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Examining the Effects of Water Surface Slope and Water Stage on Sediment Transport During Short-Lived Hydrographs: An Experimental Study

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Abstract

Flash floods in ephemeral streams are unpredictable, rare, and generally short-lived. Since bed load sediment flux in ephemeral streams is as much as 17 and 35 times that of perennial streams under comparable flows, the prediction of sediment transport is important. Developing a predictive relation between sediment transport/shear stress requires estimates of both the water-surface slope (as a surrogate for the energy slope) and the water stage. Here, 6 triangular hydrographs having peak flows varying from 0.0147 to 0.02 $m^3s^{-1}$and durations ranging from 150 to 400 seconds were run over a screeded bed of poorly sorted sediment of 4.1 mm median grain size to assess the effect of changing water stage on water-surface slope and, hence, bottom shear stress and consequent bedload flux. Results clearly indicate that the water-surface slope (S_w) and bedload sediment discharge (Q_s) relate directly to water discharge (Q_w) and stage. But each relation manifests a clockwise hysteresis: S_w and $Q_s$they are both significantly larger during the rising limb of the hydrograph than during the falling limb. This indicates the value of treating water-surface slope as a variable when predicting bedload flux during flash floods in ephemeral channels.

1. Introduction

A flash flood occurs when water rises rapidly in a low-lying area within hours of heavy rainfall. It differs from a regular flood in terms of speed and suddenness. The field of bed load in flash floods has seen extensive research in recent years. Numerous studies have explored sediment movement under the dynamic conditions of flash flood events. To determine river behavior, it is necessary to accurately describe river discharge under unsteady flow conditions. The slope of the water surface is typically assumed constant in computations of bedload sediment transport in rivers, even though it is a key controlling variable for shear stress, which is used to calculate sediment flux (Meirovich et al., 1998). Thus, understanding streamflow and its corresponding uncertainty is essential for water resources engineering practice (Basel and Kawanisi, 2018). Ephemeral gravel bed streams typically have bed surfaces that are relatively unarmored compared to the substrate below, while gravel bed streams in

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humid and snowmelt areas typically have well-armoured surfaces (Marvan et al., 2006). This is because the flashy flow regime impedes the sorting of bed sediment, resulting in unarmoured beds, as noted by (Marvan et al., 2006; Mao, 2012). Unsteady flow events, such as those res

