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Hysteresis analysis to quantify and qualify the sediment dynamics: state of the art

Simone Malutta, Masato Kobiyama, Pedro Luiz Borges Chaffe and Nadia Bernardi Bonumá

ABSTRACT

This work is a review of the use of hysteresis to quantify sediment discharge dynamics. We reviewed 71 journal articles from the year 1953 to the present day focusing on two topics: the factors that influence hysteresis; and hysteresis quantification. The main factors influencing hysteresis are: (a) magnitude and sequence of events; (b) sediment particle size distribution; (c) basin size; and (d) land use and sediment source. Hysteresis quantification can be done using several different methods that can be grouped as: (a) hysteresis indexes; (b) statistical analysis; and (c) uncertainty analysis. Most studies were conducted in Western Europe and the USA. The studies, in general, show how the factors listed above influence the shape and patterns of hysteresis. However, the sediment dynamics are complex, and the hysteresis patterns may be linked to many other factors, such as slope and drainage systems. The quantification of hysteresis still appears, mainly with the hysteresis index and statistical analysis. Therefore, there are still many other factors that influence hysteresis patterns, as well as hysteresis rates and uncertainty analyses.

Key words | hysteresis, sediment, turbidity

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INTRODUCTION

Erosion and sediment transport processes are key factors controlling water quality in rivers. Moreover, qualifying and quantifying the sediment sources may contribute to the understanding of the processes of connectivity of hillslopes to river channel (Minella & Merten 2011). Hysteresis analysis allows one to explore and evaluate the behavior of sediment transport in relation to discharge in select hydrologic events (Lloyd *et al.* 2016b). The hysteresis occurs because suspended sediment concentration (*SSC*) for a given discharge during the rising limb of the hydrograph is normally different from the falling limb due to the time lag between the discharge curve and the *SSC* curve (Mukundan *et al.* 2013). Therefore, different discharge and sediment transport processes may be identified using its hysteresis patterns (Nadal-Romero *et al.* 2008).

The hysteresis is influenced by the available amount of sediment (Gao & Josefson 2012). The magnitude and sequence of events may influence the availability of the sediment and consequently the shape of hysteresis (Asselman 1999; Hudson 2003; Rovira & Batalla 2006; Salant *et al.* 2008; Marttila & Kløve 2010). For example, if the sedimentation process is dominant the hysteresis is usually clockwise (Gao & Josefson 2012); bed and bank erosion is characterized by a counterclockwise hysteresis (Yeshaneh *et al.* 2014; Pietron et al. 2015), or an upstream section contributes to a downstream section (Asselman 1999; Salant *et al.* 2008; Smith & Dragovich 2009; Aich *et al.* 2014). The sequence of events can cause sediment exhaustion. However, other factors, such as the magnitude of the events and diameter of the particles, need to be analyzed.

The same sediment can be transported in different ways depending on the discharge magnitude (Lenzi & Marchi 2000; Salant *et al.* 2008; Landers & Sturm 2013). The particle size of the sediment will influence the transport mechanism (suspension, bearing, and skipping). In addition, sediment transport depends on the velocity of

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the water. In the headwaters, generally, the slopes are higher; in the middle course of the river, slopes decrease and velocity usually decreases accordingly, which will also lead to the deposition of this sediment, thus influencing the pattern of the hysteresis (Kronvang *et al.* 1997; Jansson 2002; Hudson 2003; Seeger *et al.* 2004; Salant *et al.* 2008; Pietron *et al.* 2015). Hysteresis patterns may also depend on the characteristics and size of the basin (Smith & Dragovich 2009).

The source of sediment can also be evaluated by using hysteresis analysis (Lefrançois *et al.* 2007; Duvert *et al.* 2010; Eaton *et al.* 2010; Minela *et al.* 2011; Hughes *et al.* 2012), such as analyzing more than one gauge station (Asselman 1999; Jansson 2002; Hudson 2003; Aich *et al.* 2014) or fingerprinting sediment (Gonzales-Inca *et al.* 2018) in catchments with different land use. There have been proposed several indexes to quantify the hysteresis patterns (e.g. Langlois *et al.* 2005; Lawler *et al.* 2006; Smith & Dragovich 2009; Aich *et al.* 2014; Lloyd *et al.* 2016a; Zuecco *et al.* 2016). Linear regression (e.g. Zabaleta *et al.* 2007; Nadal-Romero *et al.* 2008; Oeurng *et al.* 2010; Rodríguez-Blanco *et al.* 2010; Ram & Terry 2016) and multivariate statistical analysis (e.g Seeger *et al.* 2004; Zabaleta *et al.* 2007; Nadal-Romero *et al.* 2008; Oeurng *et al.* 2010; Mukundan *et al.* 2013) are commonly used to analyze the main controls on hysteresis patterns. There are still only a few studies that quantify hysteresis uncertainty (Krueger *et al.* 2009; Ziegler *et al.* 2014; Lloyd *et al.* 2016b).

In this review, we present the state of the art about the hysteresis of discharge (Q) and *SSC*. We analyze the four main factors that influence the hysteresis patterns: (I) the magnitude and sequence of events; (II) sediment size; (III) land use and sediment source; and (IV) basin size. We also describe the three main techniques used to analyze the hysteresis: (I) hysteresis indexes; (II) statistical analysis; and (III) uncertainty analysis.

BIBLIOGRAPHICAL REVIEW

We have searched mainly scientific journals written in Portuguese or English. There are a few articles on conferences (IAHS Publications) and older works that are technical reports of the government of the United States which are included due to their relevance. The main studies that contributed to the *SSC*-Q and turbidity-Q hysteresis analysis are listed in Table S1 (supplementary material). The studies are presented in chronological order with the authors' names, basin size, country where the study was developed, year of publication, and main contributions.

In Figure 1 which shows their geographical distribution, hysteresis studies are concentrated in western Europe and the USA. There are also 27 basins studied in Russia. However, these basins were analyzed in one study only (i.e., Tananaev 2013). Table S1 and Figure 1 indicate that the hysteresis study has been carried out more in developed countries. There should be more studies, especially in the Southern Hemisphere, as there is a clear opportunity to learn about hysteresis in different climate and catchment settings.

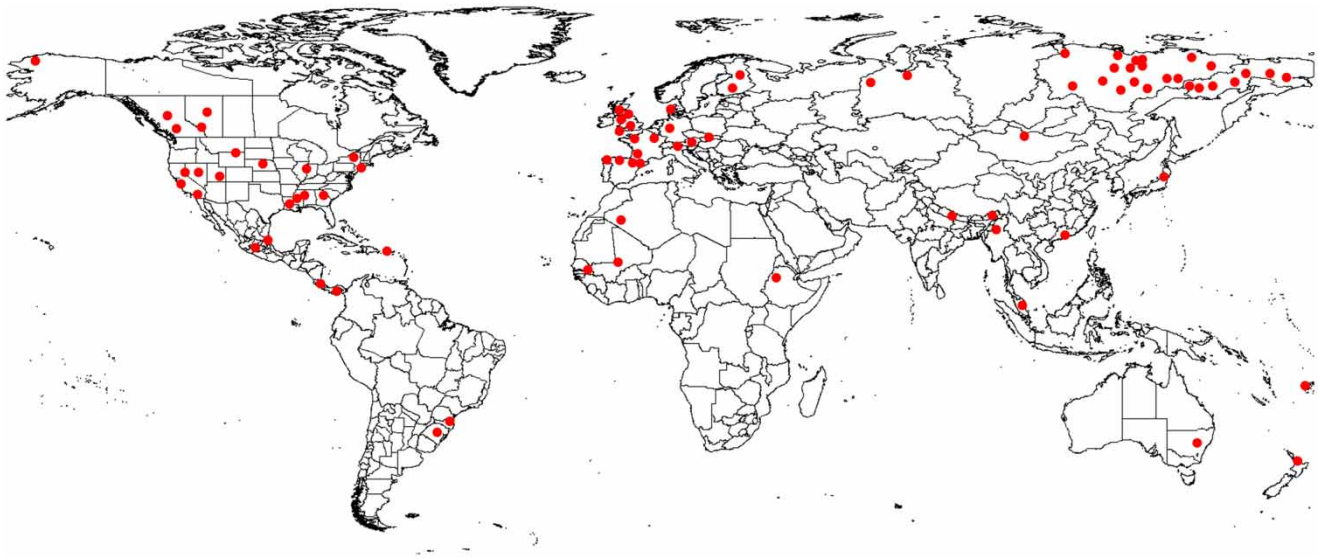

Figure 1 | Geographical distribution of the hysteresis studies in the world (list of studies presented in Table S1 – supplementary material).

