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Discussions

Technical Note: Monitoring of unsteady open channel flows using continuous slope-area method*

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Abstract. The advent of low-cost pressure transducers capable of directly measuring water surface elevation enables continuous measurements of dynamic water surface slopes. This opens up a new possibility of dynamically monitoring unsteady flows (i.e., hysteresis) during the course of flood wave propagation. Hysteresis in this context refers to a looped stage-discharge rating caused by unsteadiness of flows. Hysteresis is monitored in this study using a continuous slope area (CSA) method, which uses Manning's equation to calculate unsteady discharges based on continuously measured water surface slopes. In the rising stage, water surface slopes become steeper than a steady slope, resulting in higher discharges than steady-based discharges, while the trends are reversed in the falling stage. The CSA method is demonstrated on Clear Creek near Oxford (Iowa, USA), where it shows that CSA-based discharges deviate from the United States Geological Survey (USGS) steady-based discharges by 10% or less. The degree of hysteresis is also shown to vary depending on event scale (e.g., magnitude of unsteady forces) and vegetation condition. This evidence confirms that the CSA method has promising capabilities for dynamically tracking unsteady flows in natural streams. However, the use of a single channel bed slope (conceptually equal to the water surface slopes at every stage in uniform flow conditions) is not adequate in estimating the channel roughness, because non-uniformities of natural channels result in varying steady slopes at each stage. Therefore, "steady non-uniform slopes", which represent steady water surface slopes changing with stage, are considered. It is assumed that they can be estimated by simply averaging a pair of measured unsteady water surface slopes corresponding to the rising and falling limbs at the same stage, and the differences between steady non-uniform slopes and unsteady slopes can be considered as the effects of flow unsteadiness. The stage-dependent channel roughness values are approximated using these steady non-uniform slopes. While this approach is subject to validation in future research, the results are quite promising in this study.

* This submission was written by the author(s) acting in (his/her/their) own independent capacity and not on behalf of UT-Battelle, LLC, or its affiliates or successors.

1 Introduction

A conventional slope area method has commonly been used to estimate peak discharges based on high-water marks after large flood events, as those events are commonly rare and pose a measurement challenge in obtaining reliable sample data. The obtained data is then used for extending the upper limit of the stage-discharge rating curve (hQRC) which provides important input to inform timely flood management decisions and dissemination of imposed flood dangers to the public. The method estimates a stream (peak) discharge based on Manning's equation with inputs from the measured cross-sections, estimates for the channel roughness, and the friction slope derived from field evidence. It is also well known that the friction slope in Manning's equation is equivalent to the water-surface slope (or the streambed slope) if the channel is steady and uniform, and this consideration forms an important basis for utilizing the conventional slope area method. However, given the fact that natural channels are invariably non-uniform, an application of the conventional slope area method has been considered valid if channel non-uniformity is properly accounted for during the computation of the friction slope (Benson and Darlymple, 1967). Typically, the effects of channel non-uniformity can be minimized by computing the geometric mean of the conveyance using a series of cross-sections along the reach.

While the conventional slope area method has typically been used for estimating peak discharges, it has recently received renewed interest with the advent of low-cost pressure transducers capable of directly measuring water surface elevations, which enable continuous measurements of dynamic water surface slopes (Smith, et al., 2010). The CSA method was implemented on the Babocomari River (Arizona, USA) in 2002 by Smith et al. (2010) using eight pressure transducers deployed at both sides of the bank in four subsequent cross-sections. It was shown that the CSA method can be used to compute a continuous discharge hydrograph and to generate a steady hQRC. Researchers from University of Arizona and USGS co-published a paper regarding an implementation of the CSA gaging method at a network of sand-bedded ephemeral stream channels in southeast Arizona (Stewart et al., 2012). They concluded that the gaging efforts succeeded in monitoring and estimating discharges by comparing their estimates to the discharges estimated using a sharp-crested weir equation at the most upstream location. However, both implementations were conducted on steep channels where the effects of unsteady flows (a.k.a. hysteretic effects) were not a major concern. The available experimental data show that the difference in discharges between steady and unsteady conditions becomes significant for low gradient channels exposed to large flow unsteadiness (Di Baldassarre and Montanari, 2009; Dottori et al., 2009; Faye and Cherry, 1980; Fread, 1973, 1975; Fenton and Keller, 2001; Gunawan, 2010; Herschy, 1995). They indicated that the measured discharges between rising and falling limbs of the hydrograph at the same stage can vary approximately from 15% to 40%, and similarly, the measured stages at the same discharge can range from 10% to 25% in those studies.

The objective of this study is therefore to examine the feasibility of the CSA method for monitoring unsteady flows by continuously measuring the change of water surface slopes during flood wave propagation. Neither the conventional slope area method (Benson and Darlymple, 1967) nor the original CSA method (Smith, et al., 2010; Stewart et al., 2012) is intended to monitor unsteady flows; rather both are intended to compute a discharge based on steady flow assumptions. To

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achieve successful implementation of the CSA method, a selection of proper reaches and careful measurements are important to accurately capture the free-surface slope, inherent to the effects of unsteady flows. In the subsequent sections, a case study applied to the USGS site (05454220) on Clear Creek near Oxford (Iowa, USA) is presented. The hysteretic behavior of unsteady flows is also examined analytically using Fread's method (Fread, 1973, 1975; Lee and Muste, 2016) at the site.

