our measurement concept around the Saint-Venant shallow-water two-dimensional equations (Chow, 1959) supported by directly measured data at the gaging site. Given that the targeted outcome of the measurement is the discharge, we adopt the arrangement of these equations offered by Knight (2006):

$$Q = Q_s\sqrt{1 - \frac{1}{S_0}\frac{\partial h}{\partial x} - \frac{U}{gS_0}\frac{\partial U}{\partial x} - \frac{1}{gS_0}\frac{\partial U}{\partial t}} \quad [1]$$

where Q, is the unsteady flow discharge, Q_s is the steady-uniform discharge, h is the flow depth, U is the cross section mean velocity, t is time, and x is the distance along the channel direction. Note: typically, flow depth is determined from measurements of free surface elevation (a.k.a. stage), H. The steady-uniform flow discharge, Q_s, is derived from Manning's equation (Chow, 1959):

$$Q_s = \frac{1}{n}AR^{2/3}\sqrt{S_0} \quad = K\sqrt{S_0} \quad [2]$$

where, n is the Manning's roughness coefficient, A is the cross-sectional area, R is the hydraulic radius, S_0 is the bed slope, and $K = (1/n)\ AR^{2/3}$ is the channel conveyance (in metric units). Equation [1] is strictly valid under the following assumptions: incompressible fluid, one-dimensional flow, hydrostatic pressure distribution, and negligible vertical acceleration. For the present context, it is important to highlight that these qualifiers are essentially met if the best practice guidelines for gaging site selection as prescribed in Rantz et al. (1982b) are applied (i.e., quasi-prismatic and straight channels without lateral inflows or outflows). In the preliminary stages of the technique development, we will limit the testing of the technique to clear-cut flow situations to enable its evaluation without flow complexities. From this perspective, we will analyze flood waves propagating in channels predominantly controlled by friction (channel control) rather than channel geometric features (local control) (WMO, 2010). Moreover, we will limit our analysis to flows up to bankfull stages, as the mass and momentum exchanges between the main channel and floodplain above this stage generate additional complexities that impede hysteresis impact interpretation. Under these conditions, the major contributor to hysteresis is the flow unsteadiness and backwater that are well described by the governing equations for unsteady flow, as illustrated in (Henderson, 1966; and, Fenton & Keller, 2001).

Previous analyses of Equation [1] for channel flow routing (Ferrick, 1985; Arico et al., 2008) have shown that it provides a realistic hydraulic description of flood waves (i.e., non-uniform, unsteady flows) irrespective of their type: kinematic (first term only), diffusion (first and second terms), and full dynamic (all terms). The magnitude of the individual terms in Equation [1] is commensurate with the slope of the bed at the site and the intensity of the propagating wave (i.e., its magnitude vs. duration). The practical guidelines for identification of the potential type of waves suggest that inland rivers located on mild and small bed slopes develop full dynamic waves (e.g., Julien, 2002) while rivers located on large bed slopes develop kimematic waves (Arico et al., 2008).

For hysteresis-prone sites, it is expected that direct measurements of the variables and their gradients in Equation [1] will substantiate dependencies as illustrated in Figure 1 (Muste et al., 2020): i) non-unique relationships for the pairs of flow variables during the rising and falling limbs of flood wave propagation, as illustrated by the loops in (Figures 1a), b), and, c); ii) separation of the flow variable hydrographs (see Figure 1d). It is to be mentioned that if a monitoring method captures the loops in the flow variables relationships in time-independent coordinates, it also substantiates the phase hydrograph sequences in the time-dependent visualizations. The features conceptually illustrated in Figure 1 have been recently documented with measurements conducted by the authors at various sites using different monitoring methods, i.e., the index-velocity method (Muste & Kim, 2020) and the continuous slope-area method (Muste et al., 2019).

