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REVIEW

Sediment transport during flood event: a review

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Abstract Flow unsteadiness in flood events has a significant effect on the structure of the flow field and motion of sediment particles, thereby affecting dispersion of pollutants and river ecology. The aim of the present article was to evaluate state-of-the-art research efforts concerning flow characteristics and sediment transport in unsteady flow condition. The paper is organized in four sections: The first section deals with the unsteady parameters which affect sediment transport. In the second section, the flow characteristics in unsteady open channel flow are presented. Different studies showed that the flow characteristics which affect sediment transport including velocity distribution or shear stress during passage of a hydrograph differ from steady flow condition. In addition, measurements during passage of a hydrograph show that turbulence intensity is generally larger in the rising limb of the hydrograph rather than in the falling limb. This causes the peak of sediment load and pollutants occur during the rising limb of the storm hydrograph. The third and forth sections deal with bed load and suspended load in unsteady flow condition, respectively. Studies show that the methods which are based on steady flow conditions generally underestimate the sediment transport rates in unsteady flows. The larger the unsteadiness, the bigger is the difference. Finally, with considering different findings from previous studies, suggestions are presented for further research.

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Introduction

Flow variability is an important characteristic of river systems, with implications for river geomorphology, ecology and human uses (Puckridge et al. 1998). Many aquatic and riparian-dwelling organisms are adapted to variations in flow that characterize their native river habitats, including periodic high flows (Junk et al. 1989; Poff et al. 1997). It is reported that infrequent, episodic events, such as that in arid climate rivers (McMahon 1979; Finlayson and McMahon 1988), exert a greater influence on river form and ecology (Wolman and Gerson 1978; Hecht 1994). For example, in unsteady flows, forces acting on an organism are more complex than steady flow condition (Shield et al. 2011). Koehl (1984) stated that any organism in an unsteady flow will be subjected to acceleration forces in addition to drag. As an important constituent of river ecosystem, the sediment is not only the main reservoir of nutrients influencing river water quality (Lei et al. 2010), but also the active exchange zone of materials between water and soil interface. For example, bed forms initiating from sediment transport influence the bed stream transfer of solutes. Previous studies have indicated that a significant portion of organism load during peak flows may come from the bed sediment (Cho et al. 2010; Wilkinson et al. 2011). In fact, the bed of a river can act as a sink or source of contaminants; pollutants may enter the bed, be stored there for some time, and then be released slowly back to the water column. It can therefore be concluded that the unsteadiness of flow in flood events has significant effects on the structure of the flow field and motion of sediment particles, thereby affecting dispersion of pollutants and river ecology. Understanding the flow and sediment behavior in unsteady flow condition is therefore important for studying river behavior and ecology.

An important fact is that the most intensive transport processes in rivers occur during the passage of a flood wave (Rowinski and Czernuszenko 1998). Field studies by Chien et al. (1987) showed that during the passage of a flood, the bed load movement, the suspended load distribution as well as the river processes are different from those in a steady flow. Based on Tsujimoto et al. (1988, 1990), there are two mechanisms which might be distinguished in unsteady sediment transport: One is the direct effect of the flow unsteadiness; and the other one is a relaxation process (indirect effect) brought about by the slow response of the sediment transport and fluvial process to the flow condition. According to Wang et al. (1997), there is an urgent need for understanding of sediment transport and river deformation in unsteady flows.

Research on unsteady turbulent boundary layers has shown that the unsteadiness effects are often confined to a thin layer near the wall, while the outer region is not strongly affected. Consequently, the outer-region data may not properly reflect the unsteadiness influence on the most important inner-variable parameter which is the bed friction velocity (Carr 1981; Pathirana et al. 2006). Therefore, the structure of the flow field in unsteady flow differs from steady flow condition. However, because of the complexities which exist in unsteady flows, in most hydraulic engineering problems such as sediment transport calculations, hydrograph is often modeled as a succession of stepwise, short-duration steady flows named as equivalent steady flow. This may cause error in computing sediment yield as well as pollutant concentration at a river reach especially for streams in arid regions which large floods occur in a short period (Nouh 1988a). Different studies showed that calculation of sediment transport in an unsteady flow condition by steady flow equations lead to smaller value in comparison to actual sediment transport. The reason is that an unsteady regime causes re-suspension and transport of deposited bottom sediments (Bombar et al. 2011). This is because turbulence intensities, both stream wise and vertical, are larger in unsteady flows, causing lift forces on sediment or any other transporting particles (Song and Graf 1996).

According to Graf (2003), turbulence plays an essential role in all flows of water sediment mixtures. In order to solve this problem, some researchers tried to introduce appropriate non-dimensional parameters for characterizing the unsteadiness effects on flow structure and sediment transport in unsteady flows condition.

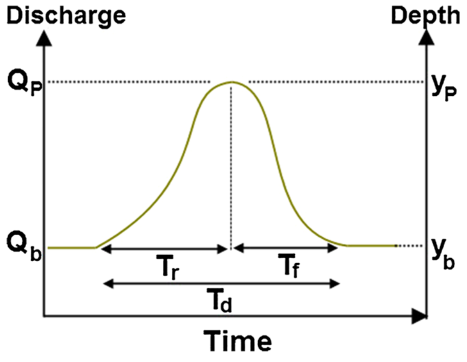

Fig. 1 Characteristics of a typical hydrograph

Although the mentioned problem is very serious and need further studies especially for channels in arid regions, the relevant studies in the literature are scarce and dispersed. The purpose of this paper is to give an overview of studies on flow characteristics and sediment transport in an unsteady flow condition. Finally, based on available research results, several topics for future researches are introduced.

Effective parameters on sediment transport in unsteady flow condition

In addition to parameters affecting sediment transport in steady flows, various non-dimensional parameters for characterizing the unsteadiness effects are defined in the literature. Figure 1 shows different parameters of a hydrograph. Takahashi (1969) was probably a pioneer of introducing the unsteady parameters. He proposed an unsteadiness parameter in order to analyze the one-dimensional equation of flood waves over slopped beds as:

$$\lambda = \frac{1}{\sqrt{g\,y_\mathrm{p}} \times \mathrm{Sin}\,\theta} \times \frac{y_\mathrm{p} - y_\mathrm{b}}{T_\mathrm{d}} \tag{1}$$

where y_b is initial flow depth (base flow), y_p is flow depth at the peak of the hydrograph, g is gravitational acceleration, T_d is duration of the hydrograph and Sin θ is the channel bed slope. This parameter implies the ratio of the rising speed of water surface to the vertical component of celerity of long waves.