2 Methodology

2.1 Study area and method

A selection of proper sites is important to ensure that governing equations on which the CSA method is based are applicable at a site. Benson and Darlymple (1967) specified that the length of the reach should be equal to or greater than 75 times of the mean depth in the channel and the fall in the reach should be equal to or greater than the velocity head with a minimum fall of 0.5 foot. Similarly, ISO 1070 (1992) stipulates requirements for the selection of proper reaches. For instance, it suggests that sites where progressive tendency of scour and fill exists, abrupt changes of the bed slope and cross-sections occur, irregular bed materials and obstacles exist, and flow regime changes be avoided to minimize the uncertainty associated with the computation of flow rates. Since finding an ideal natural channel reach that meets all these requirements is difficult, one should use their best engineering judgements in identifying proper sites under the consideration of potential uncertainties.

In this study, the USGS site (05454220) on Clear Creek near Oxford (Iowa, USA) is chosen due to this reach being accessible, straight, and uniform (Fig. 1). The additional site selection criteria presented in Benson and Darlymple (1967) and ISO 1070 (1992) were also carefully examined before the deployment of pressure sensors. It is also important to note that the site has a relatively mild channel bed slope (0.00039), which is necessary for successful implementation of the methodology during unsteady flows. For comparison, the average channel bed slopes in the studies by Smith et al. (2010) and Stewart et al. (2012) were approximately 0.009 and 0.012, respectively, and the effects of unsteady flows were negligible in those streams. Sudheer and Jain (2003) indicated that flood waves show a marked kinematic behavior when a channel bed slope is greater than 0.001. For all other cases, a variable energy slope driven by dynamic inertia and pressure forces should be considered in an analysis. Furthermore, the site's USGS stream gage is located approximately 85m from the upstream deployed sensor; therefore, it can be assumed that discharges are maintained over the short experimental reach because lateral inflows/outflows and seepages may be negligible.

The USGS steady-based discharges are utilized in estimating the channel roughness at the locations where the pressure transducers are deployed. The channel roughness at each time step can be computed using cross-sectional information and USGS discharge time series records with Manning's equation once the channel bed slope is identified. However, due to unavoidable non-uniformity of natural channel conditions, the estimation of channel roughness based on a single channel bed slope (surveyed water surface slope during low flow conditions) might not be accurate. The non-uniformity not only

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includes the geometric characteristics of the cross-sections but also may include the type and magnitude of vegetation along the reach. Therefore, the study herein proposes the use of "steady non-uniform slopes" which represents the steady water surface slopes changing with stage. It is assumed that they can be estimated by simply averaging a pair of measured unsteady water surface slopes corresponding to the rising and falling limbs at the same stage, while the differences between steady non-uniform slopes and unsteady slopes can be as attributed to the effects of flow unsteadiness. For example, if a pair of unsteady slopes is known as 0.00066 and 0.00069 in the rising and falling phases at the stage of 214m, the steady non-uniform slope can be computed as 0.000675 and the difference of 0.000015 can be considered as a result of the flow unsteadiness (Fig. 2). The suggested approach assumes that a steady water surface slope should exist somewhere between a pair of unsteady water surface slopes corresponding to the same stage. The assumption comes from the fact that a pressure gradient term (the major contributor in the momentum equation for open-channel flow) is added or subtracted from a channel bed slope for the rising and falling limbs, respectively, and this conceptually would place a steady water surface slope somewhere between a pair of unsteady slopes. This implies that if steady discharges can be constantly provided at a certain stage, the steady water surface slope would be different from the channel bed slope due to non-uniformity of the channel. However, the authors acknowledge that a simple averaging approach is a subject that should be validated in future study. The estimated steady non-uniform slopes are then used to compute stage-dependent "steady non-uniform channel roughness" by utilizing existing steady-based discharge records and surveyed cross-sections. It is also important to note that the approach implicitly assumes that a unique channel roughness value exists at every stage regardless of the phases of events, while this may not be true in reality. The effect of dynamic roughness changes during the course of events is assumed negligible simply because it is difficult to differentiate the causes. In other words, variations in the measured water surface slopes may result from the combination of complex dynamic interactions among various factors (e.g., vegetation condition changes, effects of sediment transports, and cross-sectional characteristic changes during flood wave propagation, etc.).

2.2 Experimental setup

A pair of pressure transducers, positioned approximately 200m apart, was deployed in 2015 as shown in Fig. 1. The upstream pressure transducer (PT) was installed on the left side of the bank, while the downstream PT was installed on the right side of the bank (looking downstream). Smith et al. (2010) and Stewart et al. (2012) recommended installing sensors on both sides of channel banks and at minimum of three cross-sectional locations to address any peculiarities in computing discharges and to increase reliability in the case of instrument malfunctions. Due to limited resources for this study, it is assumed that the use of two sensors can still provide the needed indication of the hysteretic behaviour.