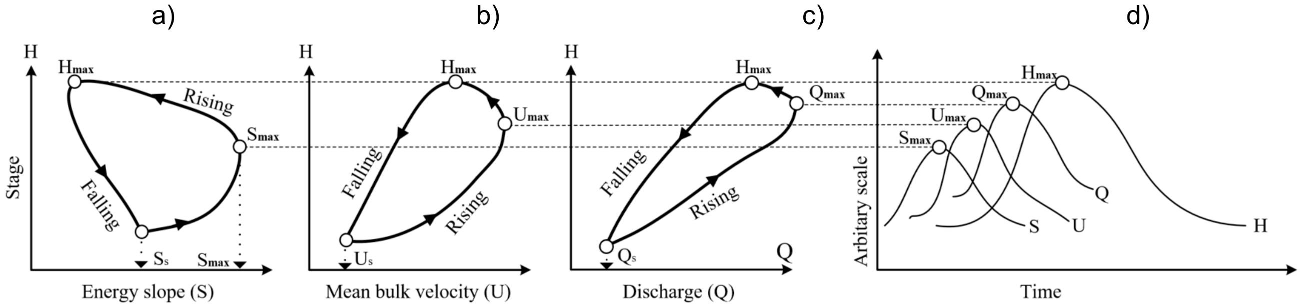

Figure 1. Hysteresis effects of flow variables during the evolution of cyclical processes (Muste et al., 2022): a) stage vs. water free-surface slope; b) stage vs. index velocity; c) stage vs. discharge; d) phase sequencing of the flow variable hydrographs. (Rising and Falling terms in figures a) b) c), and d) are used to identify the cycling of the stage (i.e., from steady flow stage to H_{max}).

The newly developed measurement concept builds on proof-of-concept measurements and analysis of unsteady flows propagating at hysteresis-prone areas as documented by the index-velocity and continuous slope-area method (Muste et al., 2020). For easiness of reading, we will label the aforementioned methods with the IVRC and CSA acronyms. The newly proposed method is distinct from the past approaches that aimed at correcting the stage-discharge rating (labeled HQRC for convenience) using free-water slope as a parameter (Dottori et al., 2009). Among the HQRC correction methods using slope as an additional monitoring variable are: a) the fall-stage relationship (Rantz et al., 1982a); b) the Hydraulic Performance Graph and Hydraulic Performance Curve developed by Yen & Gonzalez-Castro (2000) and Schmidt (2002), respectively, and c) the Dynamic Rating Curve (DyRaC) developed by Dottori et al. (2009). Our method is similar to that of Dottori et al. (2009) by assuming that the discharge between two adjacent sections is practically constant (i.e. $\partial Q / \partial x \approx 0$).

2.2 Implementation

Figure 2 illustrates a potential equipment deployment scenario that can be used with the newly designed monitoring method. Also shown in the figure is the association between the deployed instruments and measured quantities. The equipment entails a pair of stage monitoring probes, denoted with PT_1 and PT_2 in the figure and a Horizontal Acoustic Doppler Current Profilers (HADCP). In order to comply with the constant flow rate assumption mentioned above, the distance between the reach ends should be small. The distance between the stage sensors cannot be, however, drastically reduced as the measured water surface fall needs to be sufficiently large to not be hindered by the instrument resolution and water level fluctuations. The difference in the readings of the PT_1 and PT_2 gages allow to measure the water free-surface slope that is closely similar to the hydraulic energy line in uniform flows. The HADCP is set in the central part of the stream reach delineated by the stage sensors. The HADCP measurements provide two- or three- velocity components at multiple points along the instrument axis that are then averaged to provide an index velocity over the cross-section (V^i). All measurements should be sampled synchronously and frequent (e.g., 3 to 15 minutes apart) to closely track changes of the flow variables during the wave propagation.