In reviewing different studies, it can be concluded that many researchers have used the following unsteady parameter: (Graf and Suszka 1985; Yen and Lee 1995; Song and Graf 1996; Nezu et al. 1997; Lee et al. 2004; Ahanger et al. 2008; Bombar et al. 2011):

$$P = \frac{1}{u_{*\mathrm{b}}} \frac{y_\mathrm{p} - y_\mathrm{b}}{T_\mathrm{d}} \tag{2}$$

where $u_{*\mathrm{b}}$ is the bed shear velocity associated with the steady base flow before hydrograph passages. It can be seen that flow unsteadiness increases with increasing parameter P.

However, this parameter takes into account the duration of the hydrograph only and not the steepness of the rising limb of the hydrograph. Whereas some researchers believe that the duration of the rising limb is more important. De Sutter et al. (2001) showed that the rate of sediment transport of a hydrograph with $T_\mathrm{r} = 40$ s and $T_\mathrm{f} = 80$ s where T_r and T_f are duration of rising and falling limb of a hydrograph, respectively, differs from a hydrograph with $T_\mathrm{r} = 80$ s and $T_\mathrm{f} = 40$ s with the same maximum water levels, despite the fact that they have the same value of unsteady parameter P (Eq. 2). Therefore, Nezu and Nakagawa (1993) proposed the following unsteady parameter which considers only the duration of the rising limb of a hydrograph:

$$\alpha = \frac{y_\mathrm{p} - y_\mathrm{b}}{T_\mathrm{r}} \bigg/ \frac{U_\mathrm{p} + U_\mathrm{b}}{2} \tag{3}$$

where U_p and U_b are flow velocity for peak and base flow of a hydrograph, respectively. The typical value of P and α is in order of 10^{-3}.

For mountainous river with large slope, investigation by Suszka (1988) showed that the combination of following parameter with parameter P (Eq. 2) well described bed sediment transport in unsteady flow condition:

$$\eta = \frac{S_0 \cdot d_{50}}{y_\mathrm{p}} \tag{4}$$

where S_0 is channel bed slope and d_{50} is median diameter of sediment size.

By modifying parameter P, Kabir (1993) found that following unsteady parameter works better in quantifying the hydrograph effects:

$$\chi = \frac{2\left(y_\mathrm{p} - y_\mathrm{b}\right) y_\mathrm{p}}{\left(u_{*\mathrm{b}}^2 \times T_\mathrm{d}\right)^2} \tag{5}$$

Qu (2003) stated that instead of flow depth and hydrograph duration in parameter P (Eq. 2), the effect of unsteady parameter would be more obvious by taking into account the flow discharge and rising limb duration of a hydrograph as:

$$\Omega = \frac{1}{u_{*\mathrm{b}}^2} \times \frac{Q_\mathrm{p} - Q_\mathrm{b}}{T_\mathrm{r}} \tag{6}$$

De Sutter et al. (2001) stated that the excess shear velocity (relative to critical shear velocity) has significant effects on suspended sediment transport rate during passage of a hydrograph. Therefore, they modified the unsteady parameter α in Eq. (3) into the following form to represent the unsteadiness of a hydrograph:

$$\beta = \left(\frac{y_\mathrm{p} - y_\mathrm{b}}{T_\mathrm{r}} \bigg/ \frac{U_\mathrm{p} + U_\mathrm{b}}{2}\right) \times \frac{u_{*\mathrm{p}}^2 - u_{*\mathrm{cr}}^2}{u_{*\mathrm{cr}}^2} \tag{7}$$

In this Equation, $u_{*\mathrm{p}}$ is the maximum shear velocity during passage of the hydrograph, and $u_{*\mathrm{cr}}$ is the critical shear velocity for sediment particle motion.

Lee et al. (2004) introduced two other parameters which influence bed load transport during hydrograph events:

$$W_\mathrm{k} = \frac{u_{*\mathrm{b}}^2 \cdot V_\mathrm{ol}}{g \cdot y_\mathrm{b}^3 \cdot B} \tag{8}$$

$$Fr_\mathrm{u} = \frac{U_\mathrm{p}}{\sqrt{g\left(y_\mathrm{p} - y_\mathrm{b}\right)}} \tag{9}$$

In Eq. (8), V_ol represents total volume of water under the hydrograph excluding the base flow, and B is channel width. For calculation of V_ol, the base flow of the hydrograph is defined equal to the condition for sediment incipient motion. Parameter W_k which was defined as an index of the total flow work done on the movable bed has considerable effects on sediment transport. However, when the parameter Fr_u which is a slightly modified form of Froude number is appreciably less than unity, its influence on sediment transport is negligible.

Esmaeili et al. (2008) and Kashefipour et al. (2009) have listed different parameters describing sediment transport in unsteady flow condition. By dimensional analysis, in addition to P (Eq. 2), they presented the following unsteady parameter which affects sediment transport

$$\gamma = \frac{T_\mathrm{d} \cdot \Delta y \cdot U_\mathrm{b}^2}{Q_\mathrm{p} \cdot S_0} \tag{10}$$

where Δy is the difference in flow depth between the hydrograph peak flow and the base flow; μ and ρ are water viscosity and density, respectively. This parameter introduces different hydrograph and channel characteristics.

Bombar et al. (2011) concluded that the unsteady parameters (2) and (7) may not be proper expressions to describe the unsteadiness effects of a flow especially for short-duration hydrographs. Therefore, they presented the following unsteadiness parameter based on the net acceleration concept in the rising period of the hydrograph:

$$P_\mathrm{gt} = \frac{\left| g \cdot S_0 - \frac{U_\mathrm{p} - U_\mathrm{b}}{T_\mathrm{r}} \right|}{g} \tag{11}$$

However, this parameter though worked well for interpretation of the authors' experimental data in bed load, sediment transport was not as good for others data such as Qu (2003).

