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Review

Impact of Unsteady Flow Events on Bedload Transport: A Review of Laboratory Experiments

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Abstract: Recent advances in understanding bedload transport under unsteady flow conditions are presented, with a particular emphasis on laboratory experiments. The contribution of laboratory studies to the explanation of key processes of sediment transport observed in alluvial rivers, ephemeral streams, and river reaches below a dam is demonstrated, primarily focusing on bedload transport in gravel-bed streams. The state of current knowledge on the impact of flow properties (unsteady flow hydrograph shape and duration, flood cycles) and sediment attributes (bed structure, sediment availability, bed composition) on bedload are discussed, along with unsteady flow dynamics of the water-sediment system. Experiments published in recent years are summarized, the main findings are presented, and future directions of research are suggested.

Keywords: experiments; flood; hysteresis; river; sediment; bedload; bed shear stress

1. Introduction

Unsteady flow events are intensive phenomena occurring in streams and rivers in various climatic and geomorphic settings [1]. They can be triggered by snowmelts [2], glacial processes, excessive rainfall, dam water releases, or hydropower operations [3,4] and very often entail catastrophic consequences, falling into the category of flood events. Unsteady flows differ in terms of frequency, magnitude, and hydrograph shape and duration, depending on the region and flood origin. Pulsed hydrographs lasting from a few hours to a few days with a steep rising arm [1,5–7] are characteristic for abrupt flows, e.g., dam water releases or flashfloods, while flat hydrographs lasting up to several hundred hours [8,9] are characteristic for flood waves triggered by snowmelt or precipitation.

The quantification of the mobile riverbed response to these changing flow conditions poses a challenge since the effect of temporal flow variability overlaps with the effect of bed structure, bed material composition, and sediment supply. This complexity makes it difficult to separate the effects of flow and the effects of sediment characteristics and availability on bedload transport. Attempts have been made to overcome this difficulty by applying the existing theory of sediment transport in steady flow conditions to unsteady flow problems, e.g., by approximating unsteady flow as a step-wise steady flow. However, this approach has proved to be inadequate in transient flows (dam-break flows, flashfloods) [10]. It is nowadays acknowledged that findings for steady flow cannot be fully transferred to unsteady flow events [11–13] and, as such, a branch of research on sediment transport in unsteady flow conditions has been developing rapidly.

Although unsteady flow events have an enormous impact on fluvial morphodynamics, the academic discussion has still only had a small impact on engineering and water management. The reason for this is because the vast complexity of the problem limits the development of bedload calculation equations that could be applied, e.g., in numerical models. These issues make the topic of sediment transport in unsteady flow conditions one of the most significant and urgent research problems in environmental and engineering hydraulics.

Our knowledge of riverbed morphodynamics and the fate of pollutants [14] during flood events remains insufficient. One reason for this is that the violent character of unsteady flow is a serious constraint preventing field measurements of sediment transport [15]. Nonetheless, some monitoring of bedload in rivers has been conducted and has provided valuable field data [3,7,16]. However, both flow and transport processes are highly variable in time and space, and observations and measurements of detailed processes, such as dynamics of bed morphology during unsteady flow events, still pose a technical challenge.

While safety considerations very often constrain observations in the field, the laboratory assures safe conditions for researchers and apparatus and enables control over measured variables, and, as such, is advantageous over field measurements. Laboratory conditions provide the opportunity to observe and measure detailed processes from reach- to grain-scale, with the capabilities of the measurement equipment being the only limiting factor. There is a certain exception to this in large scale flood experiments, showing, for example, that controlled floods in debris fan-affected canyons of the Colorado River basin redistribute fine sediment and change the local channel morphology by bar-building and bed scour [4]. However, such experiments, although very informative, provide data at a completely different level of accuracy than those discussed in this review. Oscillatory flow experiments simulating sediment transport under waves and currents in coastal zones are another large group of laboratory investigations [17,18], which study grain motion and bedload transport in unsteady flow. However, details of these studies are beyond the scope of this review.

Numerical methods provide another rapidly developing research approach, one which is tightly connected with laboratory data. These numerical methods very often involve a one-dimensional description of the phenomenon due to its smaller numerical cost (see, e.g., Fang et al. [19]), but intensive research has also been conducted on sophisticated 2D numerical methods [20,21]. However, despite the existence of such advanced numerical methods, their progress is limited due to gaps in theory and difficulties in obtaining reliable measurements for calibration. Laboratory studies, in addition to addressing fundamental knowledge gaps, provide the data necessary for the development of numerical models.

Experiments are, therefore, a promising research approach that advances our understanding of sediment transport mechanisms and also complements field and numerical studies. Experimental investigations are indeed in the mainstream of research on sediment transport in unsteady flow since advances in instrumentation and measurement techniques are making it possible to conduct more and more sophisticated experiments [15] that may address challenging research problems. Laboratory studies rarely model conditions in a particular river (a prototype). Instead, they usually have a general context and aim to identify the mechanisms underlying fundamental processes [11].

The literature on laboratory experiments touches upon a number of detailed problems, to be addressed further on in this paper, from grain-scale to bulk transport processes, additionally complicated by the temporal and spatial variability of water flow. This may give the impression that the state of research in the field is chaotic; hence, we believe that overviews of specific areas of this complex topic will be useful. Laboratory research on sediment transport in unsteady flow has been summarized to some extent in a few review papers. They focused on sediment transport characteristics in relation to pollutant transport in unsteady flow [10], factors affecting the hysteretic relationship between flow rate and sediment transport [22], and presented current laboratory techniques applied in bedload studies, both in steady and unsteady flow conditions, and dedicated a few sections to the impact of sediment supply, armoring, and hydrograph on bedload transport in unsteady flow [15].