The installed pressure transducers are encapsulated by the steel pipe casing, designed to measure a water column up to 10ft deep, which approximately corresponds to the bank full elevation at the site (see the top right picture in Fig. 1). After the deployment of sensors, a geodetic survey was conducted using Topcon Total Station[1] to record the water surface elevation at

[1] Use of trade, product, or commercial names does not imply endorsement by the authors or authors' institutions.

each sensor tip. This is important because the elevation at the tip of each sensor is used for the conversion of water surface elevations into a known vertical datum. To successively accomplish this, the USGS reference mark near the stream gage station was chosen to provide a known geodetic point that can serve as reference vertical datum of the Total Station survey. Based on this reference point, each sensor elevation is converted to North American Vertical Datum of 1988 (NAVD 88). This conversion is necessary to facilitate the data interpretation based on the same reference system. In addition, cross-sections at each PT were also surveyed using this instrument (Fig. 3). Even though there are some local differences, the cross-sections have very similar geometric characteristics. These probe surveys have been repeated to ensure there was no vertical displacement of sensor tip elevations and no change in the cross-sectional geometry during each site visit. Should the vertical elevations of sensors move during storm events, this movement may lead to the erroneous estimation of water surface slopes. Moreover, other site conditions, such as the type of bed materials and the presence of transition points where a vegetation type is changing, were also identified to help interpret the results. It was observed that the channel bed was composed primarily of clay and the channel bank was covered with thick vegetation. Additionally, the spatial distance between the pressure sensors along the centerline of the channel and the water surface slope (bed slope) at low flows was surveyed when deploying the pressure transducers. The water surface slope at low flows was measured using Topcon Total Station by taking shots on the water surface along either side of banks. The results were consistent regardless of the side of banks. The surveyed slope was 0.00039, which closely agrees with the survey conducted by US Army Corps of Engineers (USACE). It is important to acknowledge that the measured bed slope is used only for the computation of unsteady flows when using analytical solution (Fread, 1973, 1975; Lee and Muste, 2016), and is not needed for the computation of the CSA based discharges. Fread's method computes either stages or discharges corresponding to unsteady flows using a full one-dimensional momentum and Manning's equation once the steady time series of the other is given. Lee and Muste (2016) modified the original Fread's method to better account for the actual geometry of cross sections and improved the accuracy associated with the estimation of conveyance factors and energy slopes, which is particularly useful for small to mid-size streams/rivers such as the site selected in this study.

2.3 Selection of hydrologic events

A total of seven small to large scale events have been recorded during the measurement campaign in 2015 at the site. Among them, the three largest events presented in Figs. 4a), 4b), and 4c) are selected for demonstration of the CSA method. The stage hydrographs presented in Fig. 4 are the recorded water surface elevations from the installed pair of pressure transducers. Throughout each of the events, the water level has increased approximately 10 ft., 7 ft., and 6 ft., respectively, representing medium to large scale events at this site.

3 Results and discussion

Figure 5 shows the computed variation of water surface slopes between the pressure transducers as a function of stage at the downstream PT for the three selected 2015 events. The axis scales are set consistent across the figures to help compare their relative event scales. The water surface slopes are computed using the measured water surface elevations at each pressure transducer and the distance measured along the centerline of the channel between them. The results clearly confirm the existence of hysteresis in water surface slopes in the rising and falling limbs. It is also found that hysteresis loop in this study rotates counter-clockwise direction as generally known as the direction of hysteresis. A clockwise movement behavior, typically as attributed to the effects of vegetation has rarely been observed (e.g., Gunawan, 2010). Authors herein believe that clockwise movement occurs when vegetation produces large resistance to the flow in the rising limb, thus reducing the magnitude of hysteresis. At the same time, the vegetation is being inclined due to the excessive shear exerted by flows during that process. This leads to less friction in the falling limb, thus increasing water surface slopes in the falling limb. Clockwise hysteresis therefore seems to be driven by a combination of unsteady forces with the forces induced by dynamics of vegetation, while the typical counter-clockwise pattern observed in this study seems to be mainly triggered by unsteady momentum. It is also observed that the variation of water surface slopes becomes larger as the scale of events becomes greater as shown in Fig. 5a), ranging approximately from 0.0003 to 0.0007. As the event scale increases, dynamic forces would become strong. Figure 6 demonstrates a comparison of the CSA discharges when the channel roughness is estimated using either steady slopes or steady non-uniform slopes at downstream PT. Figures 6a), 6b), and 6c) show steady, measured unsteady, and steady non-uniform slopes, and Figures 6d), 6e), and 6f) indicate the calculated channel roughness using either steady or steady non-uniform slopes for the events 1, 2, and 3, respectively. The channel roughness is subsequently calculated using the measured cross-section at the downstream PT, USGS steady discharge records, and Manning's equation. While the channel roughness falls into the typical ranges (between 0.03 and 0.05) for the events 1 and 2, the value for event 3 is very high. Authors strongly believe that this is an artifact of errors caused by cross-sectional changes. Authors found evidence that there have been a few shift adjustments of the current rating curve after event 2, even though the threshold value for changing the rating curve version has not been met. However, Chow (1959) described that the maximum channel roughness value of 0.15 is sometimes not impossible for very weedy reaches, deep pools, or floodways with a heavy stand of timber and underbrush in open channel flow. Considering that vegetation was dense and there had not been a major flood event after event 2, there is a small possibility of being this case. Figures 6g), 6h), and 6e) compare the CSA discharges when either steady or steady non-uniform channel roughness is used. For events 1 and 2, major differences are observed near peak discharges as a result of large differences in the channel roughness at high stages (Figs. 6d) and 6e)), while peak discharges match well for event 3. The large differences associated with events 1 and 2 seem to be caused by the use of a single steady slope for deriving the channel roughness.