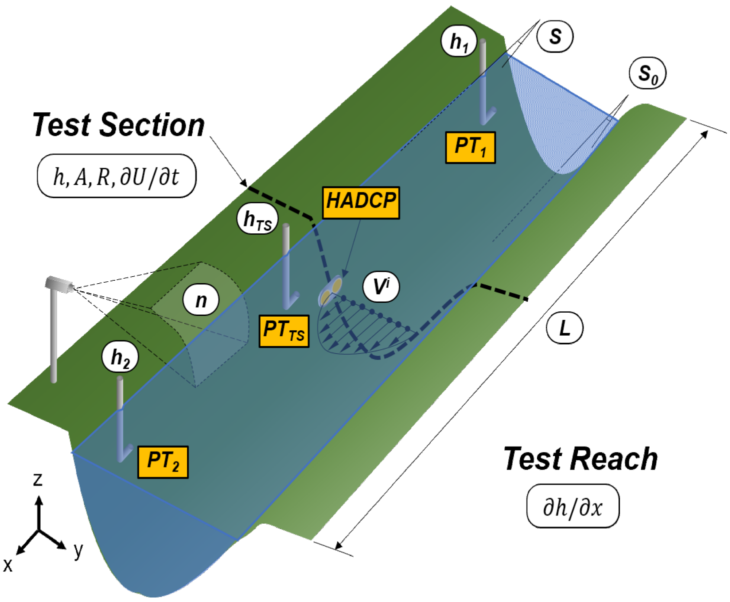

Figure 2. Layout of the experimental arrangement and measurement locations for the terms in Equation [1].

To fully automate the real time delivery of the streamflow data, we need a reliable relationship for converting the index velocity (V^i) measurements into bulk cross-sectional flow velocity (U) and for determining the bulk velocity gradient $\partial U/\partial x$ in Eq. (1). The conversion of the index velocity to bulk velocity can be made with several approaches: a) power and logarithmic laws (e.g., Le Coz et al., 2008); b) semi-empirical velocity distribution laws for natural streams developed by (Rijn, 1986); and c) probabilistic methods applied to index velocity time series, proposed by (Chen et al., 2012). Searching for optimal solutions for the conversion of index velocity to bulk velocity can be tested against direct discharge measurements acquired with ADCP transects. This type of ADCP measurements (a.k.a. calibration/validation measurements) are periodically collected for verification of the rating curves at USGS stations and for enforcing the rating at high flows. Estimation of the $\partial U/\partial x$ in Eq. (1) can be obtained using the approach developed by Sriwongsitanon et al. (1998). In this approach, the wave speed (obtained from the free-surface slope) is related to bulk flow velocity, with separate relationships for the rising and falling hydrograph phases. A minimum of one-time topographic survey is needed to capture the geometry of the beginning and end of the reach section and to located the instruments' positioning after deployment. The slope of the stream bed is estimated either from available information (high-resolution DEM) or direct measurements (Lidar surveys). Optionally a web-camera can be installed on the stream bank to track significant changes in riparian vegetation and other river flow features (e.g., debris or ice accumulations).

3. EXPECTED RESULTS

Tracking flow variables with high-temporal resolution in real time has the potential not only to improve the accuracy of streamflow monitoring in unsteady flows but also to reveal dependencies among the flow variables that offer new insights into stream processes and their forecasting. Of special importance for the present context, is the unraveling of the relationships among flow variables as the wave propagates at sites prone to hysteresis where most of our knowledge is based on theoretical knowledge associated with simplifying assumptions for the type of wave acting and their transformation during the unfolding event.

To substantiate the discussion on the potential benefits of the proposed monitoring methodology, we present selected results obtained with sub-components of the methodology, i.e., the index-velocity method (IVRC) and Continuous Slope-area method (CSA). While the results complement each other in confirming intrinsic features of the stream hysteretic behavior illustrated in Figure 1, they were obtained on two streams considerable different by size, flows, and hysteresis magnitude. Another impetus for presenting this type of experimental evidence is the fact that, while the data present below are publicly available, the analysis of the available evidence as conducted in this paper is quite rare (if done at all).

3.1 Pulse Characterization

Ensuing from the graphical description in Figure 1d, is that the propagation of one non-kinematic flood wave produces flow variable hydrographs that are phased in time. The simplified illustration in Figure 1d is valid for a single-pulse storm. The single-pulse storms are quite rare in natural streams, as observed in the analysis of 6 years of data at the USGS index-velocity station #05558300 (Muste & Kim, 2020). The phasing of the hydrographs for the index-velocity and stage for a single-pulse storm recorded at this station is shown in Figure 3a. The time ratios between the rising and falling stage of single-pulse storm hydrographs varied at this site between 1:3 and 1:10, depending on the magnitude and intensity of the storm pulses. Figure 3 contains additional notations that are used to characterize individually single- or multi-pulse hydrographs, their interdependence in time, and rates of variable changes (Muste et al., 2022). Most of the storms contain multiple pulses that combine their impact during the flood wave propagation. The effect of the superposition of the individual pulses for a multi-pulse storm can be tracked in the index-velocity and stage hydrographs plotted in Figure 3b. We deem that this distinction between single- and multiple-pulse storms is important for the analysis and forecasting of the flood crest, as the magnitude and timing of the flood crest are determined by the incremental changes of the flow variables on the rising limb of the stage hydrograph (Muste et al., 2022). Moreover, the number and characteristics of the pulses on the rising limb of the stage hydrograph are decisive for determining the severity of the hysteretic loops (De Sutter et al., 2001; and, Mrokowska & Rowinski, 2019).