Flow characteristics in an unsteady open channel flow

Turbulence plays an important role in open channel flows in transport of momentum, heat and mass. Turbulence structures and flow field properties in steady open channel have been well investigated over the past century. However, this issue in unsteady open channel flow condition is rather new. The reasons may be due to complexity in turbulence concept for unsteady flow and difficulties in measurement techniques and experimental equipments. Research on unsteady turbulent boundary layers has shown that the unsteadiness effects are often confined to a thin layer near the wall, while the outer region is not strongly affected (Carr 1981). Consequently, the outer-region data may not properly reflect the unsteadiness influence on the most important inner-variable parameter which is the bed friction velocity. Henderson (1966) presented a way to estimate shear velocity in unsteady flows ($u_{*\mathrm{un}}$) by employing de Saint–Venant equation of motion. According to this equation:

$$u_{*\mathrm{un}} = \sqrt{g\,y\left(S_0 - \frac{\partial y}{\partial x} - \frac{U}{g}\frac{\partial U}{\partial x} - \frac{1}{g}\frac{\partial U}{\partial t}\right)} \tag{12}$$

where y is the flow depth, U is flow velocity, x is space variable and t is time. By defining wave celerity as $C = U + \sqrt{g\,y}$, then Eq. (12) can be rewritten as

$$u_{*\mathrm{un}} = \sqrt{g\,y\left(S_0 + \frac{1}{C}\frac{\partial y}{\partial t}\right) - \left(y\frac{\partial U}{\partial t}\left(1 - \frac{U}{C}\right)\right)} \tag{13}$$

Tu (1991), Tu and Graf (1992a, b, 1993) studied the velocity and shear stress distribution in unsteady flow condition. They also found that the friction velocity estimated form Eq. (13) do not coincide with ($u_{*\mathrm{s}} = \sqrt{g\,y\,S_0}$) which is correct in steady uniform flow. They presented the following relation for the ratio of shear velocity in unsteady and steady condition as:

$$\frac{u_{*\mathrm{un}}}{u_{*\mathrm{s}}} = \sqrt{1 + \frac{3}{5\,S_0\,U}\frac{\partial y}{\partial t}\left(1 - \frac{4}{9}Fr^2\right)} \tag{14}$$

where Fr is the local Froude number. The ratio of $u_{*\mathrm{un}}/u_{*\mathrm{s}}$ can be larger or smaller than unity based on flow depth variation (rising limb or falling limb of the hydrograph) and Froude number. Based on this study for an equal water depth in a hydrograph, $u_{*\mathrm{un}}$ is larger in the rising limb than in the falling branch and it reaches its maximum value before the arrival of the peak flow depth of the hydrograph. This study also showed that, the difference of the shear velocity in rising and falling limb gets smaller with the increase of water depth.

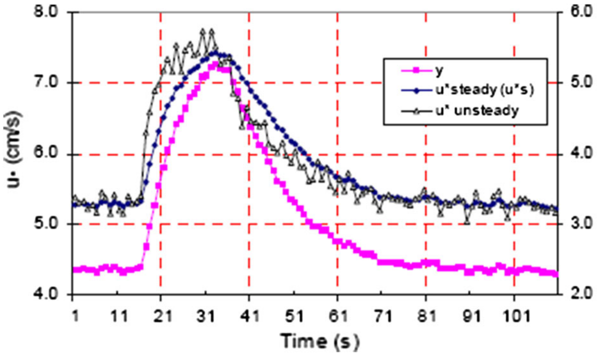

Fig. 2 Variation of water depth and bed shear velocity in an unsteady flow (Pathirana et al. 2006)

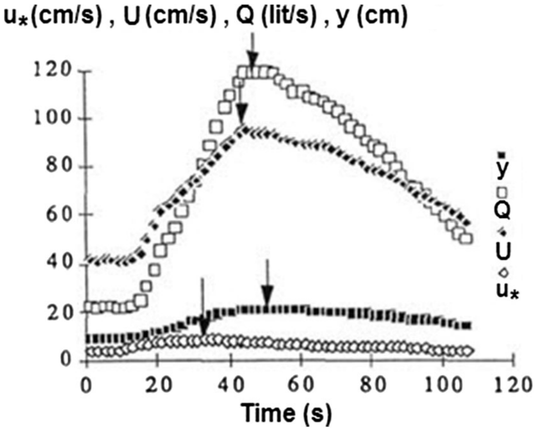

Fig. 3 Time records of u_*, U, Q and y; in a hydrograph (Tu and Graf 1993)

After more than a decade, Pathirana et al. (2006) also confirmed that the shear velocity in unsteady flow and steady flow is not the same. They observed that, for the rising limb of the hydrograph, the shear velocities ($u_{*\mathrm{un}}$) based on unsteady flow equation (Eq. 12) are larger than that from the steady state formula ($u_{*\mathrm{s}}$), and this behavior is opposite during passing of the falling limb. This phenomenon is shown in Fig. 2. In addition, they observed that when unsteady nature of the flow increases, the difference in shear velocities between rising and falling limb increases significantly. They also reported that the lag time between the peak shear velocity and the peak of the hydrograph is in the range of 0.02–0.1 of hydrograph duration time (T_d).

It is interesting to note that peak bacterial concentrations in streams are found to occur usually during the rising limb of the storm hydrograph (Davies-Colley et al. 1994; Jamieson et al. 2005) well ahead of the discharge peak and close to the line of maximum flow acceleration (McKergow and Davies-Colley 2010; Nagels et al. 2002). Ghimire (2010) stated that a reason for the early peak in bacterial

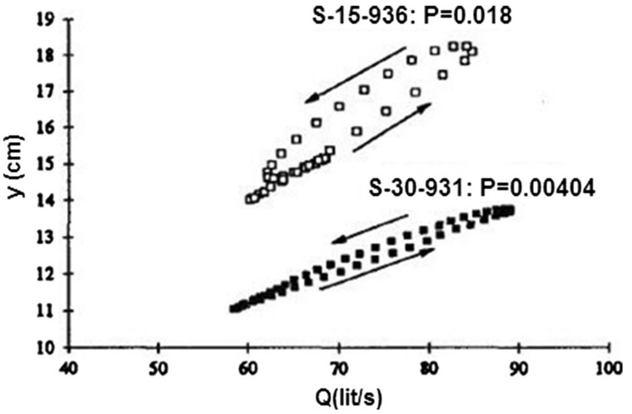

Fig. 4 Hysteresis curve relationship between flow discharge and depth during a hydrograph (Song and Graf 1996)

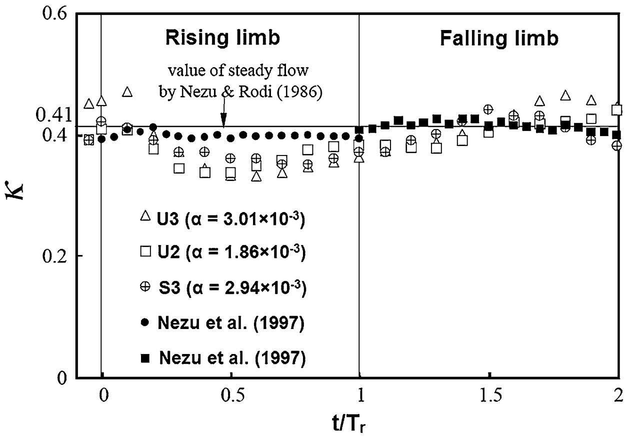

Fig. 5 Variation of von Karman Constant against normalized time (Onitsuka and Nezu 1999)

concentrations is that the maximum bed shear stress occurs well before the discharge reaches its peak.