The present review focuses on the transport of coarse-grain bedload from the perspective of experimental studies, and the aim is to summarize existing directions in laboratory research on sediment transport in unsteady flow conditions and to point out future perspectives for experimental investigations developing this research topic. This review does not aim to be exhaustive and focuses on selected issues: (1) to summarize recent laboratory studies in terms of experimental conditions and modeling issues; (2) to present existing interpretations of the hydrodynamics of unsteady flow; (3) to present current knowledge on the interaction between unsteady flow and riverbed, and (4) to discuss the research questions addressed in previous studies and future needs and perspectives. Laboratory studies are presented within the wider context of sediment transport research including field, numerical, and theoretical studies since experiments are inherently connected with these researches. They all contribute to the understanding of bedload transport processes and generate new research questions that may become topics of laboratory experimentation.

2. Experimental Conditions

Laboratory experiments are designed so that certain, independent variables can be controlled to assess their impact on other, dependent variables, which is not possible in field observations. Hydrograph characteristics, initial bed composition and structure, and sediment supply are usually taken as independent variables, and their effect on sediment transport characteristics is measured. The number of combinations is endless, and Table 1 summarizes some of the experimental conditions considered in recent studies, with a focus on experiments looking at coarse-grain and bi-modal bed material composition.

The hydrographs applied in experimental studies vary in shape, duration, flow magnitude, time-to-peak flow, and proportion between rising and falling limb duration, so as to model various types of flood waves occurring in natural conditions (Figure 1). Triangular [13], trapezoidal [23], and step-wise [24–26] hydrographs have been considered. Other researchers have designed more naturally-shaped hydrographs in the form of smooth curves [27–29]. The duration of hydrographs has varied from a few minutes [12] to a few hours [5]. Cycled hydrographs have been designed to model the influence of successive floods or other unsteady flow events on the bed texture and sediment transport [11,25,27,30–33].

The bed of experimental channels has been composed of unimodal sand or gravel [11,13,27,34], sand–gravel [12,25,35], silt-gravel and silt-sand mixtures [26,32], and tri-modal sand–gravel mixtures [36]. An idealized bed structure, i.e., well-mixed and screeded, has been applied to exclude the influence of initial bed morphology prior to single [24,34] and cycled hydrographs [32]. A bed water-worked by antecedent flow prior to a single hydrograph has been applied to simulate conditions similar to those in nature [12,23,28]. Other studies have combined structured water-worked gravel beds with cycled hydrographs [31]. Some studies have applied a more complex planar morphology, for instance, to simulate alternate bar topography [27].

Sediment supply has been controlled in laboratory studies to simulate sediment feeding or sediment starving conditions [24,30]. Sediment-feeding conditions occur when a sediment load from upstream is provided, and the rate of supply is larger than the bedload transport capacity; in the converse, as in the case of flow below dams, sediment-starved conditions occur. Sediment supply also has a technical motivation, as a way to control scour and deposition during an experiment when the variation of bed level is undesirable [11,30,31,34]. Erosion processes may considerably affect the water surface level when the water depth is relatively small in laboratory flumes [34].

Table 1. Laboratory studies on sediment transport under unsteady flow conditions.