Figures 7 and 8 provide computed dynamic hQRCs and discharge hydrographs at downstream PT, respectively based on the measured water surface slopes between the pressure transducers, the surveyed cross-section at downstream PT, and the channel roughness estimated using steady non-uniform slopes. Also plotted are the discharges based on steady USGS records and the modified Fread's method for comparisons. The unsteady discharges based on the CSA method indicate that discharge values may deviate from USGS-based values by up to 10%, while the modified Fread's method indicates differences of up to 30%. The 20% difference between these methods is believed to result from vegetation effects. The modified Fread's method is not able to properly account for complex dynamic interactions between the water surface slopes and the channel roughness during the course of event; those interactions can be better accounted for by the CSA method. While the modified Fread's method is able to provide a good indication when the vegetation is minimal, the CSA method can be used more generally in natural streams where complex interactions between the water surface slope and the vegetation are expected. It is worth noting that the CSA method is designed to use a minimum of two gages, so it is supposedly more accurate than the Fread's method, which uses a single gage and assumes longitudinal uniformity of the channel.

4 Conclusions and future work

This study provides evidence of the CSA method's capabilities for dynamically tracking unsteady flows in natural streams. While the magnitude of hysteresis depends on event scales and site conditions including the effects attributed to unsteady forces and vegetation, the CSA method applied on Clear Creek near Oxford (Iowa, USA) estimates the difference in discharges by 10% or less compared to the USGS steady-based records. It is also found that the use of the steady water surface slope surveyed at low flow conditions (representative of the channel bed slope) may not be ideal for deriving the channel roughness since the channel roughness changes with stage due to non-uniformity of natural channel characteristics. Therefore, a concept of "steady non-uniform slopes", which represent the steady water surface slopes changing with stage, is considered. The stage-dependent channel roughness values are approximated using these steady non-uniform slopes, estimated by simply averaging a pair of unsteady water surface slopes corresponding to the rising and falling limbs at the same stage to provide the best approximations of steady water surface slopes for non-uniform conditions. The exact value of defining the steady non-uniform slopes between a pair of unsteady water surface slopes (not as a simple average) would need more investigations in future study. It is also shown that the results from the modified Fread's method (Lee and Muste, 2016) demonstrate a larger hysteresis loop than one computed by the CSA method. As the modified Fread's method is not able to account for dynamic interactions attributed to unsteady forces and vegetation changes, the CSA method seems to provide a better solution for monitoring unsteady flows in natural channels where the vegetation plays a significant role. For a successful implementation of the CSA method in future study, a collection of validation data using direct discharge measurements would be necessary. This information with the measured water surfaces from the CSA method would inform a more accurate way of evaluating dynamic channel roughness. In addition, transducer clock drifts when the battery is low, the time synchronization errors between gages, sensor movements, and sediment induced errors should also be carefully examined when utilizing the CSA method (Stewart et al., 2012).

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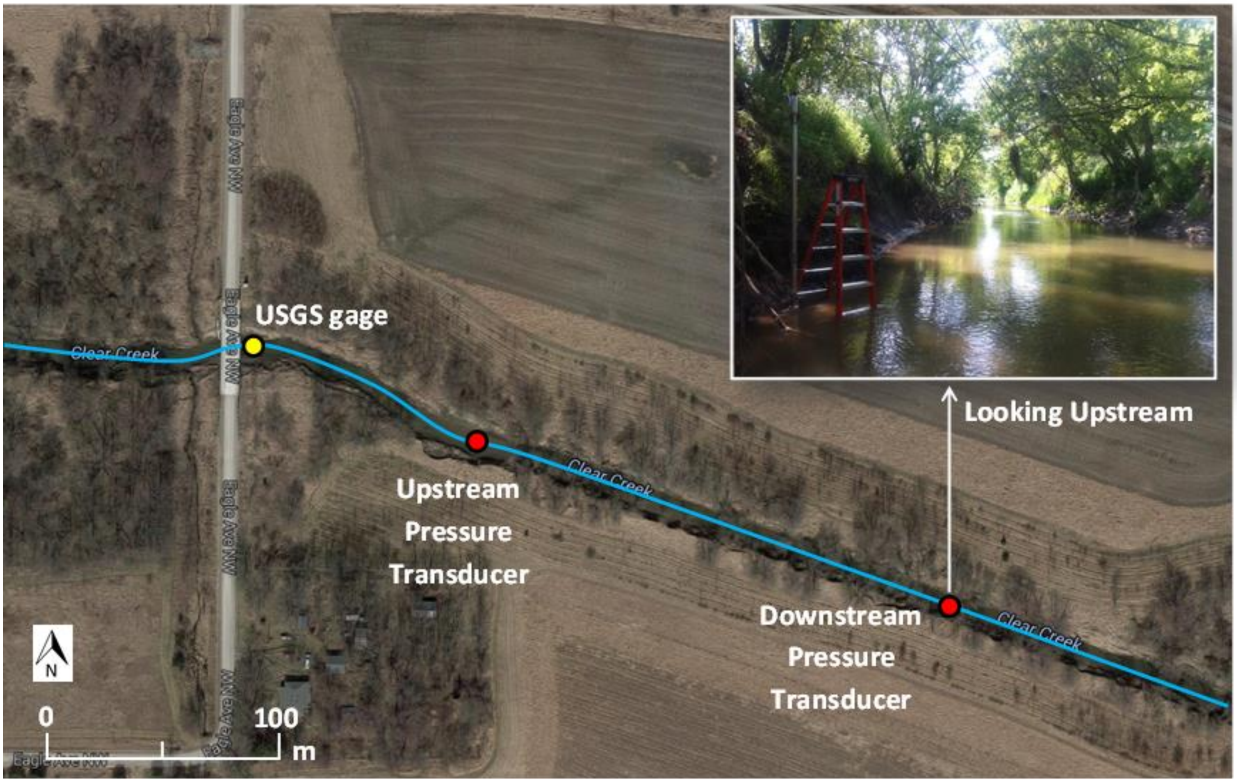