Tu and Graf (1993) observed a time lag between $u_{*\max}$, $U_{\max}$, $Q_{\max}$ and $y_{\max}$ in unsteady flow in their experiments (Fig. 3).

Based on the experimental investigations carried out for shear velocity computations on rough bed due to unsteady flow conditions, Kabir (1993) concluded that the second term of Eq. (13) had almost negligible effect on shear velocity values. Therefore, the following simplified equation was presented for shear velocity in unsteady flow condition:

$$u_{*\mathrm{un}} = \sqrt{g\,y\left(S_0 + \frac{1}{C}\frac{\partial y}{\partial t}\right)} \tag{15}$$

The distribution of the velocity and turbulence, and bed shear stress in fixed and movable bed under unsteady condition was studied by Song (1994), Song et al. (1994), Song and Graf (1994, 1996, 1997), Graf and Song (1995) and Song and Chiew (2001). Similar conclusion as Tu (1991) for time variation of different parameters during hydrograph (Fig. 3) was reported by these studies. These studies show that, the unsteady parameter, P, (Eq. 2) affects the mean flow properties of unsteady open channel flows and it becomes more evident as the unsteady parameter increases.

Song and Graf (1996) as well as French (1985) indicated the hysteresis relationship between flow discharge and depth during a hydrograph. The term hysteresis in hydraulic engineering refers to situations where properties such as the flow depth or the sediment concentration have different values for a given water discharge during the rising and falling stages (Brownlie 1981). As shown in Fig. 4 presented by Song and Graf (1996), the larger value of the unsteady parameter, P, the more pronounced is the hysteresis form of the rating curve. However, for the case of uniform steady flow, a one-to-one relationship between the discharge and water stage in the channel can be constructed by concomitantly measuring discharges and stages (Ahanger et al. 2008; Ho 2010). Therefore, use of steady flow rating curve for both steady and unsteady flow situations introduces errors that have been recognized for a long time (Fenton and Keller 2001; Aschwanden et al. 2009).

In addition, Song and Graf (1996) clarified that the velocity profile in the inner region of an unsteady flow can be expressed by the log low and that, in the rising limb of the hydrograph, the components of turbulence kinetic energy $\sqrt{u'^2}$ and $\sqrt{v'^2}$ values are generally larger than those in the falling limb.

Based on the Reynolds and continuity equations in two-dimensional flows, Dey and Lambert (2005) developed equations to calculate Reynolds stresses and bed shear stress in non-uniform unsteady flows in open channels. They found that their relationship was in good agreement with the experimental data of Song (1994).

Nezu et al. (1997) investigated turbulence structure and velocity distribution in unsteady depth varying open channel flows over a smooth bed. They used Laser Doppler Anemometer (LDA) and a water wave gage simultaneously to get the instantaneous velocity components. Velocity distribution near the wall is given as (Nezu and Rodi 1986):

$$\begin{aligned} \frac{u}{u_*} &= \frac{u_* y}{\nu} && \frac{u_* y}{\nu} \le B \\ \frac{u}{u_*} &= \frac{1}{k}\ln\left(\frac{u_* y}{\nu}\right) + A && B < \frac{u_* y}{\nu} < 0.2Re_* \end{aligned} \tag{16}$$

where κ, A and B are known as von Karman constant, integral constant and damping constant. In addition, Re_* is Reynolds number based on friction velocity (u_*), flow

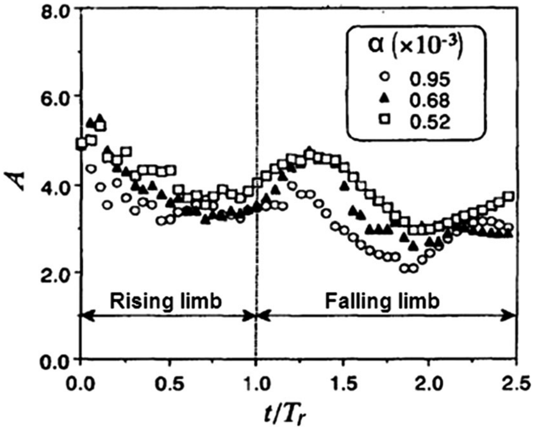

Fig. 6 Integration constant *A* in the velocity distribution log law against normalized time (Nezu et al. 1997)

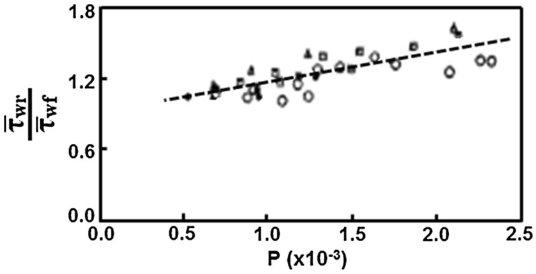

Fig. 7 Ratio of bed shear stress in rising stage to that in the falling stage against unsteadiness parameter (Nezu et al. 1997)

depth (y) and water kinematic viscosity (ν). Studies in steady flow condition showed that the parameter κ is equal to 0.41 independent of the mean flow properties. In addition, based on Nezu and Rodi (1986) study, the value of $A = 5.3$ and $B = 26$ can be used for steady smooth open channel. Nezu et al. (1997) found that similar to steady flow condition in unsteady flow condition, the von Karman constant is equal to 0.41. However, this finding was later modified by Onitsuka and Nezu (1999) who showed that von Karman constant changes with a complex pattern against the time during passage of a hydrograph for larger unsteady parameter. As is shown in Fig. 5, they found that the value of κ increases suddenly near the initial time and decreases before the time to peak. After this stage, κ increases with time and decreases before the end of hydrograph. In addition, the deviation of von Karman constant κ from the steady value (=0.41) increases in proportion to the unsteadiness parameter α defined in Eq. (3).