ulting from intense rainfall events, can cause sediment hysteresis in alluvial rivers (Gunsolus et al., 2017). The types of hysteresis are divided into the following groups based on their loop: 1) clockwise, 2) anticlockwise or counterclockwise, 3) single value, 4) single value with loop, e) figure eight (Ahangar et al., 2008). If flume experiments done using unsteady flow are rather limited (Mrokowska et al., 2019). In very short-duration hydrographs, sediment transport rates are significantly influenced by hydrograph duration, water surface slope, and water levelThe water surface slope indicates the slope or gradient of the water surface elevation along the length of the river or channel. In unsteady flow, the water surface slope S_w it is not necessarily parallel to the channel bottom slope because of flow acceleration and deceleration. During unsteady flow events, such as floods, a hysteresis effect can occur, in which the water surface slope differs between the rising and falling limbs of the flood wave at the same discharge. This is due to unsteady and downstream backwater effects, such as accelerations and decelerations (Basel and Kawanisi, 2018). The water stage at a cross-section directly relates to the water surface slope (S_w) through the energy equation. A steeper S_w corresponds to a higher water stage for the same discharge. Generally, the S_w influences the water stage through unsteady effects captured in the energy equation, and this relationship can exhibit hysteresis during flood waves because of unsteady flow behavior. In open channel flow, the S_w plays an important role in calculating the magnitude of the shear stress acting on the channel bed. The difference in shear velocities predicted by steady and unsteady formulations increases with the unsteadiness of the flow. In addition, the shear velocity in accelerating flows is generally higher than that in decelerating flows. This information is very useful for sediment transport studies in unsteady flows (Pathirana et al., 2006). Shear stress is a significant factor in determining bed load transport. Tian (2024) showed that hydrodynamic models like MIKE 11 can accurately simulate water surface profiles and slopes under varying flow conditions. The water surface slope is a critical parameter for understanding and predicting water level changes in rivers. Mao & Recking (2024) offered a comprehensive review of sediment transport dynamics under unsteady flow conditions, highlighting the challenges and opportunities in this during experimental flash floods over dry beds and flowing water. This research shows that bed shear stress can significantly influence sediment transport under unsteady conditions. The S_w varies over time within a single river reach (Reid et al., 1998). The slope values during the rising limb are steeper than those of the hydrograph's falling limb (Dingman, 1984). However, S_w is often considered constant for predicting bedload sediment transport due to a lack of data at monitoring stations. Nonetheless, significant changes in the S_w occur in rivers, particularly during flash floods in desert streams. Water surface slope has a pronounced impact on sediment transport assessment, especially in thick-yield ephemeral streams. Meirovich et al. (1998) reported that when water surface slope is treated as a variable in applying a bed load equation, flood bedload yields are 8% higher than those derived with the same equation but with the water surface slope held constant and approximating the channel bed slope Basel and Kawanisi (2018) demonstrated the corresponding S_w hysteresis during various rainfall events, indicating three hysteresis loop patterns, with clockwise hysteresis occurring during highly intense hydrological events. The impact of the S_w may be mitigated in longer period channels. Bombar (2016) published measurement data on water levels along rising limbs in an 18-meter-long channel. Zwolenik and Michalec (2023) demonstrated that the water surface slope did not affect Manning's roughness coefficient in gravel-bed streams. Various hydraulic parameters can influence bed load sediment transport. Therefore, it is essential to study ephemeral water slopes to better understand their impacts and potential risks. Erosion processes may affect the water surface level when water depth is relatively small in experimental flumes (Mrokowska et al., 2018). This research could enhance disaster preparedness and management and provide a better understanding of the overall water cycle and its intricate dynamics. Very few studies have been conducted to estimate bed shear stress in unsteady flows over rough channel beds. This paper analyzes the relationships among sediment transport rates, flow hydrographs, water surface slope, water levels, and variable shear stress under unsteady flow conditions. While the influence of flood sequences on bedload transport has been recently demonstrated (Askari et al., 2024), the concurrent role of water-surface slope and water stage in modulating shear stress and sediment flux during short-lived hydrographs has received significantly less scholarly attention. In most practical applications, the water-surface slope is presumed to be constant and equal to the bed slope. This approximation may be particularly inadequate in cases of flash floods, where rapid flow acceleration and deceleration occur. Askari et al. (2024) observed that the absence of armoring in their experiments allowed coarse sediments to remain mobile throughout the hydrographs, although they did not explicitly quantify the temporal evolution of the water-surface slope. Consequently, this study extends prior research by systematically measuring water-surface slopes and stages during similar types of flash hydrographs, with the objective of providing a physically based linkage between unsteady flow hydraulics and bedload flux. Such findings will assist in evaluating the validity of employing the water-surface slope as a dynamic variable in shear stress computation within ephemeral channels.

2. Materials and Methods

The experiments were conducted in a rectangular flume measuring 10 m long, 0.3 m wide, and 0.5 m deep (Fig. 1). The upstream half of the flume (5 m) was roughened by glueing sediments to the bed. In contrast, the downstream half contained a well-mixed 10-cm layer of sediment. The water level was measured at 10 points, spaced 50 cm apart, along the flume portion filled with loose sediments. Additionally, three cameras were installed along the side of the flume to take pictures every 20 seconds and record water depth (Fig. 1). The sediment mixtures (Table 1), poorly sorted with a median size of 4.1 mm, were used in the experiments. The experiment was conducted without sediment feed from the upstream end of the flume. The entire active layer of the bed was thoroughly mixed to avoid vertical layering. The sediment porosity was calculated to be 0.39.

Table 1. Sediment characteristics

Classification	σ_g	D_{16}(mm)	D_{84}(mm)	D_{50}(mm)	D_{min} (mm)	D_{max} (mm)
Poorly-sorted	1.60	2.5	8	4.1	2	8

The runs consisted of symmetrical triangular hydrographs with different durations and magnitudes. Six different hydrographs have been simulated (Fig 2). Four hydrographs featured approximately the same duration of 150 sec but differed in terms of peak (14.77 l/s) for type A, (16.2 l/s) for type D, (17.4 l/s) for type B, and (20.2 l/s) for type C, and further two hydrographs had the same peak as type D (16.2 ls^{-1}) but had longer durations of 300 sec (type E) and 400 sec (type F). The bed was flattened at the beginning of every experimental run. In all the tests, the slope of the flume was constant at 0.0089. Sediment transport rates were measured over 30 s intervals using a sediment trap located at the downstream end of the flume. However, this depended on the transport rate (i.e., the interval was larger when the transport rate was lower).

