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

Magdalena M. Mrokowska and Paweł M. Rowiński

Institute of Geophysics, Polish Academy of Sciences, Ks. Janusza 64, 01-452 Warsaw, Poland; m.mrokowska@igf.edu.pl (M.M.M.); p.rowinski@igf.edu.pl (P.M.R.)

Received: 25 February 2019; Accepted: 26 April 2019; Published: 29 April 2019

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 | screwed and water-worked | gravel, \( d_{50} = 4.8 \text{ mm} \) | N/A           |
| Curran et al., 2015 [37]  | S, stepped            | 11 × 0.6 × 0.5 slope: 0.022   | duration: 76 min      | well-mixed, screwed    | 70% sand; 30% gravel; \( d_{50} = 0.5 \text{ mm} \); sediment recirculation | N/A           |
| Ferrer-Boix, and Hassan,  | S, pulsed             | 18 × 1 × 0.3 slope: 0.036     | variable duration (1–10 h) low flow 0.065 m²/s, followed by 1.5 h constant high flow pulse 0.091 m²/s | water-worked             | \( d_{50} = 5.65 \text{ mm} \), constant feed rate 2.1 g/m²s | N/A           |
| 2011 [31]                 |                       |                                |                       |                        |                              |               |
| Garvey 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, \( d_{50} = 3.4 \text{ mm} \), no supply | C, CC         |
| Hassan et al., 2006 [5]   | S, stepped triangular  | 9 × 0.6 × 0.5 slope: 0.03     | 0.012–0.055 m³/s, duration: 0.83–64 h | water worked           | range of grain size 0.180–45 mm; no supply | N/A           |
| Humphries et al., 2012    | naturally-shaped (lognormal) | 28 × 0.86 × 0.86              | peak flow: 35 L/s, 25 L/s, duration: 14.5 h, 8.5 h | armored                 | \( d_{50} = 4.1 \text{ mm} \) sediment pulses | S             |
| Lee et al., 2004 [13]     | S, triangular          | 21 × 0.6 × 0.6 slope: 0.002   | base flow: 0.04 m³/s, peak flow: 0.03–0.14 m³/s, duration: 21–80 min |                        | \( d_{50} = 2.08 \text{ mm} \) no supply | CC            |
| Li et al., 2018 [29]      | naturally-shaped (smooth sinuosoidal curves) | 35 × 1.2 × 0.8 slope: 0.03   | peak flow 0.018 m³/s and 0.038 m³/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/m²s | \( d_{50} = 2.08 \text{ mm} \), no supply | N/A           |
| Mao, 2012 [24]            | S, stepped symmetrical | 8 × 0.3 slope: 0.01           | 0.024–0.085 m³/s      | mixed and screwed sediment | 20% sand, 80% gravel, \( d_{50} = 6.2 \text{ mm} \), continuous recirculation | C             |
| Mao, 2018 [25]            | C, three types of stepped symmetrical | 8 × 0.3 slope: 0.01           | 0.024–0.085 m³/s      | water-worked by steady antecedent flow | 20% sand, 80% gravel, \( d_{50} = 6.2 \text{ mm} \), supply | C, CC         |
| Martin and Jerolmack, 2013 | S, pulsed and triangular | 15 × 0.92 × 0.6 slope: 0     | peak flow: 83.4, 1117 L/s, low flow: 39.1, 63.1 L/s, duration: several hours | water-worked by low flow | \( d_{50} = 0.37 \text{ mm} \) no supply | N/A           |
| Mrokowska et al., 2018 [34] | S, triangular          | 12 × 0.49 × 0.6 slope: 0.0083 | base flow: 0.0035–0.031 m³/s, peak flow: 0.0387–0.0456 m³/s, duration: 400–800 s | well-mixed, screwed, without and with antecedent flow | \( d_{50} = 4.93 \text{ mm} \) supply | C             |
| Mrokowska et al., 2016 [39] | S, triangular          |                                |                       |                        |                              | N/A           |
| Nelson et al., 2011 [40]  | S, square-wave         | 6 × 0.25 × 0.4 slope: 0.002   | peak: 0.02 m³/s       | well-sorted           | sand \( d_{50} = 0.58 \text{ mm} \) 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 m³/s to 0.0547 m³/s | water-worked           | \( d_{50} = 6.8 \text{ mm} \) and bimodal gravel-sand and gravel-silt | no            |
| Pierret et al., 2018 [26] | C, stepped symmetrical | 18 × 1 × 0.8 slope: 0.01     | -                     | loose and packed gravel beds, infiltrated with fine grains | gravel \( d_{50} = 6.8 \text{ mm} \) and bimodal gravel-sand and gravel-silt | N/A           |
**Table 1. Cont.**