Nezu et al. (1997) also found that parameter A in Eq. (16) varies with time during the passage of the hydrograph. As shown in Fig. 6, the value of this parameter at the beginning of the hydrograph is nearly equal to 5.3 similar to steady flow conditions. However, it decreased in rising limb and then increased in falling limb. In addition, this parameter is also dependent on the hydrograph unsteadiness parameter α (Eq. 3) and increases by decreasing the flow unsteadiness. This conclusion reveals the difference in flow field between unsteady and steady flow conditions. This study also showed that the turbulence is stronger in the rising limb than in the falling limb of a hydrograph. By calculating wall shear stress $\tau_w = \rho u_*^2$, Nezu et al. (1997) presented Fig. 7 as the variation of time averaged bed shear stress in the rising limb to the falling limb $\bar{\tau}_{wr}/\bar{\tau}_{wf}$ ratio, during the passage of a hydrograph. As is shown in this figure, the ratio is more than one and increases with the unsteadiness parameter (Eq. 3). This reveals that sediment transport rate may be higher in the rising limb compared with the falling limb.

Bed load sediment transport in an unsteady open channel flow

The phenomenon of the sediment transport in steady, uniform flow conditions is studied intensively, and many equations are available for prediction of sediment transport rate in steady flow condition (Graf 1984). The problem is more complicated when flow unsteadiness is taken into account, though such conditions occur more frequently in natural rivers.

Nearly, all of the studies in the literature were focused on comparison of a hydrograph effect with equivalent steady flow (that is modeling of a hydrograph by succession of steps as is mentioned in Introduction). Generally speaking, methods which are based on sediment transport equations developed in steady flow conditions underestimate the sediment rates transported at unsteady flows (Graf and Suszka 1985). Scott (2006) reported related researches about sediment transport in desert ephemeral channels during flash floods. These floods are characterized by a steep rise and a rapid recession, and their flow is extremely unsteady and non-uniform (Nouh 1988b, c).

Nouh (1988a) carried out field measurements over 37 ephemeral straight channels in Saudi Arabia. The methods presented by Diplas (1987), Samaga et al. (1986a), and Proffitt and Sutherland (1983) were considered to calculate bed load transport rates in these channels. All of these methods were developed for steady flow condition. He found that in an unsteady flow condition, none of these methods were satisfactory in estimating bed load transport based on equivalent steady flow for the investigated channels. To improve the applicability of Diplas (1987) and Samaga et al. (1986a) methods in ephemeral channels, he modified these methods for the rising and the falling limbs of hydrographs based on unsteadiness parameter presented in Eq. (2).

Reid et al. (1980, 1985, 1995, 1998) and Laronne and Reid (1993) and Powell et al. (2001) installed and developed the Birkbeck automatic bed load samplers on channels in the northern Negev desert to determine the bed load carried by flash floods in ephemeral gravel-bed streams. They found that at a certain period during the passage of the flood wave, the maximum sediment transport may occur earlier or later than the peak of the water depth. They also found that isolated flood events require a loosening of the bed material as discharge increases before transport rates are significant. Therefore, they concluded that the bed load occurs predominantly on the falling limb.

Reid et al. (1996) rated different predictive bed load sediment transport equations developed for steady condition using the hydrograph peak flow as the steady discharge against a unique set of field data collected by automatic slot samplers during flash floods. Their analysis showed that the bed load fluxes measured in desert flash floods are close to the value predicted by using the Meyer-Peter and Muller (1948) and Parker (1990) equations, but are considerably under-predicted by the Bagnold (1980) and Parker et al. (1982) equations.

Reid et al. (1998) investigated the bed load movement in a coarse grained ephemeral stream. In this river, the passage of the initial flood bore was surprisingly slow, but the rising limb of the flood hydrograph was rapid with a median time of rise of 10 min. They reported that the calculated channel average bed load transport rates during flash floods were as high as 6.7 kg $\text{min}^{-1}\,\text{s}^{-1}$, while locally the highest recorded rate was 12.6 kg $\text{min}^{-1}\,\text{s}^{-1}$. These values are considerably higher than the maximum measured sediment transport at similar condition in many perennial channels. They also reported that in the condition of their study, the relationship between channel average bed load transport rate and channel average shear stress can be represented well by a simple power law function of excess shear stress as:

$$q_s^* = 4.21(\tau^* - 0.03)^{1.37} \tag{17}$$

where q_s^* is dimensionless bed load discharge defined as $q_s^* = (q_s/\rho_s)\left[g \cdot d_{50}^3(\rho_s - \rho)/\rho\right]^{-0.5}$ where q_s is average bed load transport rate and τ^* in Eq. (17) is the dimensionless average bed shear stress during passage of the hydrograph flow defined as $\tau^* = \tau_w/g \cdot d_{50} \cdot (\rho_s - \rho)$ where ρ_s is bed sediment density.

Based on data analysis and Eq. (17), Reid et al. (1998) concluded that the critical dimensionless shear stress (τ_c^*) for gravel-bed sediment in the studied desert rivers is 0.03, a value which is also used to describe incipient motion in steady state gravel-bed streams (Parker 1979; Andrews 1994). However, this value in sand bed rivers is calculated as 0.047 (Mayer-Peter and Muller 1948) or 0.056 (Shields 1936).

Besides all these field studies, many experimental investigations were carried out on bed load transport under unsteady flow condition. Qu (2003) investigated unsteady open channel flows over a fixed and a movable bed both experimentally and theoretically. They observed time lags among hydraulic parameters in unsteady flow similar to Tu (1991). For mobile bed, they also observed time lags between the shear velocity, u_* and the bed load transport, Q_s and that the flow unsteadiness affects this time lag. For relative small unsteadiness (parameter P), Q_s attains its maximum value preceding U, Q and u_*. However, for large unsteadiness, Q_s always attains its maximum after the parameters u_*, U and Q. This may imply that the bed load transport responses slowly to the flow condition for flows with large unsteadiness (Tsujimoto et al. 1990).

Griffiths and Sutherland (1977) studied bed load transport by translation waves experimentally. They found that no significant difference exists between the measured bed load transport rate in unsteady and equivalent steady condition. They also reported that the maximum size of sand dunes occurred after the flow peak discharge in a time lag equal to 5–10 % of the hydrograph duration. However, Suszka (1988) made a different conclusion from his studies. He studied the effect of the unsteadiness of flow on the sediment transport rate of mountainous streams. The characteristics of these rivers are large bed slopes with gravel bed which causes large relative roughness. For this case, he introduced two unsteady parameters (Eqs. 2 and 4) which affect the sediment transport process. He indicated that the hydrograph durations in the experiments by Griffiths and Sutherland (1977) were too long and therefore, the results they obtained could not well reflect flood unsteadiness effects. He also found that the sediment volume transported by a hydrograph is always larger than the calculated volume derived from equivalent steady flow. Further studies showed that the difference between these two conditions depends on the unsteadiness parameter presented in Eq. (2). The larger the unsteadiness parameter, the bigger is the difference (Graf and Suszka 1985; 1987; Suszka and Graf 1987). Suszka (1988) proposed an empirical relationship to calculate the difference of sediment transport volume during the passage of a hydrograph (V_{uns}) and that calculated for equivalent steady flow (V_s) as

$$\frac{V_{\text{uns}} - V_s}{V_s} = -0.2878 + 39.173\,P + 193.454\,\eta \tag{18}$$

where P and η are unsteady parameter of hydrograph presented in Eqs. (2) and (4), and S_0 is channel bed slope. The parameter V_s in the above relationship can be calculated by an equation that Suszka (1988) developed based on his steady state experimental results. Similar results were obtained by other investigators from separate experimental results. Interestingly, Yen and Lee (1995) found similar results in a channel bend having a central angle of 180°. They found that the scour depth, deposition height, transverse sorting and total sediment discharge all increase with increasing unsteady parameter value (Eq. 2).