Study	Type of Hydro-Graph [1]	Channel Dimensions [2] and Slope	Flow	Initial Bed Conditions	Sediment and Supply	Hyste-Resis [3]
Bombar et al., 2011 [23]	S, triangular, trapezoidal	18.6 × 0.8 × 0.75 slope: 0.005	peak about 80 L/s duration: 67–270 s	screeded and water-worked	gravel, d_{50} = 4.8 mm	N/A
Curran et al., 2015 [37]	S, stepped	11 × 0.6 × 0.5	duration: 76 min	well-mixed, screeded	70% sand, 30% gravel; d_{50} = 0.5 mm; sediment recirculation	N/A
Ferrer-Boix, and Hassan. 2015 [31]	S, pulsed	18 × 1 × 1 slope: 0.022	variable duration (1–10 h) low flow 0.065 m^2/s, followed by 1.5 h constant high flow pulse 0.091 m^2/s	water-worked	d_{mean} = 5.65 mm; 20% sand; constant feed rate 2.1 g/m/s	N/A
Guney et al., 2013 [12]	S, triangular	18.6 × 0.8 slope: 0.006	base flow: 9.5 L/s; peak flow: 49.6 L/s; duration: 10 min	well-mixed, water-worked	gravel/sand mixture; d_{50} = 3.4 mm, no supply	C, CC
Hassan et al., 2006 [5]	S, stepped triangular	9 × 0.6 × 0.5	0.012–0.055 m^3/s; duration: 0.83–64 h	water worked	range of grain size: 0.180–45 mm; no supply	N/A
Humphires et al., 2012 [27]	S, naturally-shaped (lognormal)	28 × 0.86 × 0.86	peak flow: 35 L/s, 25 L/s; duration: 14.5 h, 8.5 h	armored	d_{50} = 4.1 mm sediment pulses	S
Lee et al., 2004 [13]	S, triangular	21 × 0.6 × 0.6 slope: 0.002	base flow: 0.04 m^2/s; peak flow 0.05–0.14 m^2/s; duration: 21–80 min		d_{50} = 2.08 mm no supply	CC
Li et al., 2018 [29]	S, naturally-shaped (smooth sinusoidal curves)	35 × 1.2 × 0.8 slope: 0.003	peak flow 0.018 m^2/s and 0.038 m^2/s		gravel (2–4 mm), sand (0.1–2 mm), 100% gravel; 100% sand; 53% gravel and 47% sand; 22% gravel and 78% sand; constant feed rate 2.1 g/(m s)	N/A
Mao, 2012 [24]	S, stepped symmetrical	8 × 0.3 slope: 0.01	0.024–0.085 m^2/s	mixed and screeded sediment	20% sand, 80% gravel, d_{50} = 6.2 mm, continuous recirculation	C
Mao, 2018 [25]	C, three types of stepped symmetrical	8 × 0.3 slope: 0.01	0.024–0.085 m^2/s	water-worked by steady antecedent flow	20% sand, 80% gravel, d_{50} = 6.2 mm, supply	C, CC
Martin and Jerolmack, 2013 [38]	S, pulsed and triangular	15 × 0.92 × 0.65 slope: 0	peak flow: 81.4, 111.7 L/s; low flow: 39.1, 63.3 L/s, duration: several hours	water-worked by low flow	d_{50} = 0.37 mm no supply	N/A
Mrokowska et al., 2018 [34] Mrokowska et al., 2016 [39]	S, triangular	12 × 0.49 × 0.6 slope: 0.0083	base flow: 0.0035–0.0131 m^3/s; peak flow: 0.0387–0.0456 m^3/s; duration: 400–800 s	well-mixed, screeded, without and with antecedent flow	d_{mean} = 4.93 mm supply	C
Nelson et al., 2011 [40]	S, square-wave	6 × 0.25 × 0.4 slope: 0.002	peak: 0.02 m^3/s	well-sorted	sand d_{50} = 0.58 mm no supply	N/A
Orru et al., 2016 [36]	S, one step	14 × 0.4 × 0.45 slope: 0.0022	stepped increase form 0.0465 m^3/s to 0.0547 m^3/s	water-worked	tri-modal sediment mixture d_{50} = 1 mm, d_{50} = 6 mm, d_{50} = 10 mm; no supply	no
Perret et al., 2018 [26]	C, stepped symmetrical	18 × 1 × 0.8 slope: 0.01	-	loose and packed gravel beds, infiltrated with fine grains	gravel d_{50} = 6.8 mm and bimodal gravel–sand and gravel–silt	N/A

Table 1. *Cont.*

Study	Type of Hydro-Graph [1]	Channel Dimensions [2] and Slope	Flow	Initial Bed Conditions	Sediment and Supply	Hyste-Resis [3]
Phillips et al., 2018 [11]	C, four different shapes: triangular and rectangular	30 × 0.5	-	-	unimodal well-mixed, d_{mean} = 7.2 mm	N/A
Piedra et al., 2012 [41]	S, stepped, increasing discharge	7 × 0.9 slope: 1/150	peak: 29–34 L/s	-	gravel d_{50} = 6.6 mm no supply	No
Redolfi et al., 2018 [30]	C, square-wave and triangular	24 × 2.9, 24 × 0.8 slope: 1.0%	square-wave: 1.2–2.5 L/s, 1.5–2.5 L/s;triangular: 0.5–2.5 L/s	well-sorted sand, water-worked by antecedent low flow	sand d_{50} = 1 mm supply	C
Shvidchenko and Kopaliani, 1998 [42]	S, stepped	outdoor plot: 84 × 10; flume: 100 × 1; recirculating tilting flume: 18 × 2.46	-	braided channel	d_{mean} = 0.69 mm d_{max} = 5–8 mm recirculating flume: d_{50} = 4.3 mm	No
Waters and Curran, 2015 [32]	C, stepped	9 × 0.6 × 0.5	duration: 76 min, cycled with 2 h base flow between, peak flow: 0.073, 0.131 m^2/s, base flow 0.029 m^2/s	well mixed screeded flat, antecedent low flow	70% sand, 30% gravel, d_{50} = 0.55 mm and 70% sand, 30% silt, clay d_{50} = 0.27 mm no supply	F8, CC most frequent
Wang et al., 2015 [28]	S, natural-shaped	8 × 0.3 × 0.3 slope: 0.0083	base flow 8 L/s, peak flow 13.5–18 L/s; duration: 120–141 s	screeded, antecedent flow	range of grain size: 1–16 mm; d_{50} = 5 mm, unimodal and bimodal	C
Wong and Parker, 2006 [33]	C, triangular	22.5 × 0.5	peak flow: 0.065–0.102 m^3/s; duration 15–60 min	well-sorted	gravel, d_{50} = 7.1 mm, constant feed	N/A

[1] S—single, C—cycled; [2] length (m) × width (m) × depth (m); [3] Hysteresis in the relationship between total sediment transport rate and flow rate; C—clockwise, CC—counterclockwise, F8—figure-8 shape.

