Periodic surges and sediment mobilization

Richard J. Heggen
Department of Civil Engineering
University of New Mexico
Albuquerque, NM 87131 USA

ABSTRACT Periodic surges are frequently obseved in ephemeral discharge. Such surges may arise from a rapid increase in runoff, or may develop in response to fluid instabilities in steep channels at a steady mean discharge. Periodoc surges initiate as small undulations; with growth they become traveling hydraulic jumps. The analytic fundamentals of surge hydraulics are identified. Criteria for surge formation are evaluated. The geomorphic consequences of surges are discussed. Using a case study, surged flow is shown to increase suspended sediment and bed material transport. Mobilized particle diameter is increased manyfold. Periodic surges appear to play a significant role in the discontinouos process of sediment mobilization in ephemeral watersheds.

INTRODUCTION

Whereas flood-borne sediment discharge in perennial watercourses often can be described by extrapolating from normal hydraulic conditions, ephemeral sediment transport occurs as discrete, almost discontinuous events. According to Wertz (1966), the flood stage in ephemeral mountain streams is "impossible to study as it occurs." An undersanding of ephemeral sediment mechanics is complicated by lack of controlled experimental data. Fortunately, some theoretical and semiempirical insight can mitigate portions of this problem.

Leopold & Miller (1956) provide an account of one periodic surge event which will be employed in this paper as a case study.*

> "A flood in Canada Ancha Arroyo, July 26, 1952, provided an exceptional opportunity to observe the surges or bores. At maximum flow the width was about 100 feet, mean depth was estimated to be 1 foot, and mean velocity slightly exceeded 5 feet per second. During the 5 minutes immediately preceding peak state, a series of bores each 1/2 to 1 foot high moved down the channel at a velocity estimated to be greater than that of the water itself.
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> "The approach of the third bore made it apparent that they were spaced rather regularly in time. Thereafter, we measured with a stopwatch the intervals between successive bores which were 31, 35, 34, 48 and 60 seconds respectively. Between surges the water stage decreased somewhat, as judged by submergence and reemergence of a gravel bar in the channel. Furthermore, the peak state was much less than the sum of the heights of the eight individual wave fronts.
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> "The nearly constant period between five of the eight surges seems to rule out the possibility that they resulted from successive arrivals of flood peaks from different upstream tributaries. Rather the bores are a type of momentum wave associated with the hydraulics of the channel itself."

*As this paper surveys an array of studies which employ English units, that dimensional system is retained here.

Fig. 1 is a stage hydrograph for the case study. The surges are spiked in the manner of Brock's (1969) laboratory evidence and Holmes' (1936) field report and motion picture record of similar surges.

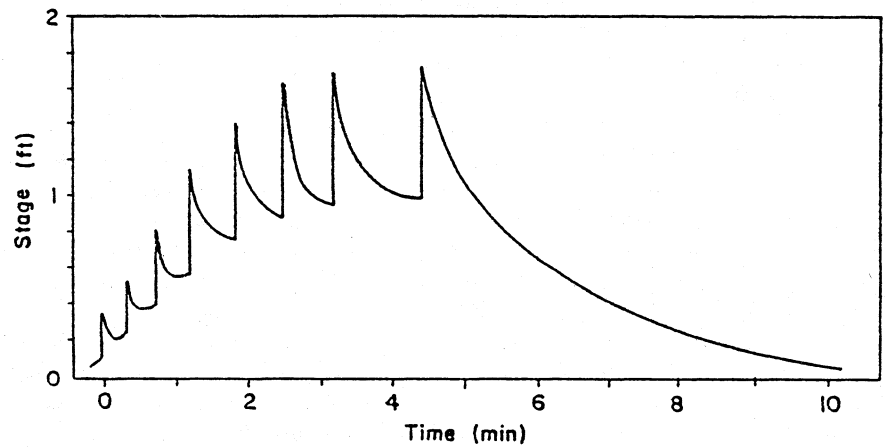

FIG.1 Surge hydrograph

In three observation within a 10-minute period, runoff increased from 40 to an estimated 173 cfs and diminished to 2.8 cfs, the peak corresponding to roughly a biannual event. Flow width changed from 58 to 100 to 18 ft.; mean depth, from 0.16 to 0.35 to 0.09 ft. Velocity changed from 4.4 to 4.9 to 1.9 fps. The Froude number changed from 1.93 to 1.45 to 1.05. Suspended sediment load varied from 2 to 5 to 1 % by weight.

