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HYSTERETIC BEHAVIOR OF LIQUID DISCHARGE AND SUSPENDED SEDIMENTS CONCENTRATION DURING FLOODS IN THE JIU RIVER BASIN (ROMANIA)

Gabriela Adina MOROȘANU[1,2], Liliana Zaharia[3], Gabriel MINEA[4], Gabriela IOANA - TOROIMAC[3], Jérémy BONNEFOUS[5]

[1] Romanian Academy, Institute of Geography, Str. Dimitrie Racoviţă 12, 023994, Bucharest, Romania, +40213135990
[2] Division of Earth, Environmental and Life Sciences, the Research Institute of the University of Bucharest, University of Bucharest, 36-46 Bd. M. Kogălniceanu, Sector 5, 050107, Bucharest, Romania, tel. +4021-3054676
[3] University of Bucharest, Faculty of Geography, Blvd. Nicolae Bălcescu 1, 010041, Bucharest, Romania, tel. +40213053822
[4] National Institute of Hydrology and Water Management, 97 E Bucureşti - Ploieşti Road, Sector 1, 013686, Bucharest, Romania, tel. + 4021 318 1115
[5] Enerdata, 47 Av. Alsace Lorraine, 38000 Grenoble, France, tel. +33 4 76 42 25 46, E-mail: *gabriela.adina.m@gmail.com*

Abstract. During the recent years, the debate over the consideration of sediments as key elements in the life of rivers was fed by the need to understand the importance of mechanisms controlling the sediment dynamics during floods, given the high variability of hydro-sedimentary processes (flow velocity, erosion, sediment transport and deposition) specific to these extreme hydrological events.In this context, the present paper investigates the relationships between the liquid discharge (Q, in $m^3 \cdot s^{-1}$) and suspended sediments concentration (SSC, in $g \cdot m^{-3}$) during the 10 most intense floods in the 2001 - 2010 period, using data from 22 hydrometric stations within Jiu River basin (south-western Romania). The examination of hydro-sedimentary behavior in terms of the predominant area of formation of alluvial sources during floods was done by calculating a hysteresis index, in order to classify the lag between liquid and solid discharge. For most of the events, the small sub-basins appear to be widely controlled by the sediment storages available on the slopes' domain (probable reactivation of materials deposited in fragile equilibrium following geomorphic processes), whereas in the largest, first order sub-catchments, the accumulation forms in the river channels provide, through resuspension, sufficient fine sediment sources for generating high suspended sediment concentration rates at the downstream gaging stations.
Keywords: hysteresis index, Jiu River Basin, liquid discharge, suspended sediments concentration

1. INTRODUCTION

The hydro-sedimentary behavior during floods is increasingly being researched from different perspectives, due to the need for robust, proxy methods to gain insights into the processes controlling fine sediments yield within river basins. Over time, a number of studies underlined that the rate and amount of suspended sediment exported during peak discharge is higher compared to the periods of minimum and average flow during a hydrological year (Williams, 1989; Savin, 2005; Hilton et al., 2008; Lajeunesse et al., 2018). Moreover, it has been acknowledged that the largest proportion of alluvia is produced and transported by rivers in short periods of maximum flow (Lenzi et al., 2003; Savin, 2003; Smith & Dragovich, 2009). Also, a series of studies showed that, during storm events, the concentration of suspended sediments is strongly dependent on the liquid discharge variation, regardless of the climatic, geological and geomorphological features of the river basins (Sherriff et al., 2016; Le Gall et al., 2017; Li et al., 2020).

Seen as two competing but also conjoint fluxes, suspended sediments and liquid discharge behavior during flood events have, therefore, become a growing issue in hydrology in recent years, particularly in extended, human-influenced, and non-homogeneous river basins (Lloyd et al., 2015).

In this order of thoughts, the examination of hydro-sedimentary processes and sediment sources using hysteresis patterns has been kept going in recent years, among other, this being used to identify the spatial sources delivering sediment in catchments with different characteristics (Williams, 1989; Lloyd et al., 2015; Dumitriu, 2017; Moroșanu, 2020). The temporal variation of these two fluxes may, however, differ within the same storm event, in situations when the maximum value and the periods of increase and decrease of liquid discharge and the solid ones do not completely overlap. We refer to this delay of one flux over the other as of a hysterical relationship.