Undistorted mobile bed models based on Froude similitude have usually been applied to model sediment transport in unsteady flow. A general rule applies to unsteady flow experiments: When fully rough flow occurs in a river; it is enough to assure that scaled flow is also fully rough to satisfy the Reynolds number criterion. Then the Froude number becomes the main criterion to calculate scaling between the model and the prototype [43]. The similitude of boundary shear stresses is usually obtained by applying the Shields number to satisfy the similarity of forces acting on sediment particles in a prototype and a model [43]. Mao [24] used Froude scaling to prepare a model that represents a narrow gravel-bed river. The model at a scale 1:30 represented a 10-m wide stream with a bed composed of material with d_{50} = 200 mm, while flow corresponded to a flashy flood lasting 10 h and a snowmelt flood lasting 83 h. Redolfi et al. [30] constructed a model representing a typical gravel bed river with d_{50} = 50 mm and flood duration of 1 h in a model corresponding to 7 h in a prototype. Shvidchenko and Kopaliani [42] provided in-depth theoretical commentary on similitude laws and their study presented a model of Laba River at a scale of 1:50. Lee et al. [13] commented on the applicability of Froude similitude to hydrograph design, concluding that this law can be adopted in unsteady flow even if equilibrium conditions of bed morphology are not met.

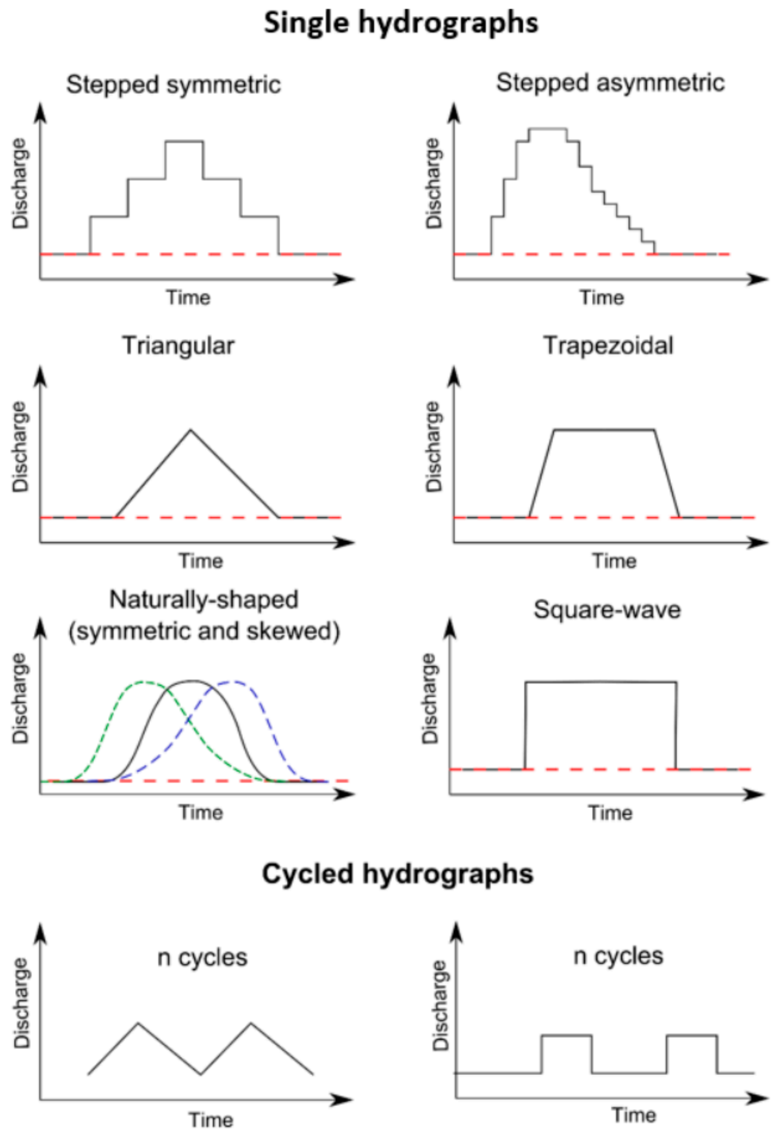

Figure 1. Main types of unsteady flow hydrographs tested in laboratory experiments. The dotted red line denotes a base flow.

3. Hydrodynamic Aspects of Sediment Transport

Bed material is set into motion as the result of forces exerted by flowing water, usually represented by drag and lift on a grain scale and friction on a larger scale. Thus, proper evaluation of these forces is necessary to assess sediment transport. Forces acting on sediment depend on the flow attributes, such as turbulence characteristics and mean flow characteristics. A variety of studies in steady flow conditions have shown that there is mutual interaction between flow properties and movement of sediment, demonstrating that flow properties are modified in the presence of bedload as compared to the clear water (an absence of sediment transport) counterpart [44–46]. For example, near-bed velocity fluctuations, and consequently Reynolds shear stresses, diminish when the channel bed is movable [47].

A better understanding of grain scale mechanics is necessary to improve the assessment methods of bed load transport [48]. Detailed laboratory measurements have demonstrated the impact of pressure gradients around grains and turbulence events on the entrainment of sediment grains in steady flow [15]. Although unsteadiness is an immanent feature of river systems, its impact on the fate of single particles has yet to be sufficiently understood. But one has to acknowledge the attempts to understand the influence of unsteadiness (hydrograph characteristics) on particular forces, for example, the magnitude of lift [49]. Another related example is a study considering the effect of turbulent flow parameters on the movement of particles in natural conditions, which has shown that flow acceleration affects bedload transport [50].