The point of observation was approximately 4000 ft. below a major bifurcation. Sinuosity was 1.2. Channel slope varied from 5 to 3 percent. The bed material had a 50-percent passing diameter of 1.46 mm and an 84-percent passing diameter of 3.95 mm. The bed had virtually no silt content. Cobbles of 0.3 ft. were evident on the surface.

ANALYTIC FUNDAMENTALS

Periodic surges are classified as unsteady, nonuniform, transient, translatory open channel flow. By mass conservation,

$$y_2 V_2 = (y_2 - y_1) V_s + y_1 V_1 \tag{1}$$

where the subscripts 1, 2 and s refer to discharge preceeding, following and of the surge itself. If the bed shear is known, momentum balance may be used to relate y_2 to y_1 as a traveling hydraulic jump for an increase in discharge,

$$\frac{y_1^2}{2} + \frac{y_1(V_s-V_1)^2}{g} + \frac{F_b}{\gamma b} = \frac{y_2^2}{2} + \frac{y_2(V_s-V_2)^2}{g} + \frac{LS(y_1+y_2)}{2} \tag{2}$$

where F_b is the bed reaction, b is bed width, S is slope, L is jump length, γ is fluid density and g is the gravatational constant. Unfortunately for surge prediction, F_b and the increase in discharge are rarely known independently.

The water surface profile between the discontinuities at surge fronts can be described by the characteristic equation,

$$(V + ac)\frac{d(V + 2ac)}{dx} + \frac{d(V + 2ac)}{dt} = g(S - S_f) \tag{3}$$

where V is mean velocity, t is time, S_f is friction slope, a is a sign variable +1 or -1, c is celerity $\sqrt{gy}$ and x is distance. V, c, and S_f are dependent on channel geometry, discharge and y; t and x are independent variables. Eq. 3 can thus be made transcendental with one unknown, y. Solution for special cases can be done numerically or graphically by the method of characteristics, but lack of data for natural systems, stochastic boundary conditions and simplified assumptions jeopardize the accuracy of the results.

FORMATION

Two cases of periodic surges must be distinguished: surges during a period of increasing flow and surges during a period of steady mean flow. One condition, rapid rate of rise, must be satisfied in the first case. Conditions of initial perturbation, Froude number, slope and channel length, must be satisfied in the second.

Rate of rise

During the rising limb of a flood, the slope of the water surface exceeds the slope of the channel bed; during the falling stage, it is less. As c varies with y, during the rising limb a gravity wave just upstream of a point overtakes a wave downstream and the two coalesce. During the falling limb, a downstream wave outruns the upstream pursuer and the two do not combine.

Folly (1978) described the onset of arroyo flow to be "a series of translatory waves of small amplitude building to full flood depth," not a single "wall of water". According to Cooke & Warren (1973), "The steep rise often has one or more vertical sections, each denoting the passage of a bore." As additional upstream watershed begins to contribute runoff, the problem is analogous to the dam-break problem. The limiting rate of rise before a surge can form is,

$$\frac{dy}{dt} > \frac{gyS\,(2 - F)\,(1 + F)}{3V} \tag{4}$$

where F is Froude number. In the case study, the water surface rose at 0.003 fps. By Eq. 4, the required dy/dt is 0.002 fps.

The case study may document several surges caused by increased discharge, but as Leopold & Miller noted, it would be an exceptional phenomenon for the entire family of regularly spaced and sized waves to have resulted from timely increases in upstream flow. It is more plausible that the latter surges were generated in reasonably-steady mean discharge satisfying conditions of initial perturbation, Froude number, slope and channel length.

Initial perturbations

Mayer (1961) attributed the incipiation of surge instabilities to surface tension forces having comparable magnitude to the momentum flux. Other observers have noted a dependency on channel roughness (Berlamont

& Vanderstappen, 1981) or Reynold's number (Priest & Baligh, 1954). Practically, ultimate causality need not be a concern, as flow in a steep channel having random roughness elements has a spectrum of perturbations sufficient to excite any potential instability.