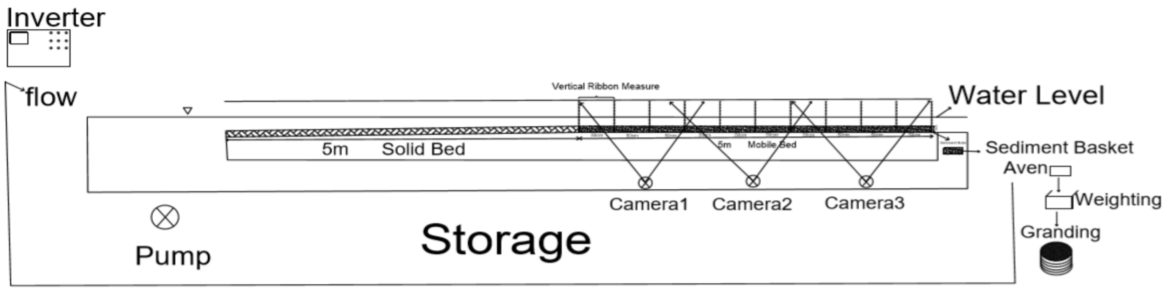

Figure 1. Schematic representation of the flume showing the cameras' positions and the locations where water depth was measured

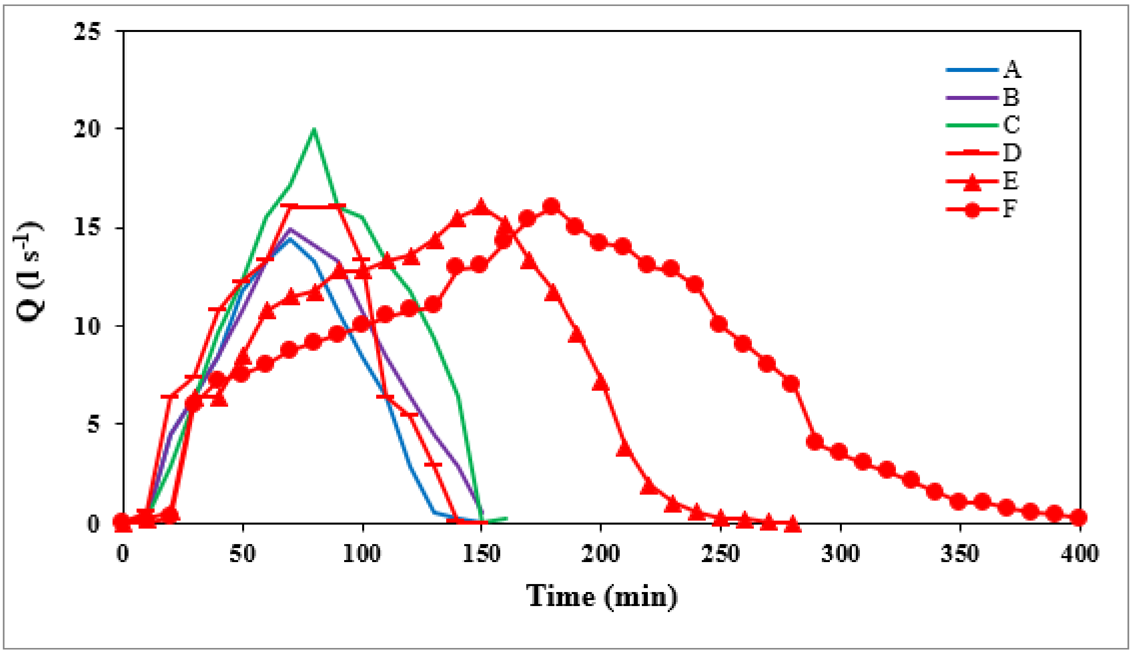

Figure 2. Symmetrical hydrographs with varying durations and magnitudes were simulated in the experimental flume. Hydrographs A, B, and C have the same duration but different peak discharges, while hydrographs D, E, and F have the same peak discharge but different durations.

2.1. Water Surface Slope (S_w)

In unsteady flow, the S_w varies with time and location. The S_w in unsteady flow is not constant, and changes as depth and velocity vary. Unlike steady flow, where depth and velocity remain constant at a given location, unsteady flow involves fluctuations in these parameters, leading to a changing S_w. The Saint-Venant equations are a set of partial differential equations used to model unsteady flow in open channels, where water depth and velocity vary with time and location. These equations consist of the continuity equation (conservation of mass) and the momentum equation (conservation of momentum), which account for inertial forces, pressure gradients, and friction losses. In unsteady flow, the water surface slope (S_w) is not constant and changes dynamically due to fluctuations in depth and velocity. The Saint-Venant equations are particularly useful for determining S_w in unsteady flow conditions, as they provide a framework to simulate how S_w evolves and spaces, Chow (1959) and Chaudhry (2008).In unsteady flow, for measuring slope, the Saint-Venant equation was used in flowing:

$$S_f \cong S_0 - \frac{\partial h}{\partial x} - \frac{V\partial V}{g\partial x} - \frac{1}{g}\frac{\partial V}{\partial t} \quad (1)$$