| Study                                      | Type of Hydro-Graph | Channel Dimensions $^2$ and Slope | Flow          | Initial Bed Conditions | Sediment and Supply | Hysteresis $^3$ |
|--------------------------------------------|---------------------|-----------------------------------|---------------|------------------------|---------------------|-----------------|
| Phillips et al., 2018 [11]                 | C, four different shapes: triangular and rectangular | 30 × 0.5 | -                          | -                      | unimodal, well-mixed, $d_{max} = 7.2$ 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, 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 | $d_{max} = 0.69$ 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$^3$/s, base flow 0.029 m$^3$/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 | screened, 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 food | 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 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 hand, a large body of research has reported the reverse trend, showing decreased flow resistance or a negligible effect in mobile 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 \( \tau \) (N/m\(^2\)) or friction (shear) velocity \( u_* \) (m/s) (Equation (1)) to quantify friction.

\[
u_* = \sqrt{\frac{\tau}{\rho}}
\]

where \( \rho \)—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], \( u_{\text{max}} \)—maximum friction velocity (m/s), \( U_{\text{max}} \)—maximum mean flow velocity (m/s), \( Q_{\text{max}} \)—maximum flow rate (m/s), \( h_{\text{max}} \)—maximum flow depth (m).](image)
The shear velocity in unsteady flow conditions may be conveniently evaluated from the following formula:

\[
(u_s)_SV = \left[ gR \left( I + \frac{U}{gh} \eta + \left( \frac{U^2}{gh} - 1 \right) \frac{\delta}{g} - \frac{1}{g} \zeta \right) \right]^{\frac{1}{2}}
\]  

(2)

where \( \eta = \frac{\partial h}{\partial t} \), \( \delta = \frac{\partial h}{\partial x} \), \( \zeta = \frac{\partial U}{\partial t} \), \( t \)—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 \( (I - \delta) \) 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 m²/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].

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

![Figure 3. Types of bedload transport hysteresis. Arrows denote hysteresis direction.](image-url)
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—which 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.

**Author Contributions:** Conceptualization, M.M.M and P.M.R.; methodology, M.M.M.; resources, M.M.M and P.M.R.; writing—original draft preparation, M.M.M.; writing—review and editing, M.M.M. and P.M.R.; visualization, M.M.M.; supervision, P.M.R.

**Funding:** This work was supported within statutory activities No 3841/E-41/S/2019 of the Ministry of Science and Higher Education of Poland.

**Conflicts of Interest:** The authors declare no conflict of interest.
References

1. Fielding, C.R.; Alexander, J.; Allen, J.P. The role of discharge variability in the formation and preservation of alluvial sediment bodies. *Sediment. Geol.* **2018**, *365*, 1–20. [CrossRef]

2. Millares, A.; Polo, M.J.; Monino, A.; Herrero, J.; Losada, M.A. Bed load dynamics and associated snowmelt influence in mountainous and semiarid alluvial rivers. *Geomorphology* **2014**, *206*, 330–342. [CrossRef]

3. Aigner, J.; Kreisler, A.; Rindler, R.; Hauer, C.; Habersack, H. Bedload pulses in a hydropower affected alpine gravel bed river. *Geomorphology* **2017**, *291*, 116–127. [CrossRef]