Froude number

Keulegan (1950) showed by continuity that idealized surges should not exist below an F of 2. The same result can be derived from the convexity of the characteristic curves. Lea's formula for a smooth channel gives the minimum F for surges as 1.4 (Powell, 1948). Escoffier & Boyd (1962) showed for a rectangular channel, the F required for surges was 1.5. Experimental data indicated a 1.56 to 1.64 range, consistent with the tendency of energy loss to delay the formation of breaking waves. Ishihara et al. (1961) concluded that for wide channels, the required F would be 1.74 when the energy correction factor was 1.05 and 2.17 when the factor was 1.1.

Liggett (1975) showed the required F to be 1.5 + y/b. Berlamont & Vanderstappen (1981) determined the necessary F to be approximately 1.6 for a Reynold's number of 5000. By the characteristic equations, surges themselves tend to diminish or attenuate as F is less or greater than 2 respectively. As periodic surges can form in supercritical flow when $V_{r,1}$, the surface velocity for normal flow, is less than the velocity of a small gravity wave, V + c. This implies that,

$$F < \frac{1}{V_{r,1}/V - 1} \qquad (5)$$

placing an upper limit on F. In shallow, turbulent channels, $V_{r,1}/V$ is typically about 1.3, implying that F should not exceed 3.33 for periodic surges. Thorsky & Haggman (1970) observed that flow regains stability at F above approximately 9, an indication that Eq. 5 may be oversimplified, but a confirmation that an upper limit on F exists.

In the case study V + c was approximately 10.7 fps. While $V_{r,1}$ was not reported, it was probably in the order of 6 fps. F was in the 1 to 2 range. It must be noted, however, that the waves were initiated upstream, where steeper, shallower discharge would have elevated F.

Slope

Taking the required F to be 2 and assuming uniform flow, the slope necessary for surge formation is,

$$S > 4\ S_c \qquad (6)$$

where S_c is the critical slope. For the case study, Eq. 6 yields an S of 0.052. US Army Corps of Engineers (1965) spillway criteria indicates,

$$S > 32.63\ n^2\ y^{-1/3} \qquad (7)$$

where n is Manning's roughness. For the case study, the required S is 0.029. Reports have noted S to vary between 0.01 (Mayer, 1961) and 0.35 (US Bureau of Reclamation,1978). As with the F criteria, flow in very steep channels regains some stability. Brock (1969) noted that as S increases within the surge-producing range, the magnitude and rate of formation of periodic waves increased. The case study S was 0.03 at the point of observation and 0.04 to 0.05 upstream.

Channel length

An instability can only be perpetuated as more gravity waves catch up to it. For surges to grow in phase, the surface flow velocity profile must be reasonably symmetric and constant, necessitating a long channel without excessive sinuosity.

Periodic surges in chute spillways have been observed to require in excess of 200 ft. to develop (US Bureau of Reclamation, 1978). A graphical criteria of channel length necessary for formation of well-defined pulsating surges indicates the necessary distance to be approximately 750 ft. (Montuori, 1963). This eliminates the most upstream reaches where only F and S criteria are satisfied.

Height, shape, and wavelength

Periodic surges assume one of two shapes: a smooth undulation or a breaking crest (Fig. 2). An undular wave begins to break when its leading feather edge is steepened by resistance.

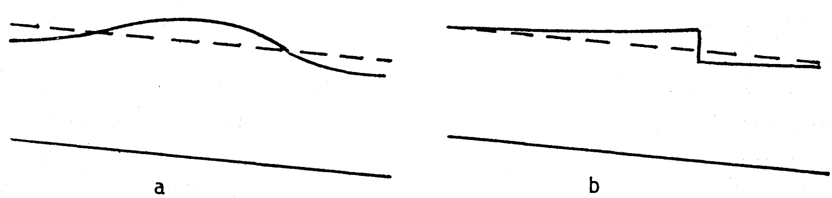

FIG. 2 Undular (a) and breaking (b) surges

For most arroyo flooding, surges are are only inches high (Antevs, 1952, Renard & Keppel, 1966). Leopold & Miller reported 2 ft. surges, but not for the case study. Catastrophic exceptions are possible, however. Holmes (1936) reported a 5 ft. surge; Escoffier & Boyd (1962), one 8 ft.

Several studies have related maximum undular height y_2 to the average depth y_1. Brock (1969) noted that in the development of periodic surges, y_2/y_1 was 1.25 to 1.35 before undular waves begin to overtake one another and break. Terzidis & Strelkoff (1970) found the maximum y_2/y_1 for nonbreaking undulations to be 1.5.