Where S_f is the friction slope, S_0 is the bed slope, $\frac{\partial h}{\partial x}$ is the diffusive wave, $\frac{V\partial V}{g\partial x}$ is a dynamic quasi-steady wave, $\frac{1}{g}\frac{\partial V}{\partial t}$ is a dynamic wave, g is gravity, and V is the mean flow velocity.
The full equation is called a dynamic-wave approximation of the Saint-Venant equation. In uniform flow, $\frac{\partial h}{\partial x}$ =0, $S_w \cong S_0$. In many applications, however, the term $\frac{V\partial V}{g\partial x}$ is very small and can be neglected. For all steady flows, as well as unsteady flows in which $\frac{1}{g}\frac{\partial V}{\partial t}$ is negligible; in most rivers, the flow is subcritical, Fr < 1, and the velocity head gradient $\frac{V\partial V}{g\partial x}$ can be neglected. The diffusive-wave approximation, $S_f \cong S_0 - \frac{\partial h}{\partial x}$, is commonly used in river mechanics. Finally, the kinematic-wave approximation is obtained in which all but the first two terms vanish (Julien, 2002).

2.2. Shear stress

The S_w has a significant role in predicting bed load transport. However, determining bedload flux is not a complex variable in a steady flow. The shear stress distribution is linear for steady, uniform flow in an open channel, decreasing from a maximum at the bed to zero at the free surface. The bed shear stress is given by:

$$\tau_0 = \gamma R S_0 \quad (2)$$

Where τ_0 is shear stress, R is the hydraulic radius, and S_0 is the bed slope. For unsteady flow, using $\tau_w = \gamma R S_w$ where $S_w = S_0 - \frac{\partial h}{\partial x}$ can calculate shear stress. The Table shows the WSS for some experiments with their shear stress. Sediment transport rates (Qs) correlate with shear stress, which depends on WSS. Coarser grains mobilize when τw exceeds their critical threshold, while finer grains dominate during lower shear stress (falling limb). The absence of armoring ensures sustained sediment mobility, as bed reorganization prevents coarser grains from forming a protective layer (Meirovich et al., 1998).

3. Results and Discussion

In open-channel flow, the cap S sub w significantly determines the magnitude of the shear stress acting on the channel bed (Meirovich et al., 1998). Calculating shear stress in unsteady flow has always posed challenges for researchers. Since experiments were conducted under unsteady flow conditions to measure shear stress, the present study utilized the Saint-Venant equation for these calculations. The relationship between S_w and sediment transport is complex and interconnected, as flow dynamics, bed morphology, and hydraulic conditions play significant roles. The S_w has a pronounced impact on sediment transport, especially in high-yield ephemeral streams (Reid, 1998). Figure 3 shows hydrographs A1, A2, B1, B2, and C1, C2, which have a common time-base of 150 s but vary in peak discharge, A, B, C reaching flows of 14.7, 17.4, and 20.2 ls^{-1}, respectively. Figure 3 illustrates the clockwise hysteresis between the water stage and (S_w). During unsteady flow, the $S_w$peaks before the water stage. This is because the slope is steepest at the flood wave's leading edge, driving high discharge early while the stage continues to rise until inflow balances outflow. Basel and Kavanisi (2018) showed clockwise hysteresis between water surface slope and water stage in medium and high-intensity rainfall (Reid et al., 1998), with monitoring at Nahal Yatir and Nahal Eshtemoa indicating a clockwise hysteresis between the cap SS_w and water stages n addition, the figures on the right show tthat the cap S_w occurs before the water sstage forall graphs A2, B2, and C2. The maximum water stage occurred in C1 with most of the peak discharge (20.2 ls^{-1}), approximately 0.18 m, while S_w shows 0.022. At the lowest peak discharge A1, the maximum water stage is 0.15 m, while cap S sub w ows 0.015. That is why lthe arger peak discharge C1 transported more bed load than A1, Figure 5