4. Mueller, E.R.; Schmidt, J.C.; Topping, D.J.; Shafroth, P.B.; Rodriguez-Burgueno, J.E.; Ramirez-Hernandez, J.; Grams, P.E. Geomorphic change and sediment transport during a small artificial flood in a transformed post-dam delta: The Colorado River delta, United States and Mexico. *Ecol. Eng.* **2017**, *106*, 757–775. [CrossRef]

5. Hassan, M.A.; Egozi, R.; Parker, G. Experiments on the effect of hydrograph characteristics on vertical grain sorting in gravel bed rivers. *Water Resour. Res.* **2006**, *42*. [CrossRef]

6. Billi, P. Flash flood sediment transport in a steep sand-bed ephemeral stream. *Int. J. Sediment Res.* **2011**, *26*, 193–209. [CrossRef]

7. Reid, I.; Laronne, J.B.; Powell, D.M. Flash-flood and bedload dynamics of desert gravel-bed streams. *Hydrol. Process.* **1998**, *12*, 543–557. [CrossRef]

8. Sui, J.; Koehler, G.; Krol, F. Characteristics of Rainfall, Snowmelt and Runoff in the Headwater Region of the Main River Watershed in Germany. *Water Resour. Manag.* **2010**, *24*, 2167–2186. [CrossRef]

9. Kampf, S.K.; Lefsky, M.A. Transition of dominant peak flow source from snowmelt to rainfall along the Colorado Front Range: Historical patterns, trends, and lessons from the 2013 Colorado Front Range floods. *Water Resour. Res.* **2016**, *52*, 407–422. [CrossRef]

10. Tabarestani, M.K.; Zarrati, A.R. Sediment transport during flood event: A review. *Int. J. Environ. Sci. Technol.* **2015**, *12*, 775–788. [CrossRef]

11. Phillips, C.B.; Hill, K.M.; Paola, C.; Singer, M.B.; Jerolmack, D.J. Effect of Flood Hydrograph Duration, Magnitude, and Shape on Bed Load Transport Dynamics. *Geophys. Res. Lett.* **2018**, *45*, 8264–8271. [CrossRef]

12. Guney, M.S.; Bombar, G.; Aksoy, A.O. Experimental Study of the Coarse Surface Development Effect on the Bimodal Bed-Load Transport under Unsteady Flow Conditions. *J. Hydraul. Eng.* **2013**, *139*, 12–21. [CrossRef]

13. Lee, K.T.; Liu, Y.L.; Cheng, K.H. Experimental investigation of bedload transport processes under unsteady flow conditions. *Hydrol. Process.* **2004**, *18*, 2439–2454. [CrossRef]

14. Muirhead, R.W.; Davies-Colley, R.J.; Donnison, A.M.; Nagels, J.W. Faecal bacteria yields in artificial flood events: Quantifying in-stream stores. *Water Res.* **2004**, *38*, 1215–1224. [CrossRef]

15. Yager, E.M.; Kenworthy, M.; Monsalve, A. Taking the river inside: Fundamental advances from laboratory experiments in measuring and understanding bedload transport processes. *Geomorphology* **2015**, *244*, 21–32. [CrossRef]

16. Rickenmann, D. Variability of Bed Load Transport during Six Summers of Continuous Measurements in Two Austrian Mountain Streams (Fischbach and Ruetz). *Water Resour. Res.* **2018**, *54*, 107–131. [CrossRef]

17. Hallermeier, R.J. Oscillatory bedload transport: Data review and simple formulation. *Cont. Shelf Res.* **1982**, *1*, 159–190. [CrossRef]

18. Ribberink, J.S.; Katopodi, I.; Ramadan, K.A.H.; Koelewijn, R.; Longo, S. Sediment transport under (non)-linear waves and currents. In Proceedings of the 24th International Conference on Coastal Engineering, Kobe, Japan, 23–28 October 1994. [CrossRef]