There is no absolute maximum y_2/y_1 ratio for breaking waves. Under controled conditions Brock (1969) achieved y_2/y_1's of 2.6., though most maximums were closer to 2. The US Bureau of Reclamation (1978) in discussing steep spillway suggested a y_2/y_1 of 2 for freeboard purposes. It thus appears that the y_2/y_1 ratio of approximately 2 in the case study may be near the upper bound of periodic surge height.

Most theoretical work has employed Eq. 3 to describe the profile between surge fronts. Terzidis & Strelkoff (1970) provided a description more practical: the large part of depth change (the width of the spikes in Fig. 1) takes place in a length 5 to 10 times the depth of the wave. Leopold & Miller's impression of a long period of near-uniform conditions between each surge supports this description.

During the rising hydrograph limb, surge wavelength λ varies with the rate of stage rise. When discharge has become reasonably constant, even for the short duration of a flood peak, λ is likewise constant. Mayer (1961) indicated,

$$\lambda = 250\ y_2 \tag{8}$$

in the case study, 437 ft. Thorsky & Haggman (1970) estimated,

$$\lambda = 200 \sqrt{y_2} \tag{9}$$

approximately 265 ft. in the case study. Actual λ's varied from 150 to 300 ft.

Velocity

Energy balance is achieved at a surge velocity V_s in which trailing gravity waves replentish energy at the same rate that energy is lost to friction and turbulence. Mass balance requires a trailing surface flow to sustain forward spill over the crest. Thus,

$$c < V < V_{r,1} < V_s < V_{r,2} < V+c \tag{10}$$

where $V_{r,2}$ represents the velocity at the surge surface. V_s is about 70 percent smaller than the theoretical friction-free value for the leading surge on a dry channel bed, according to Yevjevich (1975).

Several approximate methods exist for the estimation of V_s for an undular wave. Los Angeles County (1971) estimated for flood waves,

$$V_s = V\ \frac{5b + 6y_1}{3b + 6y_1} \tag{11}$$

For wide channels, V_s thus approaches 1.67 V, 8.3 fps in the case study. Renard & Keppel (1966) found surge velocities to be approximately midway between uniform flow velocity and the speed of a gravity wave,

$$V_s = V + c/2 \tag{12}$$

approximately 7.9 fps for the case study. Leopold & Miller simply estimated V_s in the case study to be "something greater than that of the water itself", the latter being 5 fps.

Transformation

In ephemeral floods, discharge and depth increase rapidly through the top reaches as tributaries converge, but as the discharge progresses over downstream alluvial fans, infiltration losses may become large and discharge may diminish. Green's Law says that the elevation of a sinusoidal wave varies inversely with the square root of channel width. As b generally increases in the downstream direction, wave height thus decreases with translation.

Keulegan (1950) provided an approximation of the distance required for a solitary wave in a flat channel to decrease in depth. The example 2 ft. surge would diminish to 1.1 ft. in approximately 350 ft. of horizontal channel. Channel slope would prolong the distance.

Indications in the case study are that the observers saw surges at their maximum. Upstream conditions were proper for surge formation. As the waves passed the observers, the surges had grown to a relative magnitude equaling that noted in other studies. At the point of observation, slope and Froude number were insufficient for additional surge growth.

PLANAR PATTERN

Leighly (1936) surveyed arroyo planar patterns. In contrast to Leopold & Langbein's (1966) observation that river meanders resemble sine-generated curves, arroyo meanders tend to be more parabolic, sharper than river bends. Arroyo patterns "change much more rapidly than do the channels of permanent streams in humid regions." Arroyo sinuosities "are likely to be devoid of regularity."

In that arroyo flow is prone to rapid abstractions and arroyo channels are subject to radial shifts on alluvial fans, it is understandable that the repeating pattern of stable meander migration in regime systems is not found. These reasons do not, however, explain the abrupt and sporadic nature of arroyo reaches. Periodic surges may contribute to such planar contortions.

The rate of momentum change yields the magnitude of bank force F_r required to turn a surge through a bend of angle θ,

$$F_r = \frac{\gamma b}{g} (y_2 - y_1) V_s^2 \sqrt{2 - 2\cos\theta} \tag{13}$$

For a θ of 30^o in the case study, F_r would be 3690 pounds of bank attack in addition to normal flow loadings. Eq. 13 calculates the force required to deflect a surge without dissipation. In reality, a surge will emerge from a bend with only a portion of its original velocity and energy. F_r is increased above that calculated.