Furthermore, Lee et al. (2004) conducted a series of flume experiments, using different inflow triangular hydrographs to investigate the sediment transport process under unsteady flow conditions. These investigators also believed that unsteady parameters presented in Eqs. (2), (8) and (9) influence sediment transport rate. They found that by increasing flow unsteadiness parameter (Eq. 2), the total bed load yield increased, though the value of the flow work parameter (Eq. 8) was the same. By regression analysis, they determined the following relationship between the total bed load yield (W_{un}) and the unsteady parameter P (Eq. 2):

$$W_{\mathrm{un}} = 393.99 \times P^{0.4189} \tag{19}$$

With hydrograph duration of 1,260–4,800 (s), Lee et al. (2004) concluded that the ratio of the total bed load yield in an unsteady flow and the predicted bed load yield for equivalent steady flow condition is approximately 1.6. Since, the movable bed does not have time to adjust to the fast change of the flow; therefore, a lag time exists between the occurrence of peak discharge and that of the peak sediment transport rate (Plate 1994). Lee et al. (2004) observed that the lag time between maximum measured sediment and the hydrograph peak discharge is about 6 % up to 15 %.

In addition, Lee et al. (2004) expressed that because of the inertia of the movable sand bed, an adjustment time is required to build up the flow corresponding bed load transport rate in the rising period. On the other hand, an adjustment time is also needed to adjust the corresponding bed form in the falling period. Consequently, bed load transport rate is lower during the rising period and higher during the falling period of the hydrograph. Lee et al. (2004) also found that the bed load yield during hydrograph rising limb is smaller than falling limb with its ratio ranging approximately between 0.5 and 0.75. Therefore, they found a significant anticlockwise hysteresis in the bed load transport rates. In general, the existence of hysteresis means that the sediment discharge under unsteady flow conditions cannot be approximated by quasi-steady conditions (equivalent steady flow).

Similar results were obtained by Esmaili et al. (2008) and Kashefipour et al. (2009) in investigating bed load transport during flash floods. They conducted experiments with different triangular hydrographs with time to peak 40–80 s. Result of this work showed that the ratio of W_{un} for unsteady condition to the corresponding value for equivalent steady flow condition is 1.41.

However, Bombar et al. (2011) studied bed load sediment transport under triangular and trapezoidal hydrograph with duration of 67–990 (s). In contrast to previous studies, these investigators found that the total bed load yields have reverse relationship with unsteady parameter presented in Eq. (2). Therefore, they introduced a new unsteady parameter (Eq. 10) and presented the following relationship for W_{uns} in unsteady flows:

$$W^*_{\mathrm{uns}} = \frac{W_{\mathrm{uns}}}{\rho \cdot B \cdot d_{50}^2} = 2.29\,\mathrm{Exp}\left(855.3\,P_{\mathrm{gt}}\right) \tag{20}$$

where W^*_{un} is dimensionless bed load yield, and B is channel width.

Salamatian et al. (2014) implemented another experimental study for determining sediment transport under steady and unsteady flow condition. With hydrograph duration between 600 and 3,200 s, they found that, the most discrepancy between measured sediment transport and calculated by equivalent steady flow is 10 % which may be due to the effect of hydrograph unsteadiness.

Finally, Hassan et al. (2006) investigated armoring in gravel-bed rivers. The degree of armoring can be characterized in terms of an armor ratio defined as the ratio of the surface to the substrate median size. Based on a set of field data collected in this study, they concluded that an average value of armor ratio for desert ephemeral and snow melt-fed gravel-bed streams is 1.2 and 3.4, respectively. They clarified that the reason for this difference is sought in terms of hydrological characteristics and sediment supply regimes. They ran experiments with both symmetrical and asymmetrical hydrographs to study the effect of hydrograph characteristics on the degree of stream armoring. Similar to field data, they observed that the degree of armoring tended to become more pronounced with longer duration hydrograph.

Study on effect of unsteadiness on stream bed forms is rare. Wang et al. (1994) investigated the bed deformation with uniform and non-uniform sediment in unsteady flows. They found that the bed load lags behind the variation of the flow rate because of the bed's inertia. In addition with non-uniform sediment, the bed deforms to a smaller extent in unsteady flow and the inertia of the bed is enhanced because of the development of armoring layers.

Suspended load in an unsteady open channel flow

Since the suspended load is transported in the water column at approximately the flow velocity, the quantity of sediment transported as suspended load is usually much greater than of the bed load. Similar to bed load, the suspended sediment transport under steady flow condition is studied extensively. However, even in contrast to bed load sediment transport, studies on suspended load transport under unsteady flow condition are more limited.

Field measurements during large floods show that the concentration of suspended load in the body of water may be so high that the flow characteristics may change. Alexandrov et al. (2003) presented suspended sediment concentration as a function of flash flood discharge for northern Negev Desert River. The data were collected using a preprogrammed pump sampler. Mean suspended sediment concentrations of 34,000 mg/L were measured, with maximum concentration of 229,000 mg/L. Such high concentrations effectively increase the density of the fluid, thus increasing the force of the flows on the river bed. The recession of flood flows will result in deposition of suspended sediments, thus raising the channel bed and increasing the probability of future overbank flood flows (Scott 2006).

Nouh (1988b) investigated suspended sediment discharges in ephemeral channels of Saudi Arabia. He proposed that the empirical equations presented by Holtroff (1983) and Samaga et al. (1986b) for steady flow condition are not accurate in predicting suspended sediment transport rates during flash flood events in a way that the calculated sediment rates are always less than the measured rates. He observed that the accuracy of steady equations decreased as the unsteady parameter of the hydrograph (Eq. 2) increased. In addition, he stated that the accuracy of steady equations is less during the rising limbs of hydrographs than during the falling limbs of the hydrographs. In order to improve the accuracy of Samaga et al. (1986b) relationship for unsteady condition, he modified it based on unsteadiness parameter P (Eq. 2).