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HYSTERESIS PATTERNS

There are many types of hysteresis in the hydrological processes (such as tree cover–precipitation, water level–discharge) and their patterns depend on spatio-temporal scales (Gharari & Razavi 2018). Here, we focus only on the hysteresis between *SSC* and *Q* and between turbidity and *Q*, and the hysteresis concept is associated with the curves or loops that are formed. Leopold & Maddock (1953) were the first to analyze hysteresis between *SSC* and *Q*. During one event, sediment may not be temporally related only with the discharge (Old *et al.* 2003). The non-linearity and the hysteresis loop patterns formed by the relationship between *SSC* and *Q* or between turbidity and *Q* are widely studied and known as hysteresis (Walling & Teed 1971; Wood 1977; Klein 1984).

Williams (1989) classified those into five common patterns: (I) a single line, (II) clockwise, (III) counterclockwise, (IV) single line plus a loop, and (V) figure eight (Figure 2). Hamshaw *et al.* (2018) proposed 14 classes of hysteresis patterns based on a restricted Boltzmann machine (RBM) that allowed for sediment-discharge event dynamics including spatial scale, antecedent conditions, hydrology, and rainfall. Here we expand the list of studies of Gellis (2013) based on the patterns proposed by Williams (1989) (Table 1). When the peak of *SSC* and *Q* occurs at the same time and the rising and the falling limb of the hydrograph and sediment-graph are equal, the relation between these variables becomes linear (Type I in Figure 2). However, when there is a delay in one peak compared with the other (Type II, for example), the relation between these two variables is not linear. The *SSC-Q* relation in the rising limb is larger than in the falling limb for all the values during the event.

There are studies that have proposed *HI*s based on quantification of the curves or loops of the graphs. In general the *HI* is proposed for measuring the hysteresis loop at the different stages of the hydrograph (Lawler *et al.* 2006; Lloyd *et al.* 2016b) or the areas under the curve (Langlois *et al.* 2005).

Single-valued line

The single-valued line occurs when the *SSC-Q* relationship is similar in the rising and falling limbs. This pattern occurs when the travel time of the discharge wave equals the time of sediment transport velocity (Yang & Lee 2018). Mossa (1989) and Hudson (2003) concluded that this type of hysteresis is formed by fine suspension sediment. It is a consequence of transport of sediment without restriction during the event, or remobilization and transport of in-channel followed by a supply from distant sources (Wood 1977; Williams 1989; Jansson 2002; Smith & Dragovich 2009; Duvert *et al.* 2010). However, the single-valued line is not common since sediment availability is exhausted during the event (Oeurng *et al.* 2010; Gao & Josefson 2012).

Clockwise loop

The clockwise loop is the most common one (Klein 1984; Williams 1989; Jansson 2002; Hudson 2003; Rovira & Batalla 2006; Oeurng *et al.* 2010). The *SSC-Q* relation in the rising limb is larger than in the falling limb for all the values during the event. Most studies concluded that the *SSC-Q* relationship is lower in the falling limb because of the exhaustion of sediment available to be transported (Table S1). This hysteresis pattern can also be caused by the increase of the base flow during the falling limb (Walling 1974; Costa 1977; Wood 1977; Bača 2008) or be due to the fact that sediment yield areas are near river channels, and early sediment supply by the tributaries or flow paths from the source is short (de Boer & Campbell 1989; Asselman 1999; Hudson 2003; Hughes *et al.* 2012). The clockwise loop is also linked to the formation of the armoring layer before peak discharge (Williams 1989), bank erosion (Smith & Dragovich 2009), snowmelt runoff events (Gonzales-Inca *et al.* 2018), and wash load (Lenzi & Marchi 2000; Hudson 2003).

Counterclockwise loop

A counterclockwise hysteresis pattern is formed when the peak discharge occurs before the sediment peak. The counterclockwise hysteresis is linked to: (a) flood wave traveling faster than mean flow velocity; (b) sediment wave traveling slower than the discharge wave; (c) distant sediment source, upstream tributaries, and late sediment supply by the tributaries; and (d) bed or bank erosion. Hudson (2003) identified counterclockwise hysteresis in large basins because the sediment wave traveled slower than the discharge wave. Pietron *et al.* (2015) observed that the counterclockwise hysteresis is only formed by the sediments yielded with channel erosion, not with hillslope erosion. Complementing this hypothesis, Yeshaneh *et al.* (2014) found counterclockwise hysteresis during periods when the basin was protected with vegetation and suggested that the sediment results from the erosion of the channels' bed and banks.

Single line plus a loop

The single line plus a loop indicates that the sediment travel time is different from the flow travel time (Yang & Lee 2018).