Unlike a flood peak rising and diminishing in hours, occurring only once per event, surges impact almost instantaneously, diminish almost as quickly, and reoccur. Whereas the force necessary to turn nonsurge flow is developed by water surface superelevation and distributed by hydrostatic pressure around the outside of a bend, the reaction needed to turn a surge is localized at the point of impact. Unlike spiral flow dissipating energy by continuous plunging on the outside of a bend, a surge dissipates energy within the duration of the reflection. For deflection of breaking waves, the bank is subject to disproportionately high local pressures. Peak pressures 10 times the maximum dynamic pressure of the approach wave have been noted in the laboratory at or somewhat above the mean water surface (Keulegan, 1950).

A load applied and relaxed rapidly to a soil face may cause more severe consequences than the same load applied and relaxed gradually. Geomorphic adjustment to abrupt impacts is likely to be by discrete soil failures (Wolman & Bush, 1961, Schumm, 1961, Leopold & Miller, 1956). Lateral migration is frequently by bank collapse subsequent to a flood wave. An arcuate slab of channel bank, having lost shear strength by saturation, undercutting, and/or piping, collapses into the channel. Subsequent lower flows erode the slump block. Piest et al. (1975) estimated that as much as four-fifths of gully erosion may be by bank failure and delayed wasting.

CROSS SECTIONAL GEOMETRY

Arroyo cross sections are typified by wide horizontal beds. Leopold & Miller determined that b for arroyos increased with the 0.29th power of discharge and y, with the 0.36th power. Perennial streams yielded corresponding exponents of 0.26 and 0.40. Thus in ephemeral channels, b/y increases more rapidly with discharge than does the ratio for perennial watercourses. The high b/y ratio is typically attributed to a low silt-clay content. Schumm's (1960) correlated b/y of 100 for a weighted mean silt-clay percent of 4 is in accord with Leopold & Miller's observation.

Surged flow may provide hydraulic reason as well for wide arroyo channels. A surge will refract into the bank of a straight channel due to lost celerity caused by decreased depth and lost advective velocity caused by the lateral boundary layer. Having minimal lateral momentum, the refraction will impact a linear bank with minimal impulse. A more gradual rise and decline of depth on the channel wall or overbank will occur as the surge passes, generating lapping waves for arroyos not deeply incised. These waves, particularly if periodically reinitiated, will tend to widen the channel surface in a gradual manner.

SEDIMENT TRANSPORT

Thornes (1977) concluded that "the behavior of the single, or even aggregates of, rather unnatural particles, described in countless publications by hydraulic engineers, seems at present almost insuperable." Given the imprecision, the idealizations, the narrow bounds and the lack of common approach between competing theories, Thornes is correct. On the other hand, quantitative description of particle response to controlled conditions facilitates insight into the larger process. The effect of periodic surges on bed material stability is a case where such micro analysis lends reason to macro observations.

Sediment load can be partitioned into two phases: bed load transported by saltation or rolling along the channel floor and suspended load transported by fluid advection. Whereas bed load may account for less than 10 percent of total transport in a sandy arroyo channel, bed load accounts for all the movement of gravel and cobbles, the significant particles in bars and armored bedforms.

Hughes (1980) concluded that the same maximum permissible velocities applied to both constant-flow and ephemeral channels. Thus the tractive force, or Shield's model of sediment stability may be informative for transient consitions. For highly turbulent flow, the critical shear τ_c necessary to move a bed particle is,

$$\tau_c = 0.056\,\gamma\,(S_s-1)\,d \tag{14}$$

where S_s is sediment specific gravity and d is particle diameter. For a 1.5 mm sand grain in the case study, τ_c is 0.03 psf. Under normal depth, non-surge conditions, the stable particle diameter is 0.33 ft.

For uniform flow in a wide channel, the shear exerted is,

$$\tau = \gamma y_1 S \tag{15}$$

in the case study, 1.9 psf. The shear τ_s exerted under a surge is,

$$\tau_s = F_b/bL \tag{16}$$

Substituting Eq. 16 into Eq. 2,

$$\tau_s = \frac{\gamma}{L}\left(\frac{y_1+y_2}{2}(y_2-y_1+LS) - \frac{y_1}{gy_2}(y_2-y_1)(V-V_1)^2\right) \tag{17}$$

For the case study, τ_s is 9.6 psf, 5.3 times normal τ.