Studies show that the rate of suspended sediment transport in the rising limb of a hydrograph differs from falling limb for the same flow rate. Sediment rating curve provides a relationship between the water discharge and the sediment concentration. Similar to flow depth, this curve forms a hysteresis loop for sediment transport during passage of a hydrograph (Syvitski et al. 2000). The difference behavior of the sediment rate in the rising limb and the falling limb questions the use of a traditional sediment transport formula, where discharge and sediment concentration are related in a unique relation. Williams (1989) systematically explored the possible sediment rating curve relationships and concluded that there are five common classes of hysteresis loops which are single valued, clockwise, counterclockwise, single-valued plus a loop and eight-shaped. He clarified that the clockwise hysteresis is the most common class of hysteresis and is characterized by a high sediment transport rate before the peak of water discharge and a smaller sediment transport rate after the water discharge peak. Klein (1984) pointed out the importance of the location of sediment sources which may cause a counterclockwise hysteresis between suspended transport rate and discharge. In addition, Lenzi and Marchi (2000) analyzed suspended load during floods in a small stream in northeastern Italy. Both clockwise and counterclock wise hysteresis loops were observed in different floods. They concluded that the common clockwise hysteresis occurred when sediment source contributing area was channel itself. On the other hand, when sediment source forms the basin's slopes, a counterclockwise hysteresis occurred. Different investigators had different idea about hysteresis trend in suspended sediment transport. The development of bed forms such as dunes in sand bed rivers and armor layers in gravel-bed rivers are known as a prominent reason in this sediment transport hysteresis (Allen and Collinson 1974; Ten Brinke et al. 1999; Beschta 1987; Reid et al. 1985; Kuhnle 1992). In addition, based on results of Song (1994) and Nezu et al. (1997), the turbulence intensity in rising limb of the hydrograph is larger than falling limb, and therefore one can conclude that this may cause the hysteresis curve.

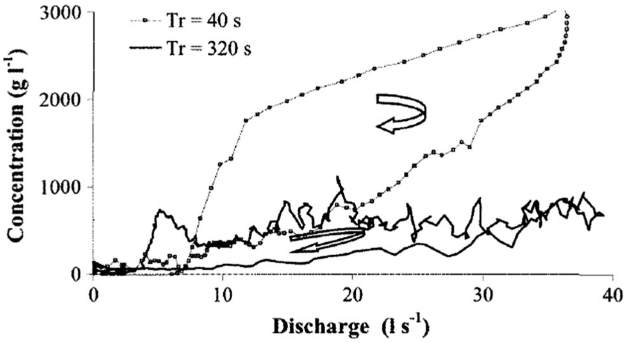

Fig. 8 Hysteresis loop of suspended load transport for two hydrographs (De Sutter et al. 2001)

De Sutter et al. (2001) investigated suspended load transport of river sediment in unsteady flows. Triangular and trapezoidal hydrograph shapes with time to peak range of 40–320 s in the laboratory and 1 h in the field experiments were tested in their study, and the concentration of suspended load was recorded by turbidity sensors continuously. Figure 8 shows the evolution of suspended load transport rate during a hydrograph with $T_r = 40–320$ s and similar peak discharge as a function of flow discharge. Clockwise hysteresis is induced by each hydrograph. As can be concluded from this figure, the rate of sediment transport is higher in the rising limb of a hydrograph than in the falling limb for the same flow rate. In addition, as the unsteadiness of the flow decreases, the hysteresis loop closes. Furthermore, a hydrograph with a higher unsteadiness (shorter duration time with similar peak discharge) has a larger sediment transport rate.

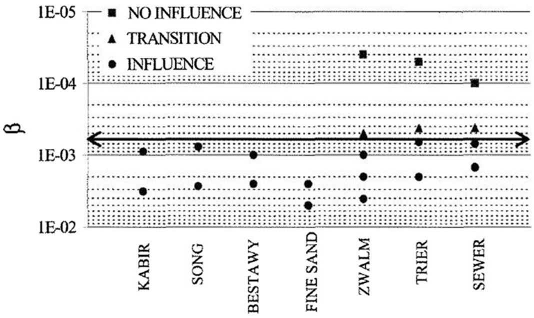

Fig. 9 Influence of unsteady flow on sediment transport by means of unsteady parameter β (De Sutter et al. 2001)

Based on the data of previous studies and their work, De Sutter et al. (2001) used parameter β (Eq. 7) to determine the flow condition at which the flow should be considered as unsteady regarding its effect on the behavior of the sediment transport. They presented Fig. 9 which illustrates that the influence of the transient flow regime on the rate of sediment transport behavior is significant for $\beta > 0.0006$, whereas it proves to be negligible for $\beta < 0.0002$.

Ahanger et al. (2008) studied the suspended sediment concentration and hysteresis in unsteady flow and presented sediment rating curve in unsteady flow condition. In contrast to other studies, during their unsteady flow experiments, sediment load of the same size as the bed material was fed at the flume inlet. They reported that the rate of sediment feed was kept equal to the sediment transport rate for an equivalent steady flow. In all the hydrographs, a prominent clockwise hysteresis in the suspended sediment discharge for different values of water discharges was observed similar to De Sutter et al. (2001).

By dimensional analysis and experimental data, Ahanger et al. (2008) presented following equations for predicting sediment discharge with time in rising and falling limbs of a hydrograph:

For rising limb,

$$\frac{q_{\mathrm{susun}}}{\rho_{\mathrm{s}} \cdot g \cdot d_{50}^{3/2} \cdot \sqrt{S_{\mathrm{s}} - 1}} = 5.315 \times 10^{-6} \times \left[\frac{y}{d_{50}}\right]^{2.465} \times \left[\frac{S_{\mathrm{e}}}{S_{\mathrm{s}} - 1}\right]^{0.343} \times \left[\frac{U}{\Delta y / \Delta t}\right]^{0.192} \tag{21}$$

For falling limb,

$$\frac{q_{\mathrm{susun}}}{\rho_{\mathrm{s}} \cdot g \cdot d_{50}^{3/2} \cdot \sqrt{S_{\mathrm{s}} - 1}} = 8.51 \times 10^{-12} \times \left[\frac{y}{d_{50}}\right]^{4.13} \times \left[\frac{S_{\mathrm{e}}}{S_{\mathrm{s}} - 1}\right]^{0.227} \times \left[\frac{U}{\Delta y / \Delta t}\right]^{0.416} \tag{22}$$

where q_{susun} is suspended sediment discharge per unit width, S_{e} is energy slope and $\Delta y / \Delta t$ is rate of change of flow depth.