Figure 1: Study area demonstrating a pair of pressure transducer locations at the USGS site (05454220) on Clear Creek near Oxford (Iowa, USA).

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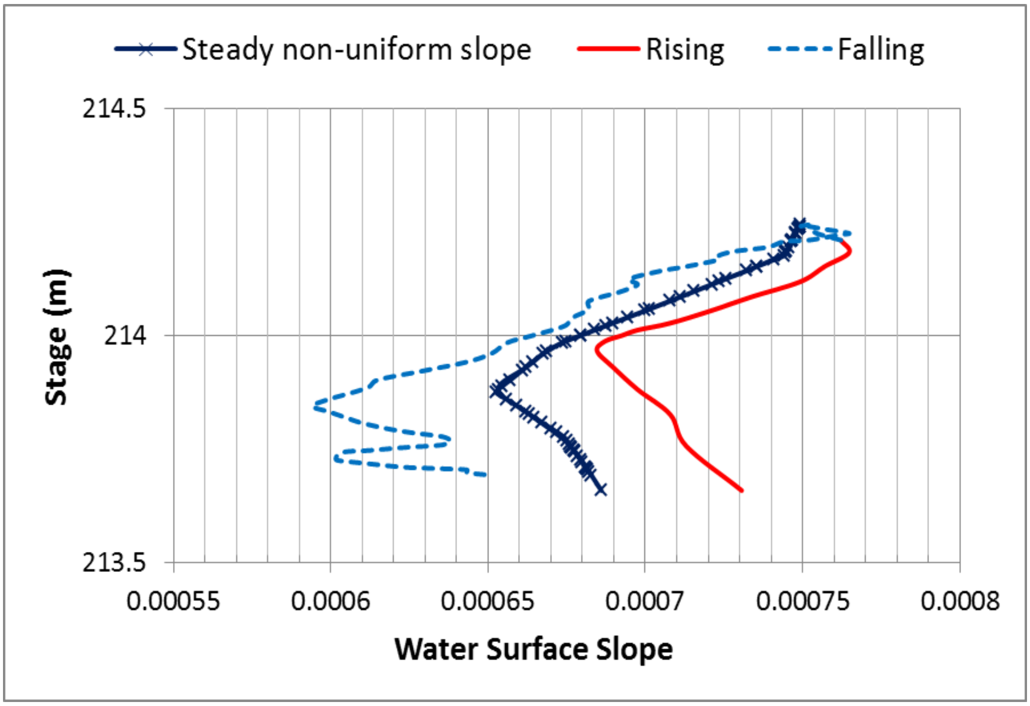


Figure 2: An example estimation of the steady non-uniform slopes by averaging a pair of measured unsteady water surface slopes corresponding to the rising and falling limbs at the same stage.