a)

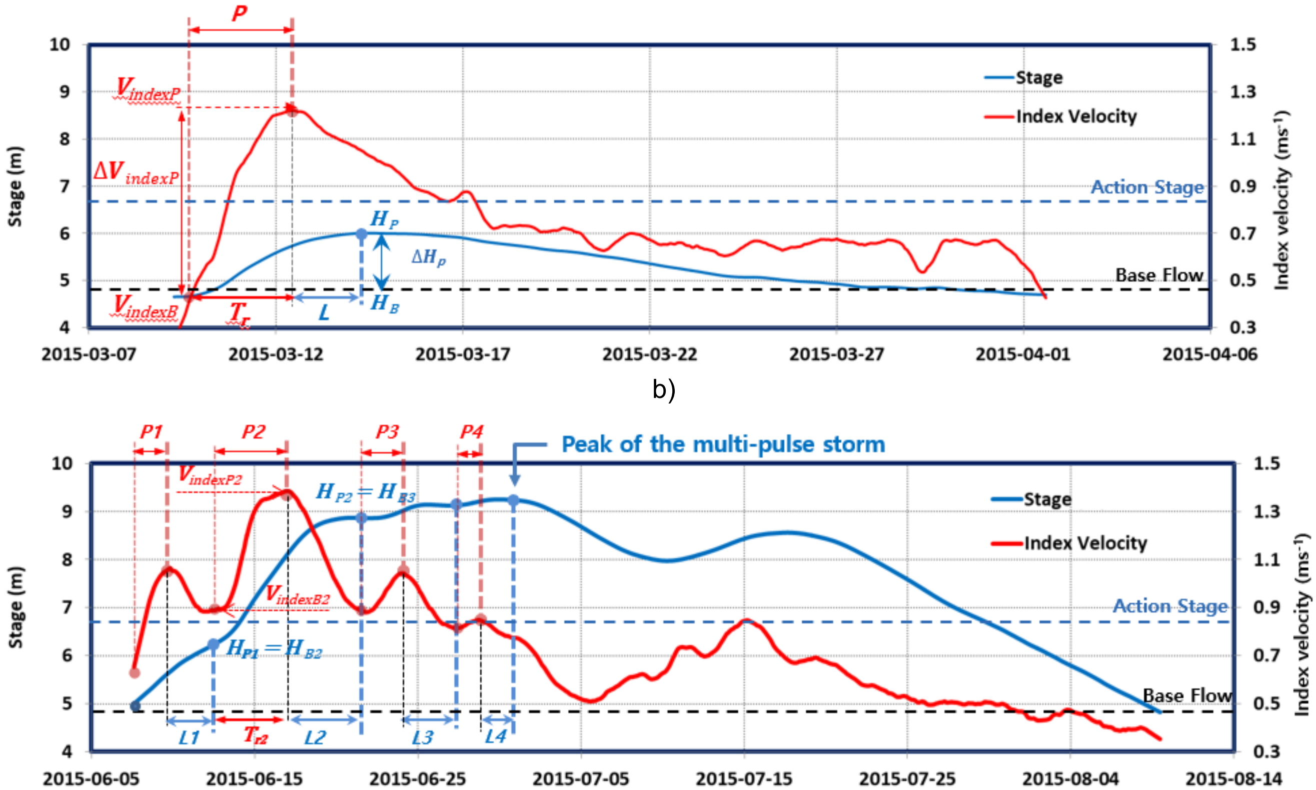

Figure 3. Identification of the hysteresis-related patterns leading to the flood wave crest: a) single-pulse storm event; b) multiple-pulse storm event. (Muste et al., 2022)