Contrasting results have been reported concerning the impact of sediment transport on flow resistance. On the one hand, bedload transport has been found to enhance flow resistance, due to additional flow energy dissipation through interactions between sediment grains and the extraction of momentum from the flow [51]. On the other, however, a large body of research has reported the reverse trend, showing decreased flow resistance or a negligible effect in movable bed conditions [44,52,53]. Since flow resistance varies due to the evolution of bed structure as water flows over movable bed, it has been proposed to apply a flow-dependent roughness factor instead of a fixed roughness coefficient to calculate bedload using resistance equations [54]. Our understanding of the abovementioned phenomena in steady flow is still incomplete and much less is known about flow resistance in unsteady flow with a movable boundary.

It has been well known that flood hydrograph characteristics affect sediment transport capacity through time-variable bed shear stresses. Recently, some progress has been made with methods to evaluate bed shear stresses in unsteady flow conditions [55–58], but these are mostly indirect methods. It is quite unfortunate that the techniques used to measure instantaneous values of shear stresses are not well developed [59]. Flow resistance in unsteady flow has been widely considered using bed shear stress τ (N/m^2) or friction (shear) velocity u_* (m/s) (Equation (1)) to quantify friction.

$$u_* = \sqrt{\frac{\tau}{\rho}} \quad (1)$$

where ρ—water density (kg/m^3).

The first report on the friction velocity in unsteady flow over a rough gravel bed was presented by Tu and Graf [60]. They found that friction velocity achieves the peak value along a rising limb before peaks of water depth and discharge, and that bed shear stress is larger along the rising limb than along the falling limb of the hydrograph (Figure 2). Similar results were later obtained by Graf and Song [56,61] and Nezu and Nakagawa [62]. Although this relationship was observed for immobile bed conditions, it appears to be significant for research on bedload transport. Since the peak of bedload is most likely around the peak of bed shear stress, the most intensive sediment transport is expected before the discharge peak, provided sediment is available. It is also more likely that armored bed is destroyed in the region of increased shear velocity.

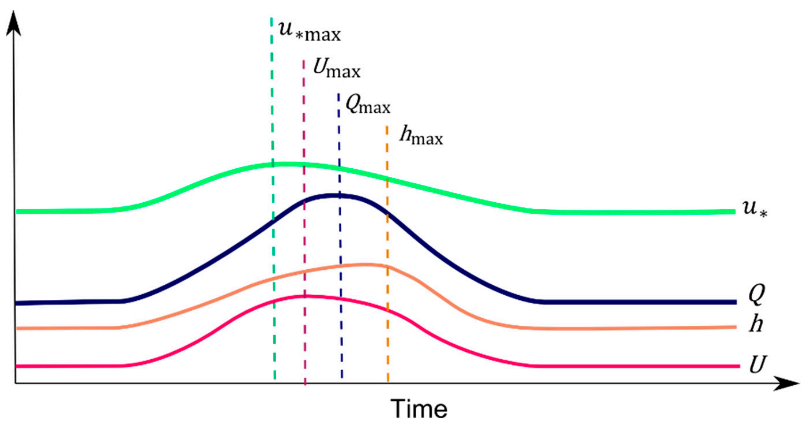

Figure 2. Schematic representation of temporal variation of flow parameters, indicating the sequence of peak values. Based on [56,61], u_{*max}—maximum friction velocity (m/s), U_{max}—maximum mean flow velocity (m/s), Q_{max}—maximum flow rate (m/s), h_{max}—maximum flow depth (m).

The shear velocity in unsteady flow conditions may be conveniently evaluated from the following formula:

$$(u_*)_{SV} = \left[gR\left(I + \frac{U}{gh}\eta + \left(\frac{U^2}{gh} - 1\right)\vartheta - \frac{1}{g}\zeta\right)\right]^{\frac{1}{2}} \quad (2)$$

where $\eta = \frac{\partial h}{\partial t}, \vartheta = \frac{\partial h}{\partial x}, \zeta = \frac{\partial U}{\partial t}$, t—time (s), U—mean cross-sectional velocity (m/s), x—horizontal spatial coordinate (m). This formula may be derived from flow equations—the momentum conservation equation and the continuity equation in the form of the Reynolds 2D model [56] or 1D Saint–Venant model [60]. It should be kept in mind that the Saint-Venant model was derived for immobile bed conditions, and the movement of bed elements may introduce some degree of uncertainty. Generally, there is a high level of ambiguity in the definition of bed shear stresses in a mobile channel boundary [63,64].

Equation (2) may be simplified in a number of cases by neglecting particular terms. For rapidly varied flows, which may occur in the case of dam-break flows or ephemeral floods, all terms of the equation are significant. However, in many cases of seasonal floods and related laboratory models, the acceleration terms are significantly smaller than the others, and they may be removed; for further information see, e.g., Mrokowska et al. [57]. Shear velocity has been evaluated with formula derived from flow equations in a number of unsteady flow studies [57,58,65–67] as well as in studies on sediment transport in unsteady flow conditions [12,28,34].

It should be noted that water surface slope $(I - \vartheta)$ is present in each form of the equation irrespective of the simplifying assumptions. Water surface slope has a pronounced impact on sediment transport assessment especially in the case of high-yield ephemeral streams [68]. At the same time, this variable is difficult to control in laboratory mobile bed conditions, where water surface fluctuations tend to occur in relatively shallow flow [34].