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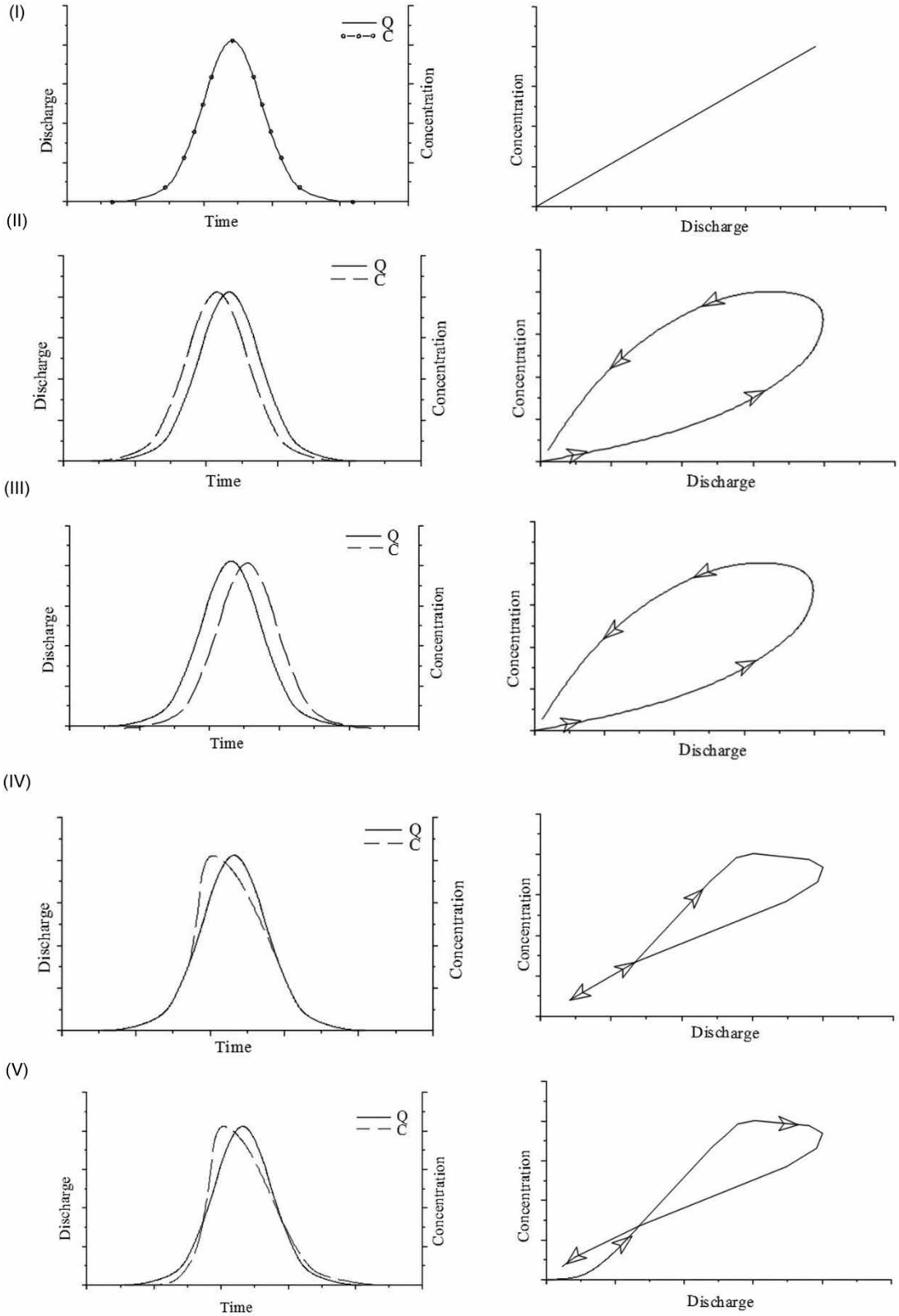

Figure 2 | Five hysteresis patterns of sediment-discharge (after Yang & Lee (2018)).

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Table 1 | Studies for each type of hysteresis pattern

Patterns	Cause of hysteresis	References
I. Single-valued line	Discharge travel time equals the sediment travel time	Yang & Lee (2018)
	Abundance of fine-grained sediments in the channel	Mossa (1989); Hudson (2003)
	Low availability of fine sediment	Walling & Webb (1982)
	Uninterrupted supply of sediment/remobilization and transport of in-channel followed by a supply from distant sources	Wood (1977); Williams (1989); Jansson (2002); Smith & Dragovich (2009); Duvert *et al.* (2010)
II. Clockwise loop or positive hysteresis	Mobilization followed by depletion of in-channel/nearby sediment sources/exhaustion effects after an initial flush of sediment	Walling (1974); Wood (1977); Costa (1977); Sidle & Campbell (1985); Kattan *et al.* (1987); Bull *et al.* (1995); Kronvang *et al.* (1997); Wang *et al.* (1998); Asselman (1999); Picouet *et al.* (2001); Lenzi & Marchi (2000); Jansson (2002); Seeger *et al.* (2004); Salant *et al.* (2008); Marttila & Kløve (2010); Smith & Dragovich (2009); Oeurng *et al.* (2010); Gao & Josefson (2012); Mukundan *et al.* (2013); Tananaev (2013); Aich *et al.* (2014)
	Formation of armored layer before peak discharge	Williams (1989)
	Bank erosion	Smith & Dragovich (2009)
	Increased base flow after peak discharge leading to dilution of sediment concentration	Walling (1974); Costa (1977); Wood (1977); Bača (2008)
	Snowmelt runoff events	Gonzales-Inca *et al.* (2018)
	Individual floods	Asselman (1999)
	Wash load (silt/clay)	Lenzi & Marchi (2000); Hudson (2003)
	Areas of the sediment yield are short/near-channel source/early sediment supply by the tributaries or flowpaths temporal and spatial differences between SS production and water discharge generation in small basin	de Boer & Campbell (1989); Asselman (1999); Hudson (2003); Hughes *et al.* (2012)
		Sammori *et al.* (2004)
III. Counterclockwise loop or negative hysteresis	Floodwave traveling faster than mean flow velocity/sediment wave travels slower than the discharge wave	Heidel (1956); Marcus (1989); Williams (1989); Brasington & Richards (2000)
	High soil erodibility	Williams (1989)
	Bed and/or bank erosion	Klein (1984); Sarma (1986); Asselman (1999), Brasington & Richards (2000); Goodwin *et al.* (2003); Rinaldi *et al.* (2004); Lenzi & Marchi (2000); Hudson (2003); Fang *et al.* (2008); Marttila & Kløve (2010); Oeurng *et al.* (2010); Mukundan *et al.* (2013); Pietron *et al.* (2015)
	Distant sediment source/upstream tributaries/late sediment supply by the tributaries	Heidel (1956); Klein (1984); Loughran *et al.* (1986), Williams (1989); Asselman (1999); Brasington & Richards (2000); Bača (2008); Oeurng *et al.* (2010); Hughes *et al.* (2012); Gao & Josefson (2012); Mukundan *et al.* (2013); Pietron *et al.* (2015)
	Seasonality, lower concentrations early in the year followed by increasing sediment concentrations	Sidle & Campbell (1985); Wang *et al.* (1998)
	Exhaustion of sediment available due to previous event	Marttila & Kløve (2010); Oeurng *et al.* (2010); Gao & Josefson (2012)
	Valley slopes form the most important sediment source	Klein (1984)
	The distribution of non-uniform sediment yield in the basin	Williams (1989)

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Table 1 | continued

Patterns	Cause of hysteresis	References
	Small events with high rainfall intensity and very dry soil conditions	Eder *et al.* (2010)
	Channel deposition (analyses sub-basin)	Jansson (2002)
	During winter freezing – river cross-sections are often fully closed with ice	Tananaev (2013)
	Influence of the sea tide on hysteresis	Kostaschuk *et al.* (1989)
	Landslide	Peart *et al.* (2005)
	Very high moisture and high antecedent rainfall conditions	Seeger *et al.* (2004)
IV. Single line plus a loop	This indicates if the sediment travel time is distinct from the flow travel time in separate runoff states	Yang & Lee (2018)
	Occurs under extreme dry conditions	Seeger *et al.* (2004)
V. Figure eight	Ice breakup	Williams (1989)
	Delayed contribution of sediment from sub-basins	Bača (2008); Eder *et al.* (2010)
	Influences of drainage system	Eder *et al.* (2010)
	Multiple peaks	Eder *et al.* (2010); Gao & Josefson (2012); Tananaev (2013)
	Sediment contribution from the streambed and its banks	Eder *et al.* (2010); Tananaev (2013)
VI. No hysteresis/random/ stationary	Uninterrupted supply of sediment/sediment was still available/soil surface was not protected sufficiently with vegetation cover	Bača (2008)
	Snowmelt and rain events	Marttila & Kløve (2010)
	Long events; multiple peaks; multitude of factors of sediment delivery	Nadal-Romero *et al.* (2008); Gao & Josefson (2012); Yeshaneh *et al.* (2014)

Seeger *et al.* (2004) evidenced this hysteresis type under extremely dry conditions.