3.2 Hysteretic Effects in the Pulses

The graphical description of the hysteresis effects shown in Figure 1 indicates that if the time phasing is apparent in the recorded hydrographs, there are certainly loops in the relationships among any of the two variables measured for the same event at that specific location. In a previous analysis conducted at a USGS index-velocity station exposed to hysteresis, we found convincing and abundant experimental evidence of the above-described dependencies, as illustrated in Figure 4 (Muste and Kim, 2020). First, the phasing in the time series of the flow hydrographs for all types of storm events follows the sequence illustrated in Figure 4a: index-velocity first, discharge next, and lastly the depth hydrograph. Similar findings about phasing of the hydrographs are noted by a recent analysis conducted on the free-surface velocity measured with radar and stage hydrographs at another station (Khan et al, 2021). It is worth mentioning, that for the largest storm of the year 2017 at this USGS gaging station, the time between the index-velocity and stage peaks was 2.5 days (see Figure 4.a). For the largest storm recorded in the 2013-2019 analysis interval, the time between the same peaks was 3.75 days! This magnitudes for the lags suggest the phasing of the hydrographs at hysteresis-prone sites can be exploited for short-term forecasting purposes.

Second, it is expected that the extent of the time phasing is proportional with the loop thickness - defined as the maximum difference between the independent variable for the same stage (e.g., on the looped index velocity in Figure 4b). The thicker the loop the larger the time between the index velocity and stage peaks. The loop thickness is in turn dependent on the intensity of the propagating wave (i.e., its magnitude vs. duration). Using the parameterization of the pulses described in Figure 3, we developed analytical relationships to uniformly quantifies the intensity (a.k.a. severity) of the pulse (Muste et al., 2022). Furthermore, we observed that each pulse in a multi-pulse storm produces its own loop in the time-independent representation of the flow variable dependencies and in the associated sequencing in the variables' hydrographs. Figure 4c illustrates all the major storms of year 2017 recorded at this station, represented in the conventional stage-discharge coordinates. It can be observed in this figure that each storm event passing through the site has a distinct signature that in turn reflects the magnitude of the individual storm pulses and their intensity up to the stage hydrograph peak (flood crest).