(A and C) 140 and 230 gs^{-1} respectively. A steeper rising limb creates a larger shear stress equal to $\tau_w = \gamma h S_w$. Unsteady flow events, such as flash floods, lead to rapid changes in S_w and water stage (Mrokowska, 2019). Figure 4 illustrates hydrograph D1, D2, E1, E2, and F1, F2 with the constant peak of hydrograph 16.2 ls^{-1} to the hydrograph under short-duration hydrographs 150, 300, and 400 Sec, respectively. The results show that D1, E1, and F1 exhibit pronounced clockwise hysteresis loops between S_w and the water stage. Figure 5 shows the sediment transport rates at the peak of the hydrograph for D, E, and F (180, 160, 150) gs^{-1} , respectively. The results indicated that as hydrograph duration increased, the sediment transport rate (Q_s) at peak decreased. This means that stress was increased more slowly. It might be that, under these conditions, the micro-scale rearrangement of the grains caused the traction threshold to be higher and, consequently, bedload flux to be lower. for instance, the slightly proud coarser grains might have been moved early by the rapid increase in stress during the short-duration hydrograph with its rapid rise in stage. In contrast, many of these might have remained in situ during the longer-duration gentler rise hydrograph and formed obstacle clasts trapping other grains. The flashiness of the hydrograph is probably the cause of this, as the very short duration of the events does not allow the surface sediments to develop a coarser armor layer, and coarse sediments are actively transported throughout the runs. The duration of the experiments was not sufficient for winnowing to play an important role in vertical sediment sorting either, which hampers the chances of surface sediments developing an armor layer. In poorly sorted sediment, coarse particles are more exposed to flow, and finer fractions increase the transport rate of coarse particles compared to well-sorted sediment. This has been observed previously, too, by Khosravi et al. (2019). Figure 5. The clockwise hysteresis in the Q_s versus Q_wRelationships in all hydrographs (A-F) reveal temporal decoupling between sediment transport rates and hydrographs, whereby sediment transport rates achieve their peaks before flow discharge. Wang (2022) showed bed load sediment transport patterns in symmetrical flows, clockwise hysteresis for the coarse size class. This pattern matches experiments in which sediment supply is high at the start but diminishes over the hydrograph duration, even in the absence of armoring. This aligns with Meirovich et al. (1998), who attributed the steeper water-surface slopes in the ascending limbs to inertial effects and flow acceleration, thereby enhancing sediment transport capacity. As the flow recedes (falling limb), reduced shear stress and flow deceleration favor the transport of finer sediments, creating a lag between peak flow and sediment response (Table 2). Pathirana (2006) showed that shear velocities in the rising limb are greater than in the falling limb. In this study, the water surface slope in the falling limb is revealed to be closer to the bed slope. As the flash flood recedes, the water surface slope tends to approach the bed slope but can still be slightly steeper (Halfi, 2018). For hydrographs, A-C (constant time, variable peak discharge) and larger peak discharges (14.7–20.2) ls^{-1} were illustrated with a higher sediment transport rate (Q_s) than smaller hydrographs, for hydrographs, D, E, and F (constant peak discharge, variable duration) and longer flow durations (150,300,400) sec would have prolonged sediment transport but still caused hysteresis through progressive bed stabilization These findings agree with Recking (2013) and Mao (2018), who attributed clockwise hysteresis to flow-sediment feedback and temporary bedload supply in unarmoured systems.