Figure eight

The figure eight pattern can be related to: (i) the sediment deposited on the bed or banks of the channel that goes into resuspension; (ii) the time of sediment travel in upstream sub-basins; (iii) the fact that there may be an upstream storage area in the basin and, after its saturation, the contribution of the discharge and sediment downstream; and (iv) influences of the drainage system (Eder *et al.* 2010). Gao & Josefson (2012) observed this type of hysteresis in events with multiple discharge peaks.

No hysteresis, random or stationary

There might not be any clear relationship between *SSC* and *Q* and, consequently, no typical hysteresis pattern occurs. Bača (2008) observed that there was no clear pattern when sediment remained available throughout the event (no depletion). Hysteresis without clear patterns is associated with long events with many peaks and suggesting the occurrence of several factors that contribute to the production and transport of sediment (Nadal-Romero *et al.* 2008; Gao & Josefson 2012; Yeshaneh *et al.* 2014). Marttila & Kløve (2010) found no hysteresis in rain events with snowmelt contribution.

FACTORS CONTROLLING HYSTERESIS

Magnitude and sequence of events

Discharge magnitude is one of the factors that cause different hysteresis patterns. The low discharge causes erosion and transports the sediment to the channel, whereas the sediment will be transported in following events with higher discharge peaks (Marttila & Kløve 2010). Therefore, the initial conditions of the sediment on the river bank and bed become important in the sediment dynamics. While in the high discharge events the sediment source may be soil erosion from the whole basin, with low discharge the sediment was from the river bed and banks

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(Salant *et al.* 2008). The re-transportation of material already eroded in the channels is triggered by high discharges and generates early sediment peaks (Hudson 2003).

Sediment dynamics of the event have a common characteristic: the limitation of sediment transport in the events (Gao & Josefson 2012). Hudson (2003) suggested that there is a contribution from the sediment source of an area where there has been no exhaustion in recent events. This phenomenon was also observed by Bača (2008), who further suggested the sediment transport in one event depends on how long it takes to occur after the previous one. Erosion and deposition of sediments in the river in previous events may modify sediment dynamics (Salant *et al.* 2008). If sufficient time has passed, the soil will be eroded in a basin and there will be sediment supply again. This limitation also depends on whether the event is a 'supply-rich flood' or an 'exhaustion flood' (Rovira & Batalla 2006, Figure 3(a)). In Figure 3(b) the hydrograph and sediment-graph are schematically designed for the case where there is a sequence of events. The first and third peaks have sediment available for transport and the size of the SSC peak is larger. In the second event, there is no more sediment available and the SSC peak is smaller.

Antecedent dry days (*ADD*, Figure 4) represents the number of days between events and can be used for the analysis of the sequence of events (Mukundan *et al.* 2013). The *ADD* indicates how many days without rain there are before the event, while the antecedent precipitation index (API), which is used in most of the studies, quantifies the rain in the previous days. Even though ADD was not used in the other studies that analyzed sequences of events, it can provide important information to be included when there is a statistical analysis of sequences and sediment exhaustion.

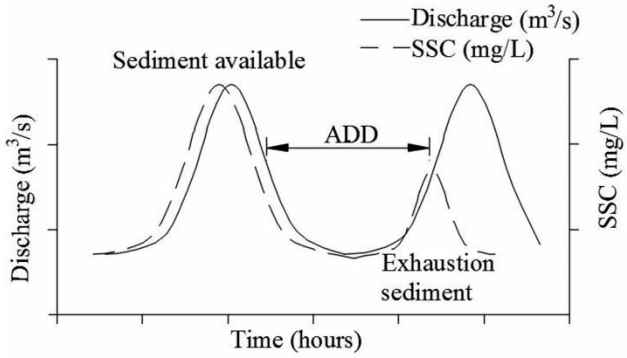

Figure 4 | Determination of antecedent dry days (*ADD*).

Sediment particle size distribution

Hysteresis patterns depend on the particle size distribution of the sediment available in the channel or in the basin. Hudson (2003) found that clockwise hysteresis loops occur due to a higher washload supplied by adjacent hillslopes, while in another basin, sediment transport was dominated by the bed material. As the discharge increases in the rising limb of the hydrograph, the concentration of fine sediment usually lowers in relation to the particle size of suspended sediments in source areas (Lenzi & Marchi 2000). Moreover, sand supply is quickly replenished, whereas the same does not happen in a gravel-dominated sub-basin (Salant *et al.* 2008).

Lenzi & Marchi (2000) analyzed the particle size variations of suspended material at an event. However, the studies showed variations in the relative percentage of sand and silt in transported sediment, possibly the material eroded from hillslopes and channel banks, and affect intra-storm variations in particle size.

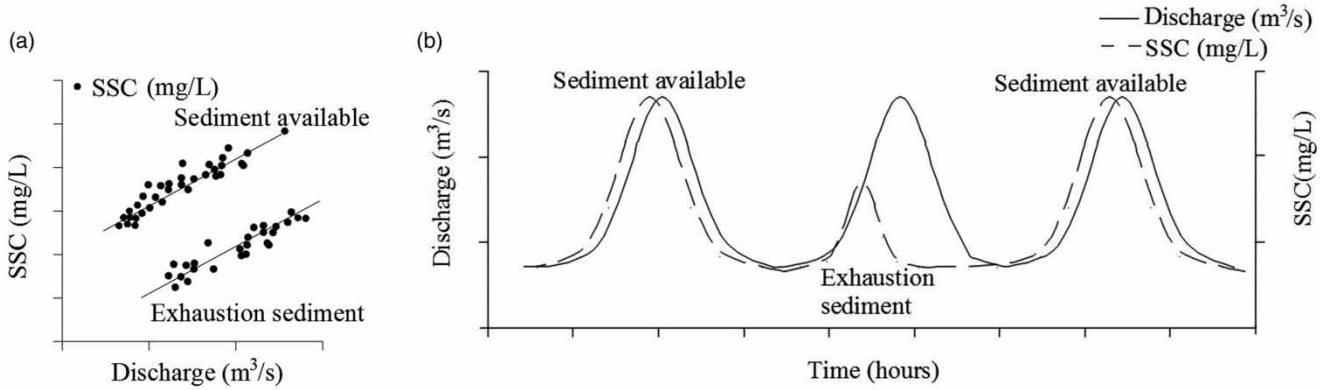

Figure 3 | (a) Relation between suspended sediment concentration (*SSC*) and discharge for 'supply-rich floods' and 'exhaustion floods' (adapted from Rovira & Batalla (2006)). (b) Influence of the sequence of the events on hysteresis.

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The particle size of the transported sediment can influence the response of optical sensors and cause interference in the construction of the turbidity-*SSC* curve (Downing 2006; Sari *et al.* 2015, 2017).

Basin size

The hysteresis patterns depend on the characteristics and size of the basin (Smith & Dragovich 2009). In small basins (less than 10 km^2), the hysteresis loop is linked to factors such as soil moisture, the difference between surface and total runoff, and bank and cannel erosion (Seeger *et al.* 2004; Langlois *et al.* 2005; Lefrançois *et al.* 2007; Sadeghi *et al.* 2008; Smith & Dragovich 2009; Gao & Josefson 2012). There are no papers that establish the criteria of limits among small, medium, and large basins regarding hysteresis. There is only one indication that small basins are less than 10 km^2 and large drainage areas are those bigger than 100 km^2 (Gao & Josefson 2012). Therefore, we assume that small basins are those smaller than 10 km^2, and the medium and large basins are bigger than 10 km^2.

The hysteresis in small basins was mainly found to be controlled by the soil moisture, hydrograph separation, and bank and channel erosion (Gao & Josefson 2012). Seeger *et al.* (2004) also found that soil moisture influences hysteresis in a 2.54 km^2 basin. Zabaleta *et al.* (2007) investigated the hysteresis in two small basins (3 and 4.8 km^2) and found that sediment yield is related to total precipitation, whereas, the *SSC* is related to precipitation intensity.