4. Impact of Unsteady Flow on Bed Structure and Composition

The texture of the riverbed may evolve rapidly during floods due to the combined effect of variable shear stresses and the availability of sediment grains. When coarse-grained riverbed is examined in natural conditions, it is almost impossible to distinguish which aspects of bed structure are the effect of steady or unsteady flow [11], since it has been shown that both types of flow trigger the same fundamental phenomena involving grain organization. An example is the formation of an armor layer (i.e., a bed surface layer of grains coarser than subsurface material). Three well-documented mechanisms of armor formation are horizontal downstream preferential transport of finer grains (winnowing), kinematic sieving, moving grains in a vertical direction, and spontaneous percolation when the coarse fraction is immobile [15,69]. A recent laboratory study considered the armoring process in the context of dense granular flow and found that vertical segregation of grains may occur not only due to the action of flowing water but also due to granular bottom-up segregation [70].

Much attention has been paid to the formation and persistence of an armor layer in steady and unsteady flows. It has been shown that low steady flow promotes channel bed consolidation and the formation of an armor layer [15,71]. However, experimental research has demonstrated that not only steady but also unsteady flows may trigger the formation of armor conditions [5]. An armoring effect has been identified for flat flood waves (as in snowmelt floods) with a long falling limb. Another laboratory study has shown the formation of coarse-grain clusters under increasing discharge [41]. A similar stabilizing effect has been demonstrated for a low magnitude hydrograph occurring before another flood wave [25]. It has been demonstrated that armoring is more likely in sediment starving conditions than when sediment is available [5]. Thus, antecedent steady flow without sediment feeding is usually applied in the laboratory to prepare an armored bed for unsteady flow experiments [12,27,36].

Bertin and Friedrich [72] reported that total mobilization of coarse sediments is only possible during high-magnitude floods [73], indicating that partial transport promoting stable armor layer formation prevails in coarse-grained riverbeds. Armor layer destruction has been observed for peaky dam water release hydrographs with high variability of flow and large stream power [74].

Various effects of unsteady flow on bed composition have been reported in the literature. Some field studies have indicated that bed composition after a flood event remained the same as before the flood [75,76]. A possible explanation is the constant supply of sediment from upstream enabling mobile armor layer formation [75]. Conversely, the laboratory experiments presented in Mao [24] showed that bed surface composition and arrangement were modified after a simulated flood event with a mobile armor layer.

It has been demonstrated that the stability of an armor layer depends on the grain size distribution of the sediment supply, with a mobilizing effect when grains finer than the bed material are provided [15,77]. Mobility of grains changes considerably in bi-modal sediments. Steady flow experiments have demonstrated that the threshold for gravel transport is reduced when sand is added [78,79]; when sand content exceeds 35 to 40% then sediment behaves like sandy material [80]. Similar effects have been revealed in unsteady flow experiments. Li et al. [29] demonstrated that transport of gravel is higher in a gravel–sand mixture than in a pure gravel bed and the transport of sand is lower due to a hindering effect. Wang et al. [28] compared the total sediment transport rate for unimodal sediments and bi-modal gravel–sand mixture and found that the mixture is transported at higher bedload rates than the unimodal counterpart. Moreover, experiments with sand–silt and gravel–sand mixtures have demonstrated that bedload transport is larger in the first case since gravel has a stabilizing effect on the second mixture [32]. Perret et al. [26] investigated the effect of infiltration of sand and silt experimentally into a gravel matrix on sediment transport in an unsteady flow event. Their approach differed from that of previous studies in that they did not use mixed sediment but instead infiltrated fine grains into the gravel matrix. They reported that cohesive sediment consolidates the bed and, thus, reduces sediment flux compared to bed composed of gravel, whereas infiltrated sand enhances sediment transport.

5. Total and Fractional Bedload Transport

The impact of flow unsteadiness on sediment transport manifests itself in the total weight of sediment transported during a flood (total sediment yield). Laboratory experiments comparing total yield for a given hydrograph and for the equivalent-volume steady flow have shown that sediment yield is higher for unsteady flow than for the equivalent steady flow counterpart, indicating that unsteadiness enhances sediment transport [13,28,29]. It has been demonstrated that total sediment yield was up to an order of magnitude higher for the naturally-shaped hydrograph (peak flow rate 18 L/s and duration 7200 s) than for the equivalent steady flow (flow rate 13.45 L/s and duration the same as for the unsteady flow hydrograph) [28]. Li et al. [29] presented data extending these observations and reported, among other findings, that for a naturally-shaped unsteady flow hydrograph (duration 7 h and flow rate peak 0.038 m^2/s) and its volume-equivalent steady flow counterpart, total yield of unimodal sediment decreased from 114.8 kg to 11.4 kg for gravel and from 440.2 kg to 271.6 kg for sand. However, Yager [15] reported a few studies that found smaller total yield during a flood event than in equivalent steady state conditions. This is indicative of the fact that other factors, such as sediment availability, have to be considered in addition to the flow characteristics in such comparisons.

Wang et al. [28] claimed that flow unsteadiness and hydrograph magnitude, and not hydrograph shape, are major factors influencing sediment transport yield, while Redolfi et al. [30] found hydrograph magnitude and shape to be the main factors influencing the averaged bedload transport.

The structure of the bed surface, sediment supply conditions, and unsteadiness of flow seem to be major factors affecting temporal bedload and fractional transport [28,32]. Bedload rate varies in time during flood wave propagation, exhibiting hysteresis in the relationship between total sediment transport rate and flow rate with time lag effects. Both a clockwise hysteresis, with the bedload peak preceding the discharge peak, and a counterclockwise hysteresis, with the reverse trend, have been observed in nature and in the laboratory, and a more complicated figure-8 shape has also been reported (see Table 1 and Figure 3).