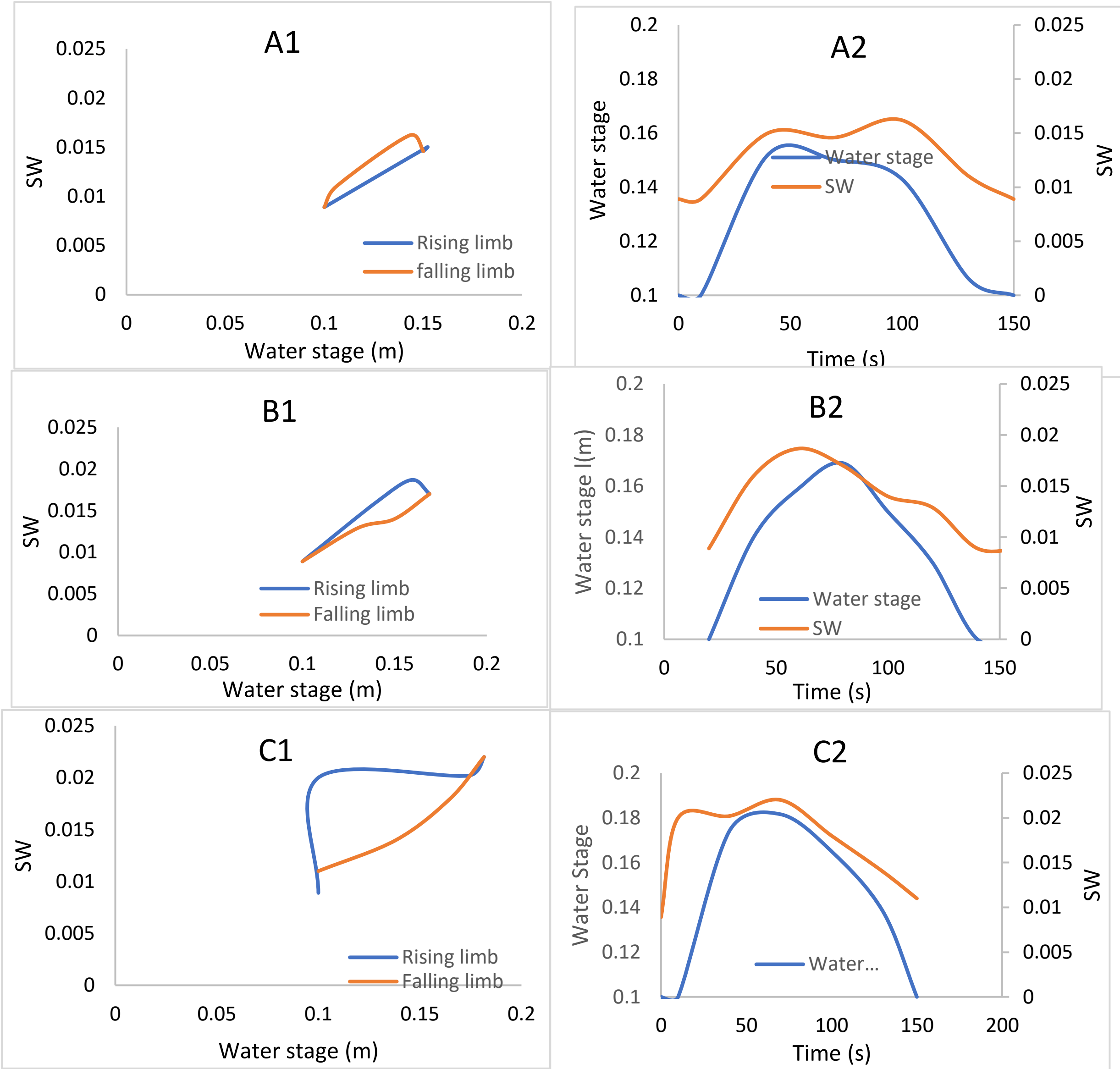

Figure 3. Temporal variations between S_w and water stage, A, B, and C, with a constant time duration and variable hydrograph peaks