Hudson (2003) identified a counterclockwise hysteresis at large basins because the sediment wave travels slower than the discharge wave. However, in larger basins it is more difficult to associate the hysteresis pattern with a single factor because there is an increasing influence of the underground and subsurface runoff, soil type, land use, and topography (Gao & Josefson 2012). In a 16 km^2 basin, Rodríguez-Blanco *et al.* (2010) showed that the total precipitation and the baseflow were the most relevant factors for the hydrological response, while a large part of the suspended sediment load was associated with the maximum discharge. Zabaleta *et al.* (2007) identified that in a 48 km^2 basin the sediment production and suspended sediment are linked neither to precipitation intensity nor to the total precipitation. While Duvert *et al.* (2010) did not find any correlation between rainfall intensity and sediment yield in a 630 km^2 basin due to the spatial variability of rainfall, Oeurng *et al.* (2010) found a significant correlation between precipitation and peak discharge, runoff, and sediment variables in a 1,110 km^2 basin. Therefore, in the case of large basins, it is essential to identify which sub-basin contributes to the water and sediment discharge and how each sub-basin influences the hysteresis.

Land use and sediment source

Sediment yield varies according to different land uses (e.g. Duvert *et al.* 2010). Minella *et al.* (2011) evaluated factors that control hysteresis related to soil management (conventional or conservationist). The authors concluded that in the conservation period a reduction of the descending limb of the sedimentogram occurred, reducing the transport and deposit sediment in the channel and generating higher *HI*. In general, the authors pointed out that in the conventional management the *HI* was lower in the events studied – this fact being attributed to the contribution of sediment in the basin.

Table 2 shows the works that analyzed how different land use can influence the pattern of hysteresis. Gellis (2013) analyzed five basins with different land use (Table 2) and found that hysteresis patterns in each basin were associated with land use and the distance of the sediment source

Table 2 | Characteristics of the studied basins

Reference	Basin name	Area (km^2)	Slope (%)	Land use
Duvert *et al.* (2010)	La Cortina	9.3	12	Forest (52%), cropland (46%)
Duvert *et al.* (2010)	Huertitas	3.0	18	Cropland (28%), rangeland (65%), gullied (6%)
Duvert *et al.* (2010)	Potrerillos	12.0	15	Cropland (46%), forest (37%), grassland (23%)
Hughes *et al.* (2012)	Mangaotama	2.68	22.5	Forest (1%), pasture (99%)
Hughes *et al.* (2012)	Mangaotama*	2.68	22.5	Forest (4%), pasture (38%), pine (58%)
Hughes *et al.* (2012)	Whakakai	3.11	23.8	Forest (100%)
Gellis (2013)	Rio Icacos	3.26	22.2	Forest (100%)
Gellis (2013)	Quebrada Blaca	8.42	33.4	Forest (21%), pasture (54%), rural (15%), cropland (8%)
Gellis (2013)	Rio Caguintas	13.7	33.2	Forest (36%), pasture (27%), rural (11%), cropland (23%)
Gellis (2013)	Rio Piedras	19.4	17.6	Urban (77%), forest (43%)

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from the monitoring point and demonstrated that, in the forest basin (Rio Icacos), 80% of events showed clockwise hysteresis. In the basins with mixed land use (Quebrada Blanca, Rio Caguitas, and Rio Piedras) the hysteresis patterns could be both clockwise or counterclockwise. Hughes *et al.* (2012) found that in the Mangaotama basin (both before and after the integrated management), a hysteresis pattern was predominantly clockwise, suggesting that the sediment source is close to the channels. And, in the Whakakai (100% forest) the most common hysteresis pattern was counterclockwise mainly due to soil erosion from the hillslope. In the pine reforestation, the clockwise hysteresis was due to channel erosion. It was also observed that, for the same discharge magnitude, the Mangaotama basin could export up to three times more sediments than the native forest basin.

Lefrançois *et al.* (2007) studied the *SSC*-Q relationship in two basins characterized by agriculture land use. Their conclusion is that the sediment supply is defined by the number of particles that can be mobilized and that it depends on the new and deposited sediment supply. While at low discharge the sediment can be derived from the mobilization of deposited fine sediments, at high discharge it is derived from deposited coarse sediments or bank erosion. By applying the sediment fingerprinting technique with cesium-137 in order to identify suspended sediment origins, Gonzales-Inca *et al.* (2018) found that the rapid sediment mobilization during the snowmelt in a basin generated a clockwise hysteresis loop. The authors considered that cropland and stream banks were the most important sources of suspended sediments.

The hysteresis pattern results not only from the exhaustion of the sediments in the channels but also from the time of the sediment supply of the tributaries (Asselman 1999). Jansson (2002) showed that in the case of counterclockwise hysteresis, there was channel deposition between sub-basins. In another sub-basin, a rapid rising and falling discharge limb, and rapidly increasing and decreasing SSC were obtained with a small loop of hysteresis. These might result from bank erosion.

QUANTIFICATION OF HYSTERESIS

Hysteresis indexes

Visually it is possible to compare the pattern and size of the hysteresis. However, Langlois *et al.* (2005), Lawler *et al.* (2006), Smith & Dragovich (2009); Aich *et al.* (2014), Lloyd *et al.* (2016a), Zuecco *et al.* (2016) and so on suggested some methods to quantify the patterns, lines, curves and angles of the hysteresis (Figure 5).

The Langlois *et al.* (2005) method calculates *HI* by plotting SSC or turbidity data (dependent variable) and discharge data as an independent variable. The curves of the rising and falling limbs are generally estimated with natural logarithms and exponential equations, respectively.

The areas under the curves for the two regression equations were estimated through integration by using the minimum and maximum discharges observed in the event as the lower and higher limits, respectively. Then, the *HI* was proposed by using the ratio of these two areas:

$$HI = \frac{\int_{Q_{min}}^{Q_{max}} SSC_r}{\int_{Q_{min}}^{Q_{max}} SSC_f} \quad (1)$$

where SSC_r and SSC_f are the concentration of suspended sediment in rising and falling limb, respectively; and Q_{max} and Q_{min} are the maximum and minimum discharge in the event, respectively (Figure 5(a)).

Aich *et al.* (2014) and Zuecco *et al.* (2016) suggested the normalization of the discharge and turbidity or *SSC* data to obtain the *HI* value that is not influenced by the absolute amount of the measurements.

The index proposed by Zuecco *et al.* (2016) is basically calculated in the same way as proposed by Langlois *et al.* (2005).

In order to improve the hysteresis analysis in events, Aich *et al.* (2014) proposed to measure the maximum distance of the rising limb (*Drise*) and the falling limb (*Dfall*), and hysteresis index (HI_A) which is defined as the sum of *Drise* and *Dfall* (Figure 5(d)). The normalization of data allows comparison of events and the information on behavior during increase (*Drise*) and the decrease in discharge (*Dfall*). In this way, the hydrograph limb can be analyzed separately, improving the interpretation of hysteresis patterns.

The Lawler *et al.* (2006) method proposed that the *HI* should be measured at the midpoint of the discharge (Q_{mid}) in both the rise and fall of hysteresis (Figure 5(b)). Equation (2) determines the midpoint discharge, at which turbidity values are to be compared:

$$HI = 0.5(Q_{max} - Q_{min}) + Q_{mid} \quad (2)$$

The TU_{RL} is the turbidity value at Q_{mid} on the rising limb and TU_{FL} is the turbidity value at Q_{mid} on the falling limb of the hydrograph.