Future research

There are several avenues for future research for calculation of sediment transport under unsteady flow condition.

The first research topic concerns the shape of hydrograph. Most of the studies used triangular hydrograph shapes; however, different hydrograph shapes such as trapezoidal or multi-peaks may occur in the nature which needs further study.

The second research work is to study the formation and characteristics of different bed forms during hydrograph event. Especially, the effect of hydrograph on movement of large bed forms such as dunes needs further attention. Measurements of different turbulence characteristics over the deformed bed can also be made, and the effect of turbulence and various unsteady parameters can also be investigated. In addition, more measurements are needed for bed load and suspended load as well as pollutants dispersion during hydrographs of various shapes with different sediment load feed from upstream and with different sediment size to be able to present a general sediment transport equation.

Previous studies in arid regions showed that hydrographs with large flow unsteadiness may occur in ephemeral channels. These hydrographs may change extensively the river bed and banks and affect the stability of in-stream or overbank structures. However, limited study is available in sediment transport in arid regions. Since vast arid and semi-arid areas exist in Iran, more studies on sediment transport and on the nature of such rivers are recommended.

Conclusion

Different studies showed that the flow characteristics including velocity distribution and shear stress during passage of a hydrograph differ from steady flow condition where this could affect sediment transport and thereby dispersion of pollutants and river ecology. Based on this idea, various unsteadiness parameters are defined which express the characteristics of a hydrograph. Measurements of velocity components during passage of a hydrograph show that the ratio of time averaged bed shear stress in the rising limb to the falling limb is more than unity and increases with the unsteadiness parameter. This reveals that sediment transport rate and pollutant concentrations may be higher in the rising limb compared with the falling limb. In addition, reports demonstrate anticlockwise hysteresis curve relationship between flow discharge and depth during passage of a hydrograph which becomes more evident as the unsteady parameter increases.

Many studies were carried out to estimate suspended and bed load sediment transport during hydrograph events.

These studies showed that modeling a hydrograph by steps of steady condition and using equations developed for steady flow conditions often underestimate the sediment rates transported in an unsteady flow condition. The larger the unsteadiness parameter, the bigger is the difference. Researchers also observed a hysteresis loop in the bed load and suspended transport rates during passage of the hydrograph. Therefore, sediment transport discharge differs from each other in the rising and falling limb of a hydrograph. In addition, the existence of hysteresis means that, in general, the sediment discharge under unsteady flow conditions cannot be approximated by equivalent stepwise steady flow. An important study on bed load sediment transport showed that this hysteresis curve is anticlockwise which means that the bed load yield during hydrograph rising limb is smaller than falling limb with its ratio ranging approximately between 0.5 and 0.75. However, for suspended sediment transport, researchers observed clockwise hysteresis curve, which means that the suspended load yield as well as pollution concentration during hydrograph rising limb is larger than falling limb. In addition, as the unsteadiness of the flow decreases, the hysteresis loop closes. It should be noted that with regards to environmental consideration, concentration of suspended particles could significantly affect bed-water exchange and the benthic and aquatic ecosystems.

Experimental studies for bed load sediment transport showed that the ratio of the total bed load yield in an unsteady flow and the predicted bed load yield for equivalent stepwise steady flow condition is approximately between 1.41 and 1.6. There is also a time lag for about 6 % up to 15 % of the hydrograph duration between maximum measured sediment and the hydrograph peak discharge.

Finally, with considering different findings from previous studies, several avenues for future research on calculation of sediment transport under unsteady flow condition were presented in the paper.

Abbreviations

λ	An unsteady parameter
P	An unsteady parameter
A	An unsteady parameter
η	An unsteady parameter
χ	An unsteady parameter
β	An unsteady parameter
γ	An unsteady parameter
W_{k}	Index of the total flow work done on the movable bed (an unsteady parameter)
Fr_{u}	A form of Froude number (an unsteady parameter)
P_{gt}	An unsteady parameter
y_{p}	Flow depth at the peak of a hydrograph
y_{b}	Flow depth of the base flow of a hydrograph
U_{p}	Flow velocity for peak flow of a hydrograph
U_{b}	Flow velocity for base flow of a hydrograph
Q_{p}	Flow discharge for peak flow of a hydrograph
Q_{b}	Flow discharge for base flow of a hydrograph
Δy	Difference of flow depth between the hydrograph peak flow and the base flow
y	Flow depth
U	Average flow velocity
u	Flow velocity
t	Time
x	Space variable
C	Wave celerity
μ	Water dynamic viscosity
ν	Water kinematic viscosity
ρ	Water density
ρ_{s}	Sediment density
g	Gravitational acceleration
T_{d}	Duration of the hydrograph
T_{r}	Duration of rising limb of a hydrograph
T_{f}	Duration of falling limb of a hydrograph
S_0	Channel bed slope
θ	Channel bed slope angle
$u_{*\mathrm{b}}$	Bed shear velocity associated with the steady base flow before hydrograph passages
$u_{*\mathrm{p}}$	Maximum shear velocity during passage of the hydrograph
$u_{*\mathrm{cr}}$	Critical shear velocity for sediment particle motion
$u_{*\mathrm{un}}$	Shear velocity in unsteady flows
$u_{*\mathrm{s}}$	Shear velocity in steady flows
τ_{w}	Wall shear stress
$\bar{\tau}_{\mathrm{wr}}$	Time averaged bed shear stress in the rising limb of a hydrograph
$\bar{\tau}_{\mathrm{wf}}$	Time averaged bed shear stress in the falling limb of a hydrograph
d_{50}	Median diameter of sediment size
q_{s}^{*}	Dimensionless bed load discharge
q_{s}	Average bed load transport rate
Q_{s}	Bed load sediment transport
W_{uns}	Total bed load yield during passage of the hydrograph
W_{un}^{*}	Dimensionless bed load yield during passage of the hydrograph
q_{susun}	Suspended sediment discharge per unit width
S_{e}	Energy slope
τ^{*}	Dimensionless average bed shear stress during passage of the hydrograph

τ_c^*	Critical dimensionless shear stress
V_{ol}	Total volume of water under the hydrograph excluding the base flow
V_{uns}	Sediment transport volume during the passage of a hydrograph
V_s	Calculated sediment transport volume for equivalent steady flow
B	Channel width
Fr	Froude number
κ	Von Karman constant
A	Integral constant
B	Damping constant
Re_*	Reynolds number based on friction velocity

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