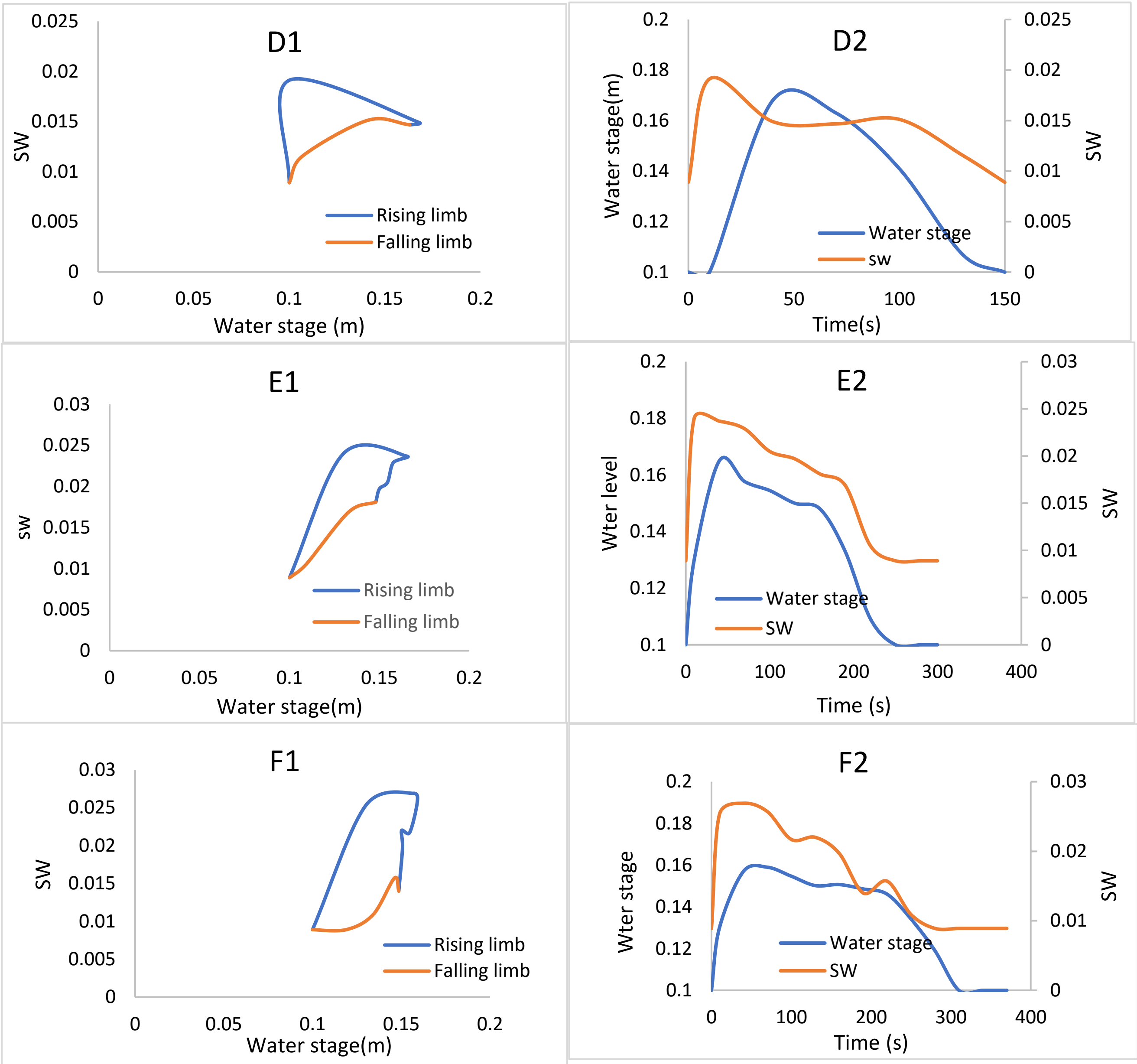

Figure 4. Temporal variations between S_w and water stages, D, E, and F, with a constant time duration and variable hydrograph peaks.