19. Fang, H.W.; Chen, M.H.; Chen, Q.H. One-dimensional numerical simulation of non-uniform sediment transport under unsteady flows. *Int. J. Sediment Res.* **2008**, *23*, 316–328. [CrossRef]

20. Caviedes-Voullieme, D.; Morales-Hernandez, M.; Juez, C.; Lacasta, A.; Garcia-Navarro, P. Two-Dimensional Numerical Simulation of Bed-Load Transport of a Finite-Depth Sediment Layer: Applications to Channel Flushing. *J. Hydraul. Eng.* **2017**, *143*. [CrossRef]

21. Soares-Frazao, S.; Zech, Y. HLLC scheme with novel wave-speed estimators appropriate for two-dimensional shallow-water flow on erodible bed. *Int. J. Numer. Methods Fluids* **2011**, *66*, 1019–1036. [CrossRef]

22. Gunsolus, E.H.; Binns, A.D. Effect of morphologic and hydraulic factors on hysteresis of sediment transport rates in alluvial streams. *River Res. Appl.* **2018**, *34*, 183–192. [CrossRef]
23. Bombar, G.; Elci, S.; Tayfur, G.; Guney, S.; Bor, A. Experimental and Numerical Investigation of Bed-Load Transport under Unsteady Flows. *J. Hydraul. Eng.* 2011, 137, 1276–1282. [CrossRef]

24. Mao, L. The effect of hydrographs on bed load transport and bed sediment spatial arrangement. *J. Geophys. Res. Earth Surf.* 2012, 117. [CrossRef]

25. Mao, L. The effects of flood history on sediment transport in gravel-bed rivers. *Geomorphology* 2018, 322, 196–205. [CrossRef]

26. Perret, E.; Berni, C.; Camenen, B.; Herrero, A.; Abderrezak, K.E. Transport of moderately sorted gravel at low bed shear stresses: The role of fine sediment infiltration. *Earth Surf. Process. Landf.* 2018, 43, 1416–1430. [CrossRef]

27. Humphries, R.; Venditti, J.G.; Sklar, L.S.; Wooster, J.K. Experimental evidence for the effect of hydrographs on sediment pulse dynamics in gravel-bedded rivers. *Water Resour. Res.* 2012, 48. [CrossRef]

28. Wang, L.; Cuthbertson, A.J.S.; Pender, G.; Cao, Z. Experimental investigations of graded sediment transport under unsteady flow hydrographs. *Int. J. Sediment Res.* 2015, 30, 306–320. [CrossRef]

29. Li, Z.J.; Qian, H.L.; Cao, Z.X.; Liu, H.H.; Pender, G.; Hu, P.H. Enhanced bed load sediment transport by unsteady flows in a degrading channel. *Int. J. Sediment Res.* 2018, 33, 327–339. [CrossRef]

30. Redolfi, M.; Bertoldi, W.; Tubino, M.; Welber, M. Bed Load Variability and Morphology of Gravel Bed Rivers Subject to Unsteady Flow: A Laboratory Investigation. *Water Resour. Res.* 2018, 54, 842–862. [CrossRef]

31. Ferrer-Boix, C.; Hassan, M.A. Channel adjustments to a succession of water pulses in gravel bed rivers. *Water Resour. Res.* 2015, 51, 8773–8790. [CrossRef]

32. Waters, K.A.; Curran, J.C. Linking bed morphology changes of two sediment mixtures to sediment transport predictions in unsteady flows. *Water Resour. Res.* 2015, 51, 2724–2741. [CrossRef]

33. Wong, M.; Parker, G. One-dimensional modeling of bed evolution in a gravel bed river subject to a cycled flood hydrograph. *J. Geophys. Res. Earth Surf.* 2006, 111. [CrossRef]

34. Mrokowska, M.M.; Rowinski, P.M.; Książek, L.; Strużyński, A.; Wyrębek, M.; Radecki-Pawlik, A. Laboratory studies on bedload transport under unsteady flow conditions. *J. Hydrol. Hydromech.* 2018, 66, 23–31. [CrossRef]