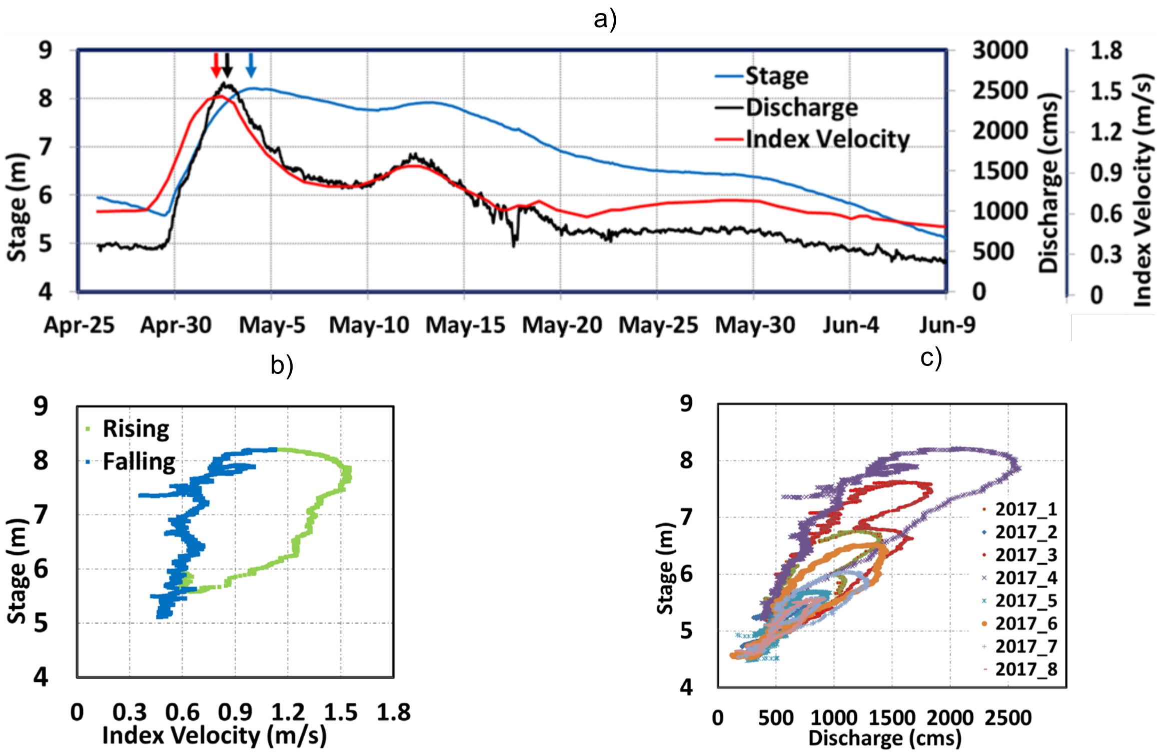

Figure 4. Hysteresis impact on flow variables at USGS index-velocity station #05558300 for water year 2017 (Muste & Kim, 2020): a) sequencing of the time series of the flow variables for storm #4; b) stage vs. index velocity relationship for storm #4; and, c) stage-discharge relationship for all major storms of 2017.

To further explore the hysteretic impact on flow variables beyond the illustrations enabled by the IVRC method, shown in Figure 4, we add herein *in-situ* measurements acquired with the CSA method during one of the spring storms passing through as hysteresis-prone site (Muste et al, 2019). The free-surface slope used in conjunction with Equation [2] was acquired with fast-sampled pressure sensors set 200m apart. Like Equation [1], the implementation of CSA using Equation [2] is only valid for sites that are controlled by friction forces over the measurement reach (i.e., quasi-constant shape and straight channels). Figures 5a, 5b, and 5c substantiate the capabilities of the CSA method to reveal: a) phasing among flow variables; b) looped relationship between free-surface slope (that is proportional to the energy slope for short reaches) vs. stage; and c) looped stage vs. discharge relationship (Muste et al., 2019).

The plots in Figure 5 display shapes similar to those illustrated in Figures 1d, 1c, and 1d, respectively. The time difference between the free-surface and stage peaks for this small stream is 2.25 hours (see Figure 5a) which is much smaller than the 2.5 days observed in the larger stream illustrated in Figure 4a. The time separation in the stage-discharge relationship shown in Figure 5a is much smaller than that in Figure 4a because of the wide difference in river size (i.e., about one order difference in stream width) and the much narrower range for the variation of the flow variables. Even for such small hysteretic effects, we observed a difference of 16% in the discharge for the same stage in the area of maximum loop thickness.

a)