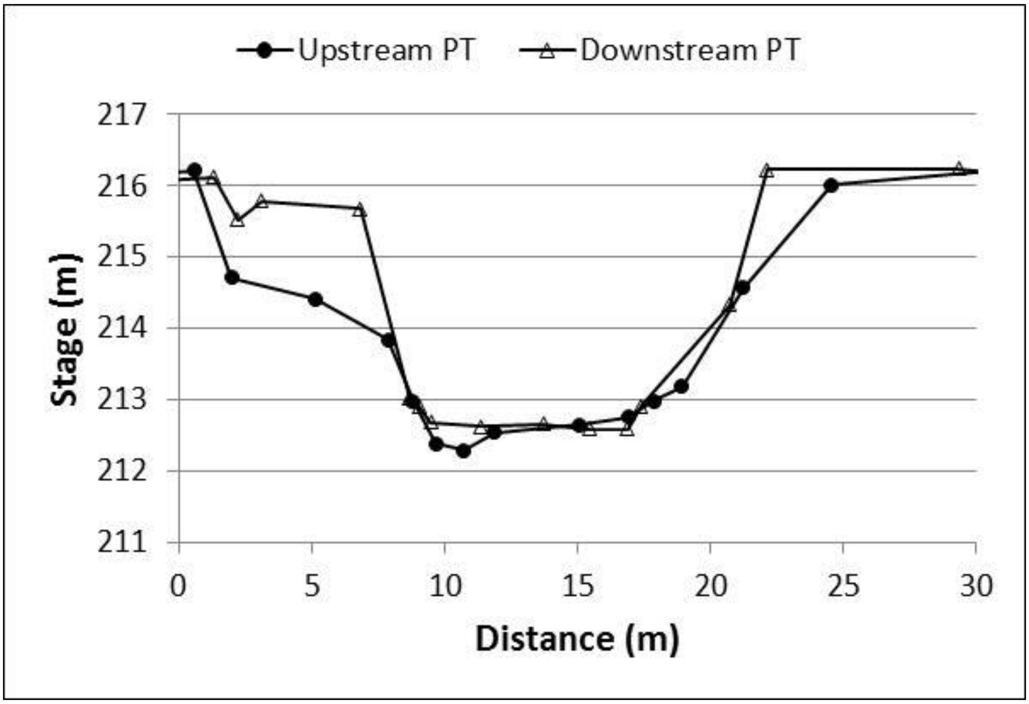
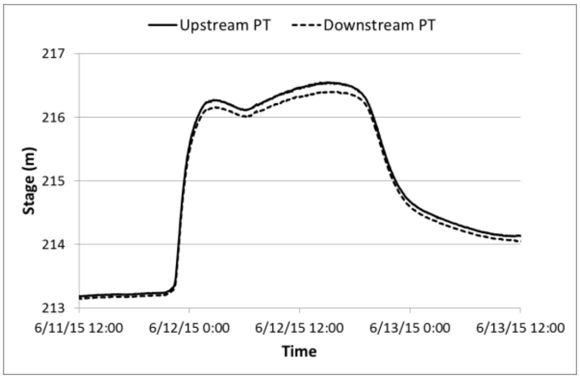
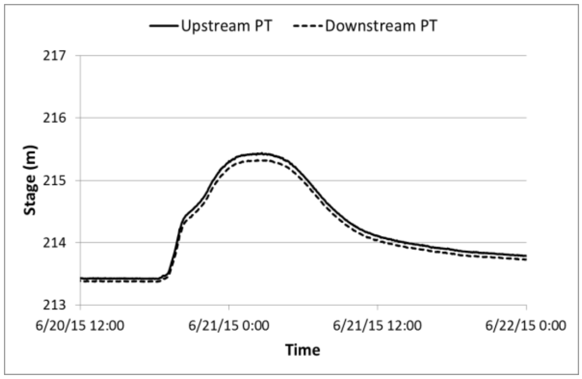


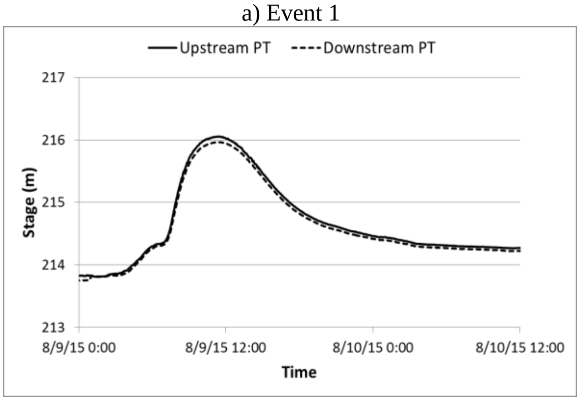
Figure 3: Surveyed cross-sections at upstream PT and downstream PT locations.



a) Event 1



b) Event 2



c) Event 3

Figure 4: Event stage hydrographs for the selected three events.

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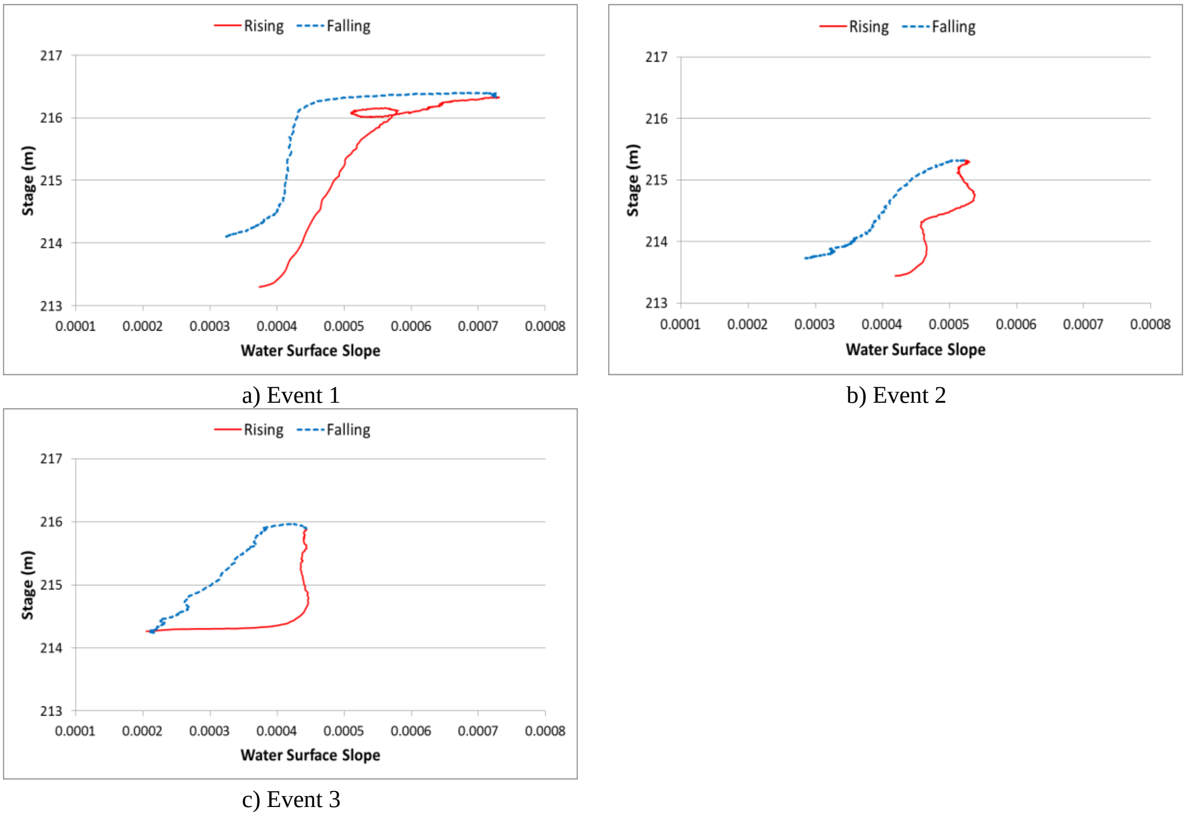