35. Curran, J.C.; Waters, K.A. The importance of bed sediment sand content for the structure of a static armor layer in a gravel bed river. *J. Geophys. Res. Earth Surface* 2014, 119, 1484–1497. [CrossRef]

36. Orru, C.; Blom, A.; Uijttewaal, W.S.J. Armor breakup and reformation in a degradational laboratory experiment. *Earth Surf. Dyn.* 2016, 4, 461–470. [CrossRef]

37. Curran, J.C.; Waters, K.A.; Cannatelli, K.M. Real time measurements of sediment transport and bed morphology during channel altering flow and sediment transport events. *Geomorphology* 2015, 244, 169–179. [CrossRef]

38. Martin, R.L.; Jerolmack, D.J. Origin of hysteresis in bed form response to unsteady flows. *Water Resour. Res.* 2013, 49, 1314–1333. [CrossRef]

39. Mrokowska, M.; Rowiński, P.; Książek, L.; Strużyński, A.; Wyrębek, M.; Radecki-Pawlik, A. Flume experiments on gravel bed load transport in unsteady flow—Preliminary results. In *Hydrodynamic and Mass Transport at Freshwater Aquatic Interfaces*; Rowiński, P., Ed.; Springer International Publishing Switzerland: Cham, Switzerland, 2016; pp. 221–233.

40. Nelson, J.M.; Logan, B.L.; Kinzel, P.J.; Shimizu, Y.; Giri, S.; Shreve, R.L.; McLean, S.R. Bedform response to flow variability. *Earth Surf. Process. Landf.* 2011, 36, 1938–1947. [CrossRef]

41. Piedra, M.M.; Haynes, H.; Hoey, T.B. The spatial distribution of coarse surface grains and the stability of gravel bed rivers. *Sedimentology* 2012, 59, 1014–1029. [CrossRef]

42. Shvidchenko, A.B.; Kopaliani, Z.D. Hydraulic modeling of bed load transport in gravel-bed Laba River. *J. Hydraul. Eng.* 1998, 124, 778–785. [CrossRef]

43. Ettema, R. Hydraulic modelling: Concepts and practice. In *ASCE Manuals and Reports on Engineering Practice No. 97*; American Society of Civil Engineers: Reston, VA, USA, 2000.

44. Carbonneau, P.E.; Bergeron, N.E. The effect of bedload transport on mean and turbulent flow properties. *Geomorphology* 2000, 35, 267–278. [CrossRef]

45. Nelson, J.M.; Shreve, R.L.; McLean, S.R.; Drake, T.G. Role of near-bed turbulence structure in bed-load transport and bed form mechanics. *Water Resour. Res.* 1995, 31, 2071–2086. [CrossRef]