The Du Boy's equation provides a quick relative estimate of bed load transport,

$$L_b = C_s \tau (\tau - \tau_c) \qquad (18)$$

where C_s is a dimensional constant. As τ_c is significantly less than τ or τ_s, the relative increase in L_b of a surge over normal conditions is the square of the relative increase in shear, τ_s/τ. In the case study, bed load capacity is increased by a factor of 28. Setting τ_s equal to τ_c, the stable d for a surge is increased by a factor of τ_s/τ. A 1.75 foot particle would thus be at incipient conditions against the surge in the case study. Movement of such relatively large particles was noted by Leopold & Miller, though not explicitly identified with a surge passage.

Two bed load transport observations by Leopold et al. (1966) may pertain in part to surges. The first relates to the movement of bed particles. In the uppermost several hundred of feet of a channel where slope exceeded 10 percent and Froude number would have been high, 6-inch particles did not move. In this most upstream reach, surges would not yet have coalesced. At approximately 400 ft. downstream, though slope had decreased to 6 percent, nearly all particles moved. It can be speculated that here surges begin to form. Nearly total movement was noted until slope decreased to approximately 4 percent; some particles here were again stationary or moved only a relatively short distance. This zone appears to be one in which surges would dissipate.

A second observation was that travel distance for bed material in a flood event could be estimated as 100 times the maximum discharge per unit width, 500 ft. for the case study. Einstein observed the average distance before collision and momentum transfer for bed material to approximately 100 particle diameters. For a 4-inch cobble, this estimate yields 33 ft. per movement. To have traveled 500 ft., the particle thus would have moved approximately 15 times.

Approximately 8 surges occured in the case study. A relation between the number of movements of large particles and the number of passing surges may have some physical basis. Shear force analysis indicates that a surge can dislodge particles otherwise stable. Once dislodged, the particle is outrun by its motive force, rapidly decelerates and resumes repose until a subsequent dislodgement (Wertz, 1966). If in the course of a surge passage, a particle is thrown forward one jump and is rolled another, the net movement is accounted for.

Terzidis & Strelkoff (1970) observed that the energy dissipated within a surge exceeded the energy dissipated on the bed. The consequent turbulence increases the capacity for transport of suspended particles. The sediment load L_s suspended over a unit area is,

$$L_s = C_o A \left(1 - e^{-y/A}\right) \qquad (19)$$

where C_o is the concentration at suspendable sediment at the bed load boundary, A is E/V_g, V_g is the settling velocity of the suspended particles, and E is eddy viscosity, large for turbulent discharge. As A becomes large, L_s approaches $C_o y$.

In the case study, suspended load concentration reached a nonsurge peak of 5 percent by weight. No samples were taken from a surge. As increased C_o and greater turbulence elevate the suspended sediment concentration in surges (particulates can often be seen in the surge front), a doubling of suspended load to 10 % within a surge is a conservative assumption of increase.

Without surges, approximately 130,000 ft^3 of water and 2200 ft^3 of sediment were discharged in the 10 minute runoff. The surges added 7700 ft^3 of water and 250 ft^3 of sediment, 6 and 11 % increases respectively. Though the magnitudes of the numerical estimates are subject to large errors, the relative results are informative. Surges may significantly contribute to the net transport of suspended material and substantially increase the transport of larger bed particles.

IMPLICATIONS

Using the criteria of rate of rise, initial perturbation, Froude number, slope and channel length, the location and conditions of periodic surge formation may be determined. Sufficient data on form and translation exists to estimate height, shape, wavelength and velocity.

Channel reaches in which periodic surges are anticipated are likely to have higher watermarks, more severe bed and bank degradation, and more sediment yield than similar non-surge reaches. Of particular difference is the surge-induced mobilization of large bed material.

Post-event surveys of floods in surged channels is likely to yeild overestimates of discharge if high-water marks and displaced bed material are assumed to be representative of peak uniform-flow conditions. While the quantification of surge behavior is imprecise, a general appreciation of surge occurance and consequence can improve hydrologic and geomorphic understanding.

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