Figure 5: Measured hysteretic behaviour of water surface slopes for the selected three events.

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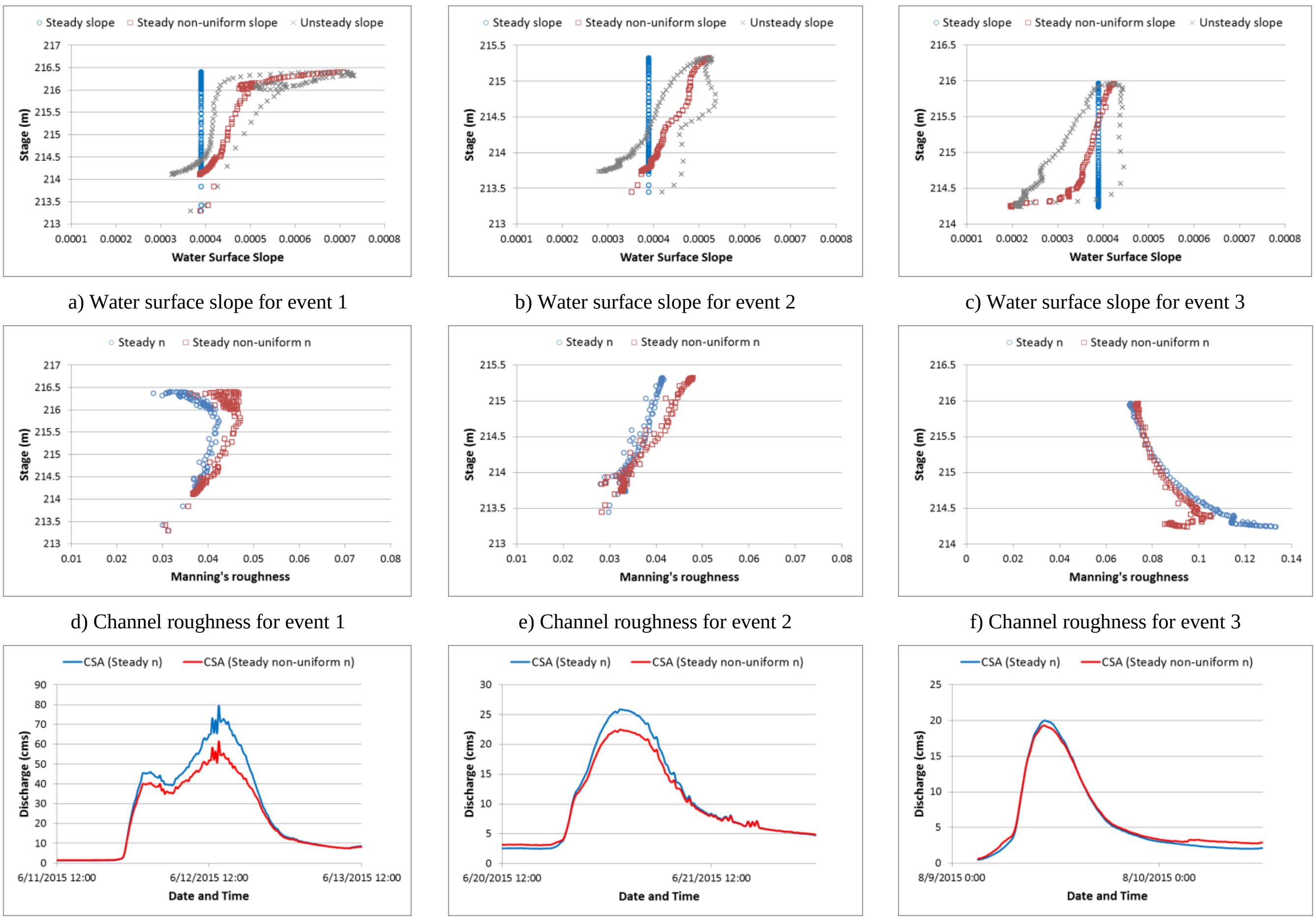

a) Water surface slope for event 1
b) Water surface slope for event 2
c) Water surface slope for event 3
d) Channel roughness for event 1
e) Channel roughness for event 2
f) Channel roughness for event 3
g) CSA discharge for event 1
h) CSA discharge for event 2
i) CSA discharge for event 3

Figure 6: Comparison of the CSA discharges when the channel roughness is estimated using either steady slopes or steady non-uniform slopes at downstream PT.