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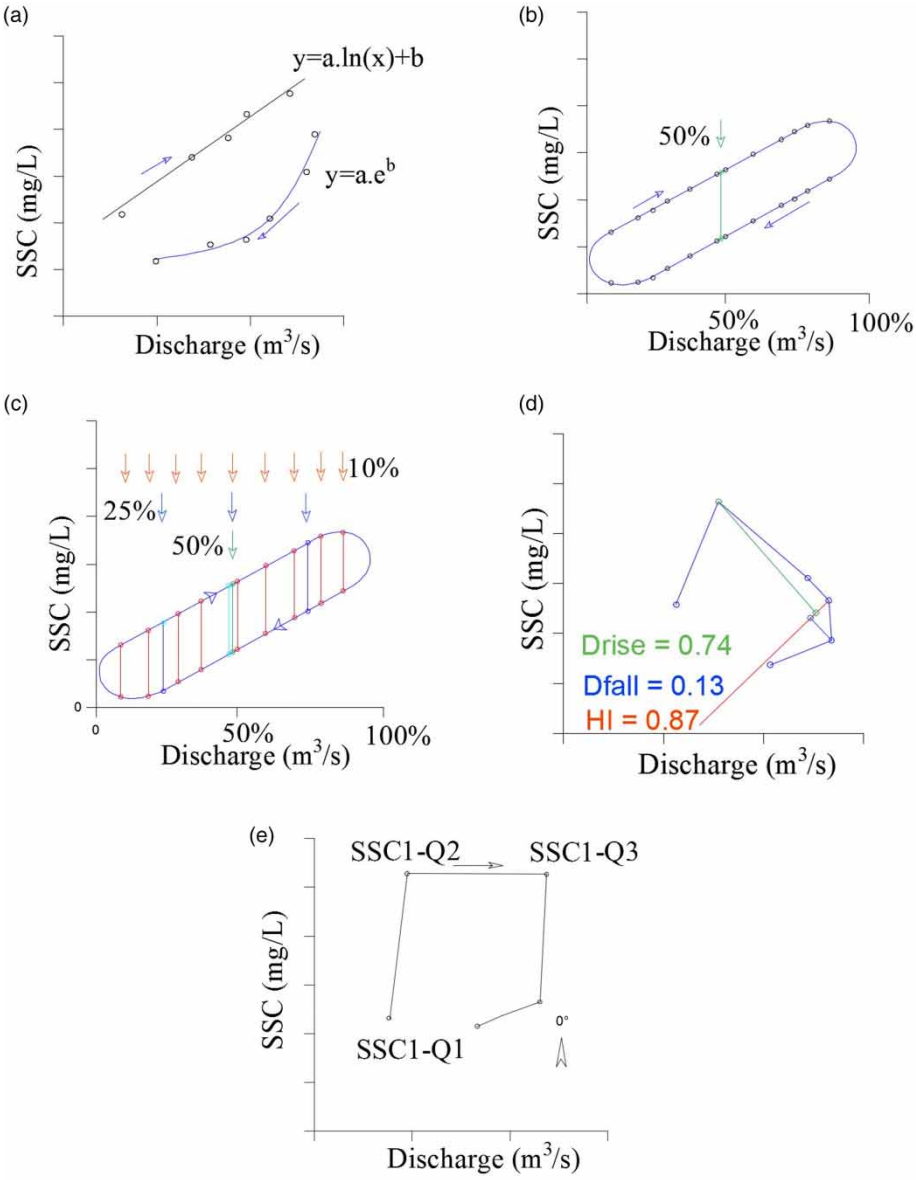

Figure 5 | Hysteresis quantification proposals: (a) Langlois *et al.* (2005); (b) Lawler *et al.* (2006); (c) Lloyd *et al.* (2016a); (d) Aich *et al.* (2014); and (e) Smith & Dragovich (2009).

The $HI_{\min}$ of the clockwise hysteresis, i.e. $TU_{RL} > TU_{FL}$, is calculated with Equation (3), and the $HI_{\min}$ of the counter-clockwise hysteresis, i.e. $TU_{FL} > TU_{RL}$, is calculated with Equation (4):

$$HI_{\min} = \left(\left(\frac{TU_{RL}}{TU_{FL}}\right) - 1\right) \tag{3}$$

$$HI_{\min} = \left(\left(\left(\frac{-1}{\frac{TU_{RL}}{TU_{FL}}}\right)\right) + 1\right) \tag{4}$$

The *HI* proposed by Lawler *et al.* (2006) is more frequently utilized in studies, for example, Minella *et al.* (2011), Gao & Josefson (2012), and Anguilera & Melack (2018).

Based on the method of Lawler *et al.* (2006), Lloyd *et al.* (2016a) proposed a new method of calculating *HI*. This method uses the difference between turbidity or *SSC* values in the rising and falling limbs of normalized events. However, instead of calculating only the point in the Q_{mid}, the analysis was done at different discharge intervals (25, 10, 5, and 1%) (Figure 5(c)). The comparison of the methods showed how to characterize almost all storm sizes and

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shape; the section should be calculated at least every 10% of the discharge range.

Smith & Dragovich (2009) presented another method to quantify the hysteresis patterns by applying a similarity function (*SF*). *SF* was derived based on individual line lengths and angles formed between *SSC* and *Q* (Figure 5(e)) for each sampling time (*t*).

Statistical analysis

Table 3 shows the variables synthesized from Table S1. The variables used by most of the studies are precipitation (*P, I, Pac* and *API*), discharge (Q_{max} and Q_{med}), and sediment or turbidity (SSC_{max} and *SST*). We can highlight that Oeurng *et al.* (2010) used variables that will characterize the discharge before the event (such as Q_{Amax} and Q_{Amed}) and that Ram & Terry (2016) used some variables to measure time, mainly turbidity dynamics (such as 'lag time'). It is also observed that only some authors used variables runoff (*R* and *C*) or base flow (Q_A and Q_{max}/Q_A).

Most studies used the Pearson correlation matrix to identify the high linear correlations between the variables. Table 4 summarizes basin size and variables with a high correlation in various studies. After analyzing the correlations through the Pearson correlation matrix, Ram & Terry (2016) and Rodríguez-Blanco *et al.* (2010) established relationships between variables to construct a model that represents the events, giving discharge and/or turbidity and/or *SSC* as output data. Smith & Dragovich (2009) showed the correlation between the precipitation and discharge variables (*P*, *Iev*, and Q_{max}) with the *SF* equations.

Nadal-Romero *et al.* (2008), Oeurng *et al.* (2010), and Zabaleta *et al.* (2007) used the variables of Table 3 as input factors for analysis of principal component analysis (PCA) and factor analysis (FA, Tables 4 and 5). Seeger *et al.* (2004) used canonical analysis and not FA.

Based on the weights of the major components Mukundan *et al.* (2013) identified three important factors to generate a large variability in turbidity for each region. Therefore, PC1, PC2, and PC3 represent one (or two) subbasin of the study area. PC1 is related to the soil moisture condition of the basin (based on the weights of the ADD and Q_{Amed} variables). The main component of PC2 is NTU_{Amed} and the season of the year. PC3 is related to Q_{Amed}. The first three major components were able to explain 82% of the variability in the data.

Furthermore, Mukundan *et al.* (2013) analyzed the variables through cluster analysis. Cluster 1 showed high values of discharge and low values of turbidity; cluster 2 showed high values of high discharge and high turbidity values. Cluster 2 and 3 showed low discharge values and high turbidity values.