46. Dixit, S.; Patel, P. Stochastic nature of turbulence over mobile bed channels. *J. Hydraul. Eng.* 2018. [CrossRef]
47. Dey, S.; Das, R.; Gaudio, R.; Bose, S.K. Turbulence in mobile-bed streams. *Acta Geophys.* **2012**, *60*, 1547–1588. [CrossRef]
48. Bialik, R.J.; Nikora, V.I.; Karpinski, M.; Rowinski, P.M. Diffusion of bedload particles in open-channel flows: Distribution of travel times and second-order statistics of particle trajectories. *Environ. Fluid Mech.* **2015**, *15*, 1281–1292. [CrossRef]
49. Spiller, S.M.; Ruther, N.; Friedrich, H. Dynamic Lift on an Artificial Static Armor Layer during Highly Unsteady Open Channel Flow. *Water* **2015**, *7*, 4951–4970. [CrossRef]
50. Paiement-Paradis, G.; Marquis, G.; Roy, A. Effects of turbulence on the transport of individual particles as bedload in a gravel-bed river. *Earth Surf. Process. Landf.* **2011**, *36*, 107–116. [CrossRef]
51. Song, T.; Chiew, Y.M.; Chin, C.O. Effect of bed-load movement on flow friction factor. *J. Hydraul. Eng.* **1998**, *124*, 165–175. [CrossRef]
52. Hohermuth, B.; Weitbrecht, V. Influence of Bed-Load Transport on Flow Resistance of Step-Pool Channels. *Water Resour. Res.* **2018**, *54*, 5567–5583. [CrossRef]
53. Campbell, L.; McEwan, I.; Nikora, V.; Pokrajac, D.; Gallagher, M.; Manes, C. Bed-load effects on hydrodynamics of rough-bed open-channel flows. *J. Hydraul. Eng.* **2005**, *131*, 576–585. [CrossRef]
54. Recking, A.; Frey, P.; Paquier, A.; Belleudy, P.; Champagne, J.Y. Feedback between bed load transport and flow resistance in gravel and cobble bed rivers. *Water Resour. Res.* **2008**, *44*. [CrossRef]
55. Ghimire, B.; Deng, Z. Event Flow Hydrograph-Based Method for Modeling Sediment Transport. *J. Hydrol. Eng.* **2013**, *18*, 919–928. [CrossRef]
56. Graf, W.H.; Song, T. Bed-shear stresses in nonuniform and unsteady open-channel flows. *J. Hydraul. Res.* **1995**, *33*, 699–704. [CrossRef]
57. Mrokowska, M.M.; Rowinski, P.M.; Kalinowska, M.B. A methodological approach of estimating resistance to flow under unsteady flow conditions. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 4041–4053. [CrossRef]
58. Rowinski, P.M.; Czernuszenko, W.; Pretre, J.M. Time-dependent shear velocities in channel routing. *Hydrol. Sci. J.* **2000**, *45*, 881–895. [CrossRef]
59. Aberle, J.; Rowiński, P.M.; Henry, P.Y.; Detert, M. Auxiliary hydrodynamic variables. Bed shear stress. In *Experimental Hydraulics, Volume 2: Methods, Instrumentation, Data Processing and Management*; Aberle, J., Rennie, C., Admiraal, D., Muste, M., Eds.; CRC Press: Boca Raton, FL, USA, 2017; pp. 322–332.
60. Tu, H.Z.; Graf, W.H. Friction in unsteady open-channel flow over gravel beds. *J. Hydraul. Res.* **1993**, *31*, 99–110. [CrossRef]
61. Song, T.; Graf, W.H. Velocity and turbulence distribution in unsteady open-channel flows. *J. Hydraul. Eng.* **1996**, *122*, 141–154. [CrossRef]
62. Nezu, I.; Nakagawa, H. Turbulence measurements in unsteady free-surface flows. *Flow Meas. Instrum.* **1995**, *6*, 49–59. [CrossRef]
63. Ferreira, R.M.L.; Franca, M.J.; Leal, J.G.A.B.; Cardoso, A.H. Flow over rough mobile beds: Friction factor and vertical distribution of the longitudinal mean velocity. *Water Resour. Res.* **2012**, *48*. [CrossRef]
64. Nikora, V.; McEwan, I.; McLean, S.; Coleman, S.; Pokrajac, D.; Walters, R. Double-averaging concept for rough-bed open-channel and overland flows: Theoretical background. *J. Hydraul. Eng.* **2007**, *133*, 873–883. [CrossRef]
65. Mrokowska, M.M.; Rowinski, P.M.; Kalinowska, M.B. Evaluation of friction velocity in unsteady flow experiments. *J. Hydraul. Res.* **2015**, *53*, 659–669. [CrossRef]
66. Bombar, G. Hysteresis and Shear Velocity in Unsteady Flows. *J. Appl. Fluid Mech.* **2016**, *9*, 839–853. [CrossRef]
67. Ghimire, B.; Deng, Z.-Q. Event flow hydrograph-based method for shear velocity estimation. *J. Hydraul. Res.* **2011**, *49*, 272–275. [CrossRef]
68. Meirovich, L.; Laronne, J.B.; Reid, I. The variation of water-surface slope and its significance for bedload transport during floods in gravel-bed streams. *J. Hydraul. Res.* **1998**, *36*, 147–157. [CrossRef]
69. Frey, P; Church, M. Bedload: A granular phenomenon. *Earth Surf. Process. Landf.* **2011**, *36*, 58–69. [CrossRef]
70. Ferdowsi, B.; Ortiz, C.P.; Houssais, M.; Jerolmack, D.J. River-bed armouring as a granular segregation phenomenon. *Nat. Commun.* **2017**, *8*. [CrossRef]
71. Reid, I.; Frostick, L.E.; Layman, J.T. The incidence and nature of bedload transport during flood flows in coarse-grained alluvial channels. *Earth Surf. Process. Landf.* **1985**, *10*, 33–44. [CrossRef]
72. Bertin, S.; Friedrich, H. Effect of surface texture and structure on the development of stable fluvial armors. *Geomorphology* **2018**, *306*, 64–79. [CrossRef]
73. Haschenburger, J.K.; Wilcock, P.R. Partial transport in a natural gravel bed channel. *Water Resour. Res.* 2003, 39. [CrossRef]