Various factors affect the loop-shaped relationship between bedload rate and discharge, e.g., the availability of sediment, including supply from upstream and the organization of bed sediments. In-depth analysis of these issues can be found in a review by Gunsolus and Binns [22]. A clockwise hysteresis has been reported most often in intact coarse-bed conditions [12,24,25,27,28,30,34]. A counterclockwise hysteresis has been observed mainly for initial armored or well-sorted conditions, where the bedload peak occurred after the breakup of consolidated material along the receding limb of the hydrograph [12,32] or, as in the case of sand [13], where it has been associated with bed forms.

Laboratory studies on bi-modal gravel–sand sediments have revealed the variation in grain size transported during a flood event, i.e., fractional transport [12,24,25,28]. The clockwise bedload–discharge relationship reported for these mixtures has been accompanied by a counterclockwise hysteresis in fractional bedload transport, that is, finer grains predominate in sediment transported along the rising limb and coarser grains dominate along the receding one. Conversely, a counterclockwise hysteresis in total bedload appeared along with clockwise loop in fractional transport [12].

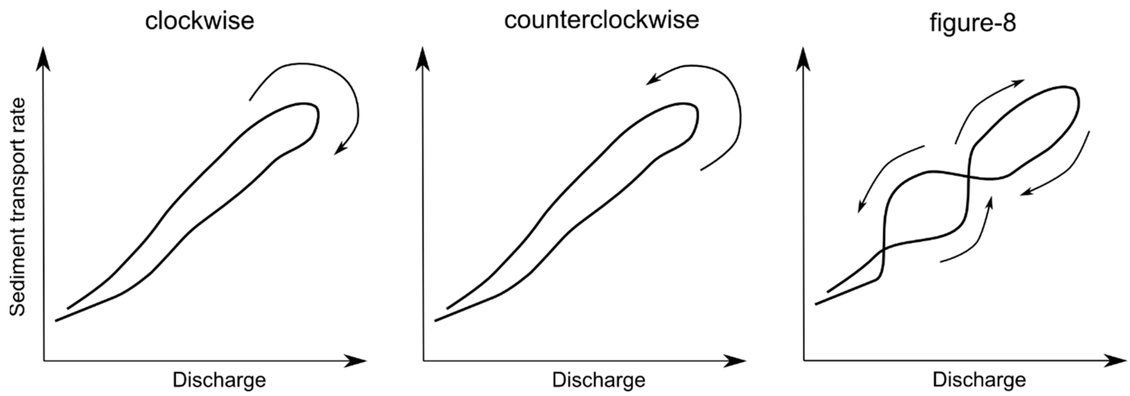

Figure 3. Types of bedload transport hysteresis. Arrows denote hysteresis direction.

Although existing data are not sufficient to quantify the effect of hydrograph shape on hysteresis in the bedload rate–discharge relationship [22], it is important to stress the significance of flow unsteadiness itself since the literature reports that hysteresis has been observed only for rapidly changing flows [11]. Wang et al. [28] demonstrated that unsteadiness affects both total and fractional bedload. Their findings show that hydrographs with a higher rate of unsteadiness (short peaky flows) transport relatively more sediment than gradual events. More significantly, the authors have suggested that in these flashy hydrographs, sediment transport may be initiated for lower flow than in the case of flat hydrographs. These observations are in line with the theory of unsteady flow, which says that bed shear stress achieves its peak along a rising limb (see Section 3), thereby making favorable hydraulic conditions for maximum bedload transport. Whether a bedload peak appears around the peak of bed shear stress or not depends on other sediment and bed-related factors, e.g., sediment availability.

6. The Impact of Flood History on Bedload Transport

Field observations have shown that single unsteady flow events may considerably modify riverbed morphology [81]. However, riverbeds evolve continuously as a result of successive periods of low flow disrupted by flood events, or repeating flashfloods, as for instance occur in ephemeral streams in arid regions [1,6,7], or pulsed flows below dams [3]. The cycles of low and high flows, i.e., flood history, have a significant influence on riverbed morphodynamics on a long-term scale [3,11,25].

Laboratory studies on the impact of preceding flow events on sediment transport during a flood have been increasingly reported in the literature in recent years. In this approach, multiple flood events are considered to check what memory a fluvial system may exhibit. A sequence of floods varying in duration, magnitude, shape, and intraflood flow have been simulated in laboratory channels to study the effects of previous flows on sediment grain arrangement in gravel or bi-modal riverbeds. Hassan et al. [5] claimed that a few cycles of flat hydrographs per year promote armoring. Experimental studies on the effect of cycled pulsed hydrographs have shown downstream fining of surface sediment and demonstrated that bed structure and bedload transport are affected by the frequency of unsteady flow and duration of low flow periods [31]. Similarly, Redolfi et al. [30] observed downstream fining and highlighted the role of low flow periods when finer material is winnowed.