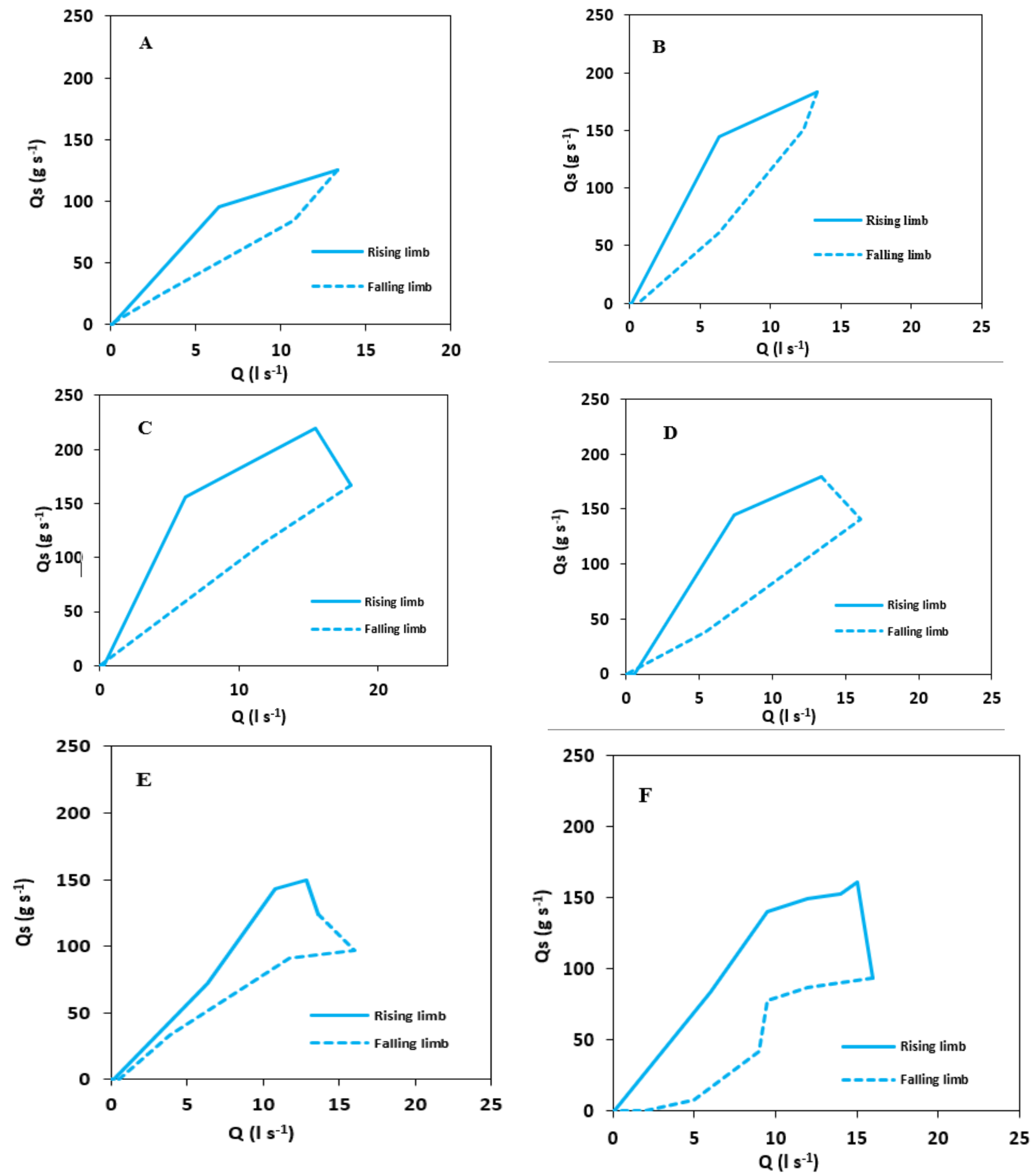

Figure 5. The relationship between sediment transport rate and flow hydrographs

Table 2 shows that with increasing S_w, shear stress, and sediment rate increased. In addition, there is a direct relationship between flow discharge and shear stress: as the hydrograph peak increases, shear stress also increases. In addition, the results indicate that the amount of shear stress in the rising limb is higher than in the falling limb, which causes the sediment transport rate in the rising limb to be more than in the falling limb. Moreover, in hydrographs A, B, and C, with increasing the peak of the hydrograph, the maximum of S_w is 0.015, 0.018, and 0.022, respectively. In contrast, hydrographs D, E, and F show that with increasing time duration of the hydrograph, the maximum of S_w is 0.017, 0.024, and 0.027 individually. That is why with increasing. $S_w$shear stress and sediment rate increased in the rising limbs. A linear regression analysis was conducted to examine the relationships between the hydraulic parameters. The first model (τ vs.

S_w) showed a strong and statistically significant relationship (R = 0.888). The second model (Q_s vs. S_w) also demonstrated a very strong and significant relationship (R = 0.981) A summary of the results is presented in Table 3.

Table 3. Summary of linear regression results

Model	R	R^2	p-value
τ vs. $\boldsymbol{S_w}$	0.88	0.78	0.001
Q_s vs. $\boldsymbol{S_w}$	0.98	0.96	0.001
Qw vs. $\boldsymbol{S_w}$	0.99	0.99	0.04

Note: τ = shear stress; S_w = water surface slope; Q_s = discharge per unit width.

4. Conclusion

Flash floods are characterized by water surface slopes that are considerably steeper than the bed slope, particularly during the rising and peak stages. This steepness allows floodwaters to surge downstream rapidly. Therefore, using the water-surface slope to calculate shear stress and predict sediment transport is advisable. The findings revealed that this shear stress difference between the calculated shear stress by the bed slope and the water surface slope is most prominent during the ascending limb of the hydrograph. In contrast, during the descending limb of the hydrograph, the slopes of the water surface and the bed are nearly equal or sometimes less. The maximum water-surface slope in longer hydrographs is also observed at the peak water level. The results showed clockwise hysteresis between S_w and the water stage, and in equal water depth in the rising limb, S_w is higher than the falling limb, so the sediment transport rate in a rising limb is higher than in a falling limb. Moreover, there is a clockwise hysteresis between Q_s and Q_w, Moreover, the peak of the sediment rate occurred before the peak of the flow hydrograph. The results indicate that with the increase in the peak of the hydrograph, S_w, τ_w, and Q_s increased. In the constant peak of the hydrograph, with increasing time duration of the hydrograph, S_w, moreover, T decreased, so the peak of ds decreased, but the total sediment transport increased. This study had some limitations, including a lack of upstream sediment supply and a narrow flume width. I recommend investigating this process on a larger scale for less drag force and considering the role of sediment feeding in future research.

Notations:

D_{16} 16th percentile of the sediment particle size distribution
D_{50} the median sediment size
D_{85} 85th percentile of the sediment particle size distribution
σ_g standard deviation
S_w water surface slope
S_0 bed slope
D_{min} minimum sediment size
D_{max} maximum sediment size
T time duration of the hydrograph

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Saeed Reza Khodashenas: Visualization, Writing – review & editing; **Amir Hamzeh Haghiabi**: Writing – review & editing; **Mohamad Nazeri Tahroudi**: Writing- review & editing.

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