Analyzing the hysteresis in the basin and one sub-basin, Aich *et al.* (2014) calculated the HI_A, *Drise*, and *Dfall*, and correlated them with the variables of Q_{max} and SSC_{max} and *Pac1d, Pac7d, Pac30d, Pac60d*. The *Pac* is the accumulated precipitation before the flood (mm), e.g. *Pac1d* – 1 day. They used the Spearman coefficient (unlike most authors using the Pearson). Then, they pointed out a different behavior of the hysteresis patterns between the basin and the subbasin.

Nadal-Romero *et al.* (2008) and Oeurng *et al.* (2010) identified two PCs representing 63.5% of the data variance. In the results of Zabaleta *et al.* (2007) the variance data were smaller in two basins (Table 5).

There are a very small number of studies which carried out the statistical analysis of the variables of precipitation, discharge, turbidity, and sediment in the events. In reality, most of the studies just estimated the variables of the events, with little use of Pearson's correlation matrix, and usually not reaching the multivariate statistical analysis such as PCA and FA.

Uncertainty analysis

The investigation of relations between methods and uncertainty can give important information on which method for each type of hysteresis pattern is better. For example, McMillan *et al.* (2012) showed benchmarking observational uncertainties for hydrology and water quality. The typical values of the relative error of discharge are ±50–100% for low flows, ±10–20% for medium or high (in-bank) flows, and a single estimate of ±40% for out-of-bank flows.

Uncertainty analysis was not presented in most of the previous studies on hysteresis analysis. There are still a few studies that analyzed the uncertainties in discharge measurements (with turbidity, sediment, or water quality parameters) with hysteresis analysis.

Based on the data presented in Lloyd *et al.* (2016a, 2016b), who used an analytical framework to evaluate uncertainty, the largest uncertainties in the *HI* were associated with the low discharge, and the largest uncertainly bounds for the loop were observed in the highest discharge.

Krueger *et al.* (2009) proposed an empirical model framework for hysteresis, where *SSC* is a function of *Q* and rate change of *Q* is proposed. The model for uncertainty analyses was the generalized likelihood uncertainty estimation (GLUE, Beven & Binley 2014).

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Table 3 | Synthesis of the variables used in statistical analysis for hysteresis studies

	Symbol	Variables	Reference
Precipitation	P	Total rainfall in the event (mm)	Seeger *et al.* (2004); Zabaleta *et al.* (2007); Nadal-Romero *et al.* (2008); Smith & Dragovich (2009); Duvert *et al.* (2010); Oeurng *et al.* (2010); Rodríguez-Blanco *et al.* (2010); Ram & Terry (2016); Sherriff *et al.* (2016)
	ADD	Antecedent dry days	Mukundan *et al.* (2013)
	I_{ev}	Average intensity in the event (mm/h)	Seeger *et al.* (2004); Smith & Dragovich (2009); Rodríguez-Blanco *et al.* (2010); Sherriff *et al.* (2016)
	I_{max5}	Maximum rainfall in 5 min (mm/5 min)	Seeger *et al.* (2004); Nadal-Romero *et al.* (2008); Duvert *et al.* (2010)
	I_{max10}	Maximum rainfall in 10 min (mm/10 min)	Zabaleta *et al.* (2007); Eder *et al.* (2010); Rodríguez-Blanco *et al.* (2010); Ram & Terry (2016); Sherriff *et al.* (2016)
	I_{max30}	Maximum rainfall in 30 min (mm/30 min)	Seeger *et al.* (2004)
	I_{maxh}	Maximum rainfall intensity of the flood (mm/h)	Oeurng *et al.* (2010); Ram & Terry (2016)[b]; Sherriff *et al.* (2016)
	KE	Rainfall kinetic energy (MJ/ha)	Rodríguez-Blanco *et al.* (2010); Duvert *et al.* (2010)
	Pac,	Accumulated precipitation before the flood (mm) (Pac1d – 1 day, Pac1 h – 1 hour and thus varying the intervals)	Seeger *et al.* (2004); Zabaleta *et al.* (2007), Duvert *et al.* (2010); Oeurng *et al.* (2010); Aich *et al.* (2014); Sherriff *et al.* (2016)
	API	Antecedent precipitation index (mm) (API1d – 1 day, API1 h – 1 hour and thus varying the intervals)	Seeger *et al.* (2004)[a]; Zabaleta *et al.* (2007); Nadal-Romero *et al.* (2008); Rodríguez-Blanco *et al.* (2010); Aich *et al.* (2014); Ram & Terry (2016); Sherriff *et al.* (2016)
	t	Discharge duration (h)	Duvert *et al.* (2010); Oeurng *et al.* (2010); Ram & Terry (2016)
Discharge	Q_{max}	Maximum discharge (m^3/s)	Lenzi & Marchi (2000); Seeger *et al.* (2004)[a]; Nadal-Romero *et al.* (2008); Salant *et al.* (2008); Smith & Dragovich (2009); Duvert *et al.* (2010); Oeurng *et al.* (2010); Rodríguez-Blanco *et al.* (2010); Gao & Josefson (2012); Aich *et al.* (2014); Sherriff *et al.* (2016)
	Q_{med}	Mean discharge (m^3/s)	Hudson (2003); Seeger *et al.* (2004); Zabaleta *et al.* (2007); Oeurng *et al.* (2010); Gao & Josefson (2012); Mukundan *et al.* (2013); Ram & Terry (2016)
	Q_{Amed}	Mean baseflow before the flood (m^3/s)	Oeurng *et al.* (2010)
	Q_{Amax}	Antecedent maximum discharge	Oeurng *et al.* (2010)
	Q_{base}	Baseflow before the flood (m^3/s or l/s)	Zabaleta *et al.* (2007); Nadal-Romero *et al.* (2008); Oeurng *et al.* (2010); Rodríguez-Blanco *et al.* (2010)
	Q_{max}/Q_{base}		Zabaleta *et al.* (2007)
	WY	Total water yield (mm or m^3)	Zabaleta *et al.* (2007); Nadal-Romero *et al.* (2008); Oeurng *et al.* (2010); Duvert *et al.* (2010); Sherriff *et al.* (2016)
	R	Runoff	Lenzi & Marchi (2000); Nadal-Romero *et al.* (2008); Rodríguez-Blanco *et al.* (2010); Sherriff *et al.* (2016)
	C	Coefficient of runoff	Rodríguez-Blanco *et al.* (2010); Duvert *et al.* (2010); Sherriff *et al.* (2016)
	t_r	Time of rise (time to reach maximum discharge)	Lenzi & Marchi (2000); Oeurng *et al.* (2010)
Sediment and turbidity	NTU_{max}	Maximum turbidity (NTU)	Ram & Terry (2016)
	NTU_{med}	Mean turbidity (NTU)	Ram & Terry (2016)
	NTU_{Amed}	Mean turbidity before the event (NTU)	Mukundan *et al.* (2013)
	SSC_{max}	Maximum suspended sediment concentration (g/L)	Seeger *et al.* (2004)[a]; Zabaleta *et al.* (2007); Nadal-Romero *et al.* (2008); Salant *et al.* (2008); Oeurng *et al.* (2010); Eder *et al.* (2010); Rodríguez-Blanco *et al.* (2010); Gao & Josefson, (2012); Aich *et al.* (2014)

(*continued*)

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Table 3 | continued

	Symbol	Variables	Reference
	SSC_{med}	Mean suspended sediment concentration (g/L)	Seeger *et al.* (2004)[a]; Nadal-Romero *et al.* (2008); Oeurng *et al.* (2010); Rodríguez-Blanco *et al.* (2010); Gao & Josefson (2012)
	SSC_{Amed}	Mean SSC before the event (g/L)	Zabaleta *et al.* (2007)
	SST	Total suspended sediment yield (kg, ton, or Mg)	Zabaleta *et al.* (2007); Nadal-Romero *et al.* (2008); Oeurng *et al.* (2010); Eder *et al.* (2010); Rodríguez-Blanco *et al.* (2010); Gao & Josefson (2012)
	NTU_d	Turbidity response duration	Ram & Terry (2016)
	LagR-NTU	Lag time from rainfall start to maximum turbidity	Ram & Terry (2016)
	$LagRI_{max}$-*NTU*	Lag time from maximum rainfall intensity to maximum turbidity	Ram & Terry (2016)
	Season	Season of year	Mukundan *et al.* (2013)

[a]The time interval of measurement was 5 minutes and 30 minutes.
[b]In this study, the authors had two rainfall measurement stations, with which the maximum intensity estimation was done.