74. Vericat, D.; Batalla, R.J.; Garcia, C. Breakup and reestablishment of the armour layer in a large gravel-bed river below dams: The lower Ebro. *Geomorphology* 2006, 76, 122–136. [CrossRef]

75. Clayton, J.A.; Pitlick, J. Persistence of the surface texture of a gravel-bed river during a large flood. *Earth Surf. Process. Landf.* 2008, 33, 661–673. [CrossRef]

76. Church, M.; Hassan, M.A. Mobility of bed material in Harris Creek. *Water Resour. Res.* 2002, 38. [CrossRef]

77. Venditti, J.G.; Dietrich, W.E.; Nelson, P.A.; Wydzga, M.A.; Fadde, J.; Sklar, L. Mobilization of coarse surface layers in gravel-bedded rivers by finer gravel bed load. *Water Resour. Res.* 2010, 46. [CrossRef]

78. Wilcock, P.R.; Kenworthy, S.T.; Crowe, J.C. Experimental study of the transport of mixed sand and gravel. *Water Resour. Res.* 2001, 37, 3349–3358. [CrossRef]

79. Curran, J.C. The decrease in shear stress and increase in transport rates subsequent to an increase in sand supply to a gravel-bed channel. *Sediment. Geol.* 2007, 202, 572–580. [CrossRef]

80. Church, M.; Ferguson, R.I. Morphodynamics: Rivers beyond steady state. *Water Resour. Res.* 2015, 51, 1883–1897. [CrossRef]

81. Julien, P.Y.; Klaassen, G.J.; Ten Brinke, W.B.M.; Wilbers, A.W.E. Case study: Bed resistance of Rhine River during 1998 flood. *J. Hydraul. Eng.* 2002, 128, 1042–1050. [CrossRef]

82. Reesink, A.J.H.; Parsons, D.R.; Ashworth, P.J.; Best, J.L.C.; Hardy, R.J.; Murphy, B.J.; McLelland, S.J.; Unsworth, C. The adaptation of dunes to changes in river flow. *Earth-Sci. Rev.* 2018, 185, 1065–1087. [CrossRef]

83. Bloschl, G.; Hall, J.; Parajka, J.; Perdigao, R.A.P.; Merz, B.; Arheimer, B.; Aronica, G.T.; Bilibashi, A.; Bonacci, O.; Borga, M.; et al. Changing climate shifts timing of European floods. *Science* 2017, 357, 588–590. [CrossRef]

84. Baynes, E.R.C.; van de Lageweg, W.I.; McLelland, S.J.; Parsons, D.R.; Aberle, J.; Dijkstra, J.; Henry, P.Y.; Rice, S.P.; Thom, M.; Moulin, F. Beyond equilibrium: Re-evaluating physical modelling of fluvial systems to represent climate changes. *Earth-Sci. Rev.* 2018, 181, 82–97. [CrossRef]

© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).