Mao [25] ran a sequence of stepped hydrographs of different magnitudes on a bi-modal bed composed of gravel–sand mixture to show that high magnitude hydrographs affect the sediment transport rate during subsequent high- and low-magnitude flood events, while the preceding low-magnitude hydrograph affects the sediment transport rate only when it is followed by a low-magnitude event. The study indicated potential reasons for the reduction of the sediment transport rate during a subsequent hydrograph when the first one has a high magnitude: (1) mobilization of coarser grains from the thicker layer of active sediments and (2) kinematic sieving reducing the availability of fine grains. The reduction of sediment transport during a low-magnitude event when it is preceded by a low-magnitude event was attributed to (1) the formation of clusters and patches which stabilize the bed and (2) the effect of coarse grain protrusion. The stabilizing effects of antecedent low-flow have been observed earlier in studies on single hydrographs with low antecedent flows, e.g., in Waters and Curran [32]. Mao [25] also reported decreasing bedload hysteresis through successive flood events and associated it with the vertical winnowing of fine grains. Phillips et al. [11] performed an experiment with unimodal sediment and observed no memory effects, which, along with the studies mentioned above, indicates that sediment composition seems to be a major factor contributing to the memory of a fluvial system.

7. Recapitulation, Open Questions, and Outlook

It should be evident from the material discussed above that understanding bed load transport under unsteady flow conditions is central to understanding the impact of flood events in water courses. Bearing in mind the complexity of the physics underlying these processes, especially when temporal changes are taken into account, we argue that the best approach to increase our knowledge of bed load transport involves laboratory flume experiments. While there are opportunities to move forward at increased pace, there are also significant challenges faced by hydraulic researchers, which have been discussed in this paper.

In principle this paper has sought to summarize the current knowledge on the dynamics of bed load transport and interactions between flow unsteadiness and riverbed. This review has discussed only a few selected topics, a selection necessarily biased by the interests and/or involvement of the authors. As mentioned in the introduction, a few reviews of this topic already exist, and they are recommended for a more complete overview of the field.

Significant advancements have been made, particularly in the last ten years, in understanding the impact of flood events in watercourses with gravel or bi-modal sediment. One reason for such interest in the subject is the practical significance of unsteady flow events in mountain regions, which are prone to flooding and serious alteration of fluvial system morphodynamics. Another reason is the eagerness to solve the complex fundamental two-phase flow problem involving water and grains with multimodal size distribution in unsteady flow conditions. Sediment transport in sand bed rivers, where the evolution of bed forms instead of grain organization affects the transport rate, has gained much less attention; however, this trend seems to be changing [82]. Even with the mentioned advancements, challenges remain, and we are far from being able to posit possible generalizations due to the limited number of various conditions studied and too few experiments performed under similar conditions.

We can, however, point out some of the limitations of the works described in this paper. First, we have assumed the sediment to be cohesionless, and we have discussed only research dealing with such situations, although we realize that such a condition does not have to be satisfied in many natural settings, particularly when the bed is covered by clay or mud. A second major assumption concerns the quite artificial shape of most of the hydrographs created in laboratory flumes. However, the variation in those hydrographs, in terms of such factors as shape, duration, and flow magnitude, does provide insight into their impact on bed load transport.

Almost every published study has brought a few open questions showing how much effort is still necessary to gain a basic understanding of sediment transport processes on a local grain scale, a reach scale, and on the scale of the whole basin. Based on those studies and our own experience and intuition, we may point to the following goals and directions of future experimental studies. There are often issues that are conceptually very straightforward but would still pose technical problems; a good example is the experimental evaluation of the gradient of flow depth and consequently friction velocity and the bed shear stress. This is associated with difficulties in avoiding water surface slope fluctuations under unsteady flow conditions in a flume. New techniques allowing the above to be solved are still in great need. If this can be satisfactorily resolved, the next task of crucial importance seems to be quantifying the effect of flow unsteadiness and variable shear stresses during the hydrograph on the sediment transport rate and hysteresis in the relationship between bedload rate and the discharge.

It is expected that trials to elucidate how sediment transport dynamics in an unsteady flow event depend on the flow memory of the system (e.g., associated with a flood event sequence) remains an active area of research for the foreseeable future. After all, we realize that the alterations in flood patterns forecast by climate change models [83,84] may enhance the variability of unsteady flow events and intraflood conditions, and the complexity of flow-sediment interactions may increase. It may be equally important to quantify the effect of kinematic sieving occurring in multi-modal grain size distributed sediment during a sequence of flood events [25].

We still do not know if it is possible to quantify sediment transport in unsteady flow given the sediment composition and characteristics of transient flow conditions—so far we are able to qualitatively observe the relationships between various quantities. Going forward, it is crucial to study how various supply conditions in terms of supply rate and grain size affect sediment transport during a flood event and a sequence of events [25]. Apart from its basic importance, this issue has practical implications for experiment design: The effect of initial bed conditions is evident in the analyses of the total supplied and transported sediment mass. Most experiments do not include complex bed configuration involving bed forms and alternate bars, but such extension seems to be absolutely necessary if we want to apply our knowledge to real rivers. Along these lines, Perret et al. [26] pointed to the study of the effect of multimodal sediment composition, considering the effect of fine sediment infiltration into the gravel matrix.

We are also convinced that the major problem in our understanding of bed load transport under unsteady flow conditions lies in the limited understanding of the hydrodynamics of unsteady flows and its interrelation with mass transport phenomena. Therefore, much attention has to be paid to quantifying the effect of flow unsteadiness and variable shear stresses during a given hydrograph on the sediment transport rate and hysteresis in the relationship between bedload rate and discharge, to studying the mutual influence between turbulence and sediment transport in unsteady flow and, last but not least, to correlating flow velocity distributions with bed load discharge.

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