Table 4 | Variables with high linear correlation

Reference	Variable	High linear correlations	Basin area (km²)
Nadal-Romero *et al.* (2008)	*P*	Q_{max}, *R*, SSC_{max}, *STT* and *WY*	0.45
	WY, *R* and Q_{max}	*P*, $Imax_5$	
	SSC_{max} and *SST*	Q_{max}, *P*, *R*	
Oeurng *et al.* (2010)	*P*	Q_{med}, Q_{max}, SSC_{max}, *STT* and *WY*	1,110
	Q_{med}, Q_{max}	*P*, Q_{Amed}, *Qbase*	
	SSC_{max} and *SST*	*P*, I_{maxh}, *R*, *Qmed*, Q_{max}.	
Zabaleta *et al.* (2007)	*P*	Q_{med}, *WY*, Q_{max}	4.8
	SST	*P*, SSC_{med}, SSC_{max}	
	SST	*P*	3
	SSC_{med} and SSC_{max}	I_{max10}	
	Q_{med}, Q_{max} and *WY*	*API1d*, *API1 h*,	48
	SST	*API1d*, *API1 h*,	
Rodríguez-Blanco *et al.* (2010)	Q_{max}, *R*, *C*	*P*, *Ke*, Q_b,	16
	ST	*P*, *Ke*, Q_{max}, *R*, *C*	
	SSC_{max}	*P*, *Ke*, Q_{max}	
	SSC_{med}	*P*, Q_{max}	
Ram & Terry (2016)	NTU_d	*P*, *Iev*, D_{max}	9.3
	NTU_{med}	*P*, D_{max}, I_{ev} I_{max10}	
	NTU_{max}	*P*, D_{max}, I_{ev}, I_{max10}	

Table 5 | Summary of study basins areas and the results of PCA and FA

Reference	Area (km²)	Variable	Variance
Mukundan *et al.* (2013)	493	*ADD* Q_{Amed} NTU_{Amed} *Season of year* Q_{Amed}	82%
Nadal-Romero *et al.* (2008)	0.45	*WY*, Q_{max}, SSC_{max}, *SST*, *P*	44%
		R, I_{max5}, *API*	19.5%
Oeurng *et al.* (2010)	1,110	*Td*, Q_{med}, *Qmax*, *P*, *WY*, *SST*	46.7%
		If, SSC_{med}, SSC_{max}, I_{maxh}	16.83%
Zabaleta *et al.* (2007)	4.8	I_{ev}, $Imax_5$, SSC_{med}, SSC_{max}, Q_{max}/Qb	29%
		P, *WY*, *Qmed*	23%
	3	Q_{med}, *Qmax*, *Qt*, *SSt*	33%
		Iev, $Imax_5$, *SSCmax*, SSC_{med}	28%
	48	Q_{med}, Q_{med}, *WY*, *API1d*, *API1 h*	47%
		SSC_{med}, SSC_{med}	22%
Seeger *et al.* (2004)	2.84	*P*, *APd3*, *SWC*[a]	78%
		P, *APd3*, *SWC*[a]	21%

[a]*SWC*, soil water content.

Thus, it is necessary to pay attention to these data as well as the process of obtaining the data and estimating their uncertainty. There was a close relation between turbidity and *SSC* (Navratil *et al.* 2011), which allows the use of turbidity as an indirect measure of *SSC*. However, it must be noted that there are several factors of uncertainty associated with this relation. The interference caused by the

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sediment was a function of the *SSC*, the particle size, shape, roughness, color, and mineralogy composition (Downing 2006; Sari *et al.* 2015, 2017).

For example, the optical sensor measures mA or mV, which is transformed into turbidity by one or more equations. Another equation transforms the turbidity into *SSC*, which consequently creates a number of factors influencing the final value of *SSC*. If a sensor could be developed for direct measurement of *SSC*, these types of uncertainty or errors could be reduced. There are some studies that do this conversion directly (Brasington & Richards 2000, for example).

As mentioned above, the particle size also interferes with the optical sensor response. Harmel & Smith (2006) carried out streamflow measurement, sample collection, sample preservation/storage, and laboratory analysis during the storm events. Then, they demonstrated that the cumulative probable uncertainty during the events varied from 3% (the best case) to 117% (the worst case). This type of interference is not often quantified in scientific studies.

Ziegler *et al.* (2014) studied hysteresis with uncertainty in the turbidity-*SSC*, and also the problems with the limitations related to the turbidity sensor. They reported an interval in their annual estimates (underestimated by 38–43% and overestimated by 28–33%).

FINAL REMARKS

In a review of 71 papers we identified the most significant factors influencing sediment-discharge hysteresis: the magnitude and sequence of events; the sediment particle size distribution; land use and sediment source; and the basin area. The sequence of events can cause sediment exhaustion; with less sediment available the hysteresis loop may get smaller. Small particle size sediments are replenished faster because they can be transported by low discharge also. Therefore, there is a binding of at least three factors (magnitude, sequence, and diameter of the particles) to be analyzed. There is still a need to systematize ways of measuring the magnitude of discharge, mainly because the study basins have different sizes and varying magnitudes of discharge.

Land use influences the amount of sediment produced, but those hypotheses related to land use were not fully tested. The basin size factor influences the hysteresis due to the different behaviors of the hydrological and sediment processes in small and large basins. Studies typically use statistical analysis to analyze which processes most influence hysteresis. In small basins the factors that influence it are soil moisture and runoff. There seems to be no consensus on quantifying hysteresis in medium and large basins. But overall, studies show that for large basins the precipitation, discharge, and sediment variables control hysteresis.

Three main techniques were identified that can be used to analyze the hysteresis quantitatively: (a) hysteresis indexes; (b) statistical analysis (simple or multivariate); and (c) uncertainty analysis. The *HI* is very commonly used. It is based on the difference in sediment concentration or turbidity in the rise and fall of the hydrograph in the different curves and quickly shows (due to the simplicity of the calculation) the measurement of the two limbs. Statistical analysis of hydrological and sedimentological variables turned out to be a tool for analyzing the processes in the events and not a quantification of the hysteresis itself. Most studies divide their samples into small and large basins and use correlation statistics to explore what processes are more significant in each case.

Even though the area of the uncertainty of estimation in hydrology has been increasingly applied over the past 20 years, there are still a few studies that used it in hysteresis analysis. Furthermore, there are studies that include only sediment uncertainty and limitations on the analysis of events on a temporal scale (annual or monthly among others. Hence, there are opportunities for further exploration of hysteresis and uncertainty analysis.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wst.2020.279.

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