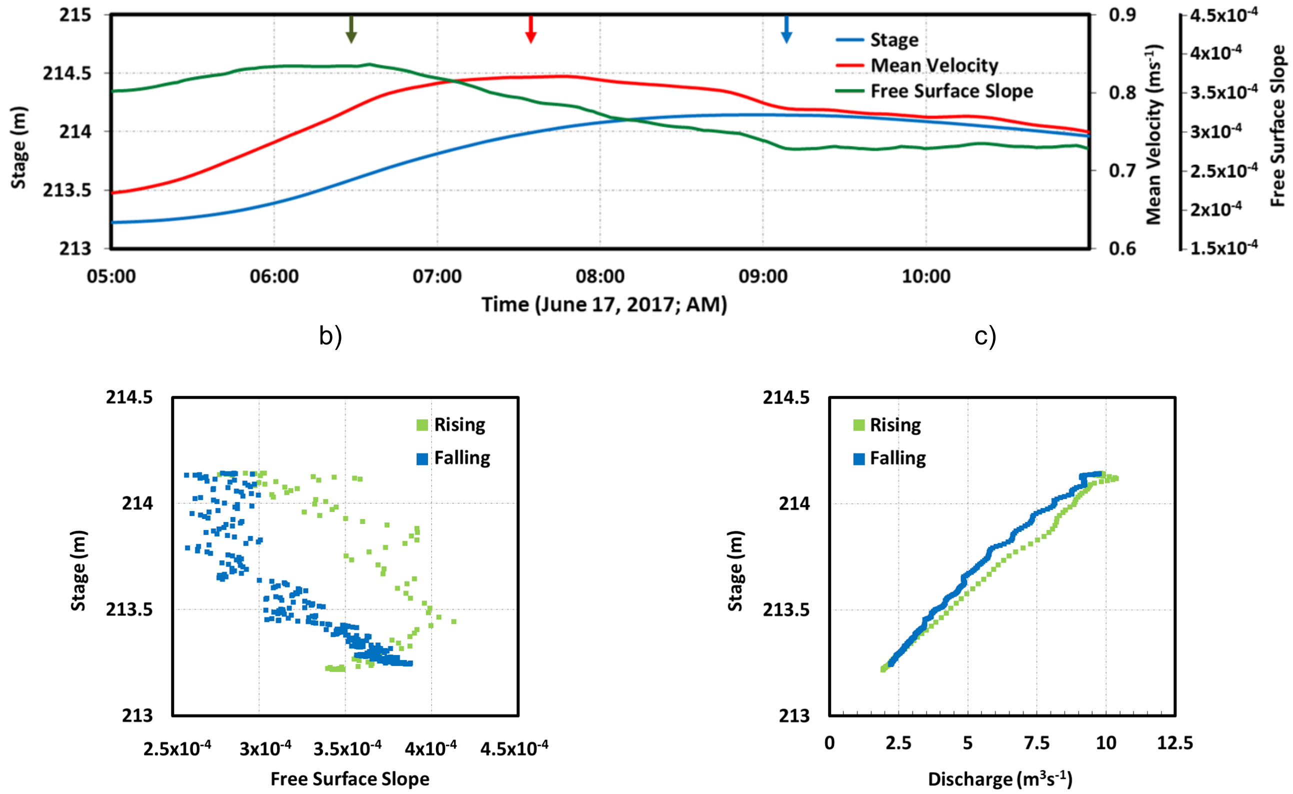

Figure 5. Hysteresis impact on flow variables captured with the continuous slope area method at a site during the propagation of single-pulse storm in the spring of 2017 (Muste et al., 2019): a) sequencing of the time series of the flow variables; b) stage vs. free-surface slope relationship; and, c) stage vs. discharge relationship. Rising and falling terms in the plots specify stage variation phases (i.e., from steady flow to H_{max}).

The plots of the direct measurements illustrated in Figures 4 and 5 reveal that sampling the flow variables *in situ* with high-temporal resolution measurements allows for capturing the hysteresis associated with the gradual propagation of flood waves, regardless of the river size. The hydrographs and the dependencies among the variables were directly measured in real-time using commercially available instruments proving that this type of measurements are actually achievable in field conditions. The experimental evidence presented in this section testifies that the fine-detail characterization of the streamflow pulses enables us to better understand the complex flow dynamics of open-channel flows subjected to hysteresis, and, in the same time, opening opportunities for further develop new approaches to explore rivers. Notable from the presented analysis is that the measurement of stage, index-velocity, or free-surface are sufficient to conceive new protocols for early flood warning alerts without the need to determine discharges, therefore circumventing the expensive and intensive effort of building the conventional ratings curves. Based on the inferences from these preliminary results, we are confident that the novel combination of the afore-mentioned methods will be better than any of the components working alone.

4. CONCLUSIONS

Motivated by the realization that there is a historic gap between the open-channel canonical governing equations and the principles for monitoring streamflow data in natural streams, we compiled in this paper some recent experimental results to illustrate that the new generation of high-temporal resolution instruments, complemented by physically-sound analytical considerations, can provide new and valuable experimental evidence on the dependencies between the streamflow variables in unsteady flows affected by hysteresis. The reported experimental results convincingly demonstrate that use of direct measurements acquired at index-velocity and continuous slope-area based gaging stations can accurately capture the hysteretic behavior associated with the gradual propagation of flood waves in real time. The two monitoring alternatives show promise in overcoming the well-known limitations of the stage-area method that basically totally ignores the hysteresis impact.

By combining the index-velocity and continuous slope-area method into one system, we set the foundations for a new, data science approach for real time estimation that enables hydrologists to estimate streamflow data more efficiently (by removing the expensive process of developing rating curves) and potentially providing short-term forecasting capabilities using only direct stream measurements. We are aware that our proof-of-concept and conclusions are based on a limited dataset. From this perspective, the outcomes of the discussion should be regarded as being indicative rather than confirmative. It is our hope, however, that these discussions illustrate the beneficial aspects of detecting and using hysteresis behavior as a reliable means of producing a new way for streamflow monitoring and forecasting using only direct in situ measurements for supporting scientific and practical purposes investigations in the riverine environments.

5. ACKNOWLEDGEMENTS

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