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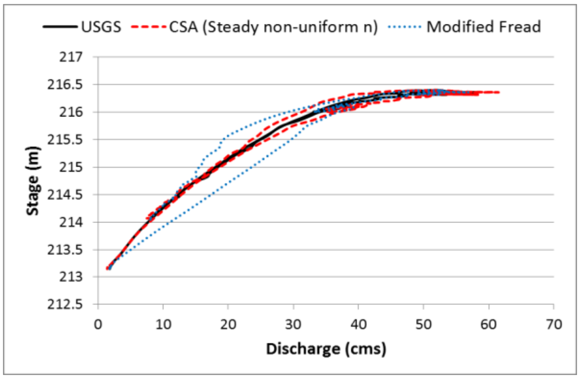
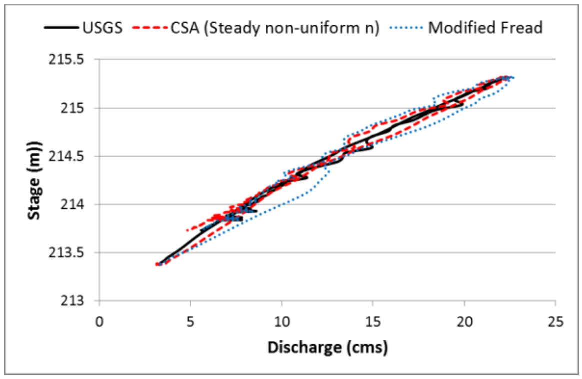
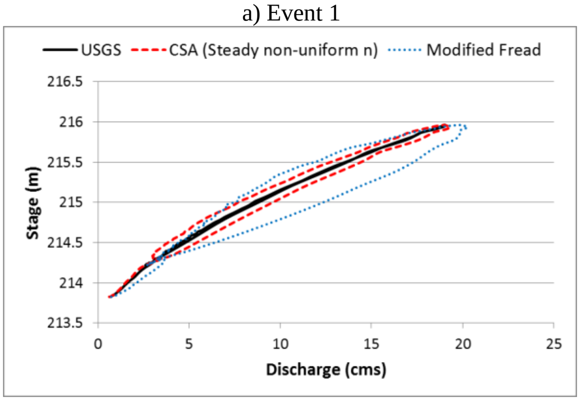


a) Event 1

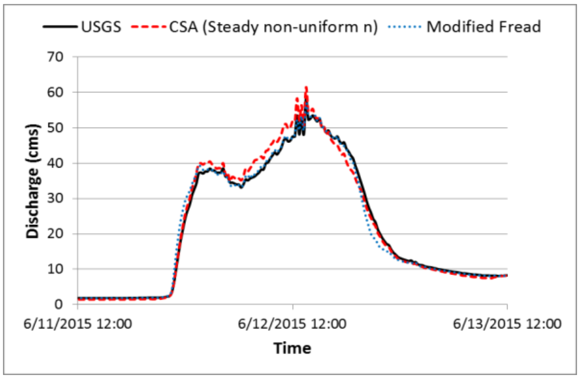


b) Event 2

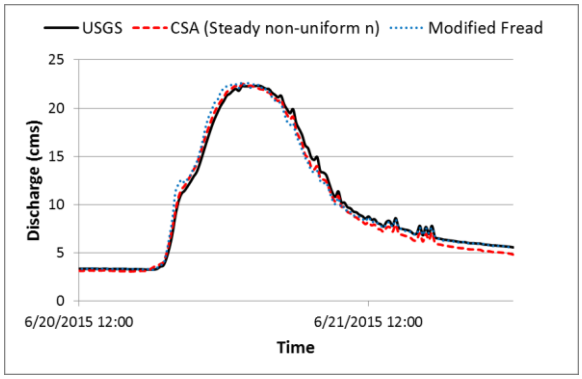


c) Event 3

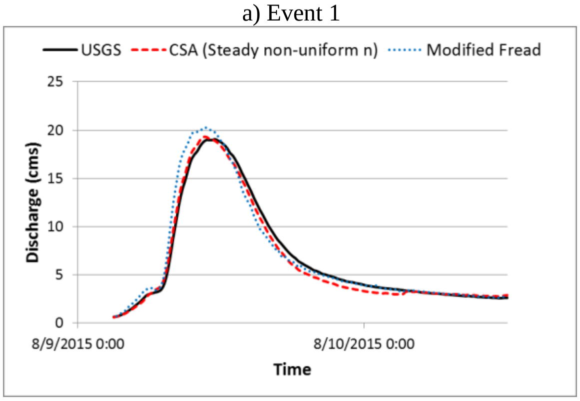
Figure 7: Comparison of hQRCs at downstream PT based on the USGS, CSA, and Modified Fread's methods for the selected three events.



a) Event 1



b) Event 2



c) Event 3

Figure 8: Comparison of discharge hydrographs at downstream PT based on the USGS, CSA, and Modified Fread's methods for the selected three events.