Hysteresis is currently seen as the collective name for the nonlinear and complex hydro-sedimentary behavior during floods events (O'Kane, 2005; Fovet et al., 2015). The simplest model of a hysteresis loop is generally called "hysteron" and, in the context of the hydro-sedimentary dynamics, it is marked by the lack of linearity and its failure to obey the superposition of the liquid and solid discharges (O'Kane, 2005). The attempt to capture the hysteretic character of a flood is part of a process of probabilistic appraisal of an extreme hydrological event, aimed at understanding the internal processes of the hydro-sedimentary system of a river basin (Fovet et al., 2015). We are no longer interested solely in the frequential analysis of maximum values, but we now extend the analysis to in-stream physical and chemical responses to flood events, in order to characterize the transport of fine sediment at a watershed scale (Lawler et al., 2006; Smith & Dragovich, 2009; Lloyd et al., 2016; Lajeunesse et al., 2018).

In complex hydrographic basins, developed under different geological and hydro-geographic conditions and which, in addition, are disturbed by anthropogenic interventions that can affect the zoning of the sediment source(s), hysteresis analysis should be regarded as a key step in apprehending the hydro-sedimentary mechanisms and processes occurring during floods (O'Kane, 2005; Chen et al., 2016).

In consequence, studying floods for experimental or operational needs requires synthetic, eventually proxy methods, reproducing flood chronicles. Thus, hysteretic loops of the hydro-sedimentary fluxes during floods can prove to be an adequate approach both in terms of the data used and in terms of ease of implementation.

In this general context, the objective of the paper is to analyze the relationship between liquid and solid discharge during flood events, by applying the hysteresis index within the Jiu River Basin. The hysteresis behavior is discussed in terms of slope (far) or riverbed (nearby) alluvial sources (or a combination of the two), from the gauged river of the analyzed sub-catchments.

Therefore, the present paper shares the interest of both hydrological sciences (in terms of the relationship between the liquid and the solid discharges) and geomorphology (from the perspective of the behavior of alluvial sources during low return period flood events, via the role played by certain morphometric, dynamic and even anthropogenic factors in the generation of suspended sediments). These insights into the problem of hysteretic patterns of alluvial sources are aimed at following an emergent research path emphasizing the relations between the liquid discharge and the suspended sediment concentration, with different approaches to hydrological and geomorphological issues such as the connectivity of alluvial sources with riverbeds, or the controlling factors of fine sediments generation and transport (Dumitriu, 2017; Morosanu, 2020).

2. STUDY AREA

The research focuses on Jiu River catchment (~10,080 km^2), located in south-western Romania, between the Southern Carpathians and the Danube River (Fig.1).

In the study area, altitude ranges from 2159 m (N) to 24.1 m (S - at the river mouth), with the basin featuring a wide range of landforms, geological facies (metamorphic rocks in the mountain area, sedimentary shale in the piedmont and plain areas; limestone in the upper mountainous and piedmont north-western area), soils, land cover and uses (dominantly arable – 49%) and slope conditions (Savin, 2003). In addition to these natural characteristics, we can also mention the impact of coal mining activities in the generation of new sources of coal – enriched fine sediments carried away by the draining rivers.

Mean annual temperature (period of data availability and processing 1961 – 2016) decreases from 10.8 °C at Craiova meteorological station (192 m a.s.l.) to 3.4°C at Parâng meteorological station (1548 m a.s.l.), while the multiannual discharge for Jiu River at Podari gauging station (approx. 60 km upstream the confluence with Danube River) is 88.5 $m^3 \cdot s^{-1}$ (Moroșanu, 2020). Likewise, the average multi-year suspended sediments load also varies from 0.13 kg·s^{-1} at Câmpu lui Neag h.s. (in the upper basin of Jiu River), to 165 kg·s^{-1} at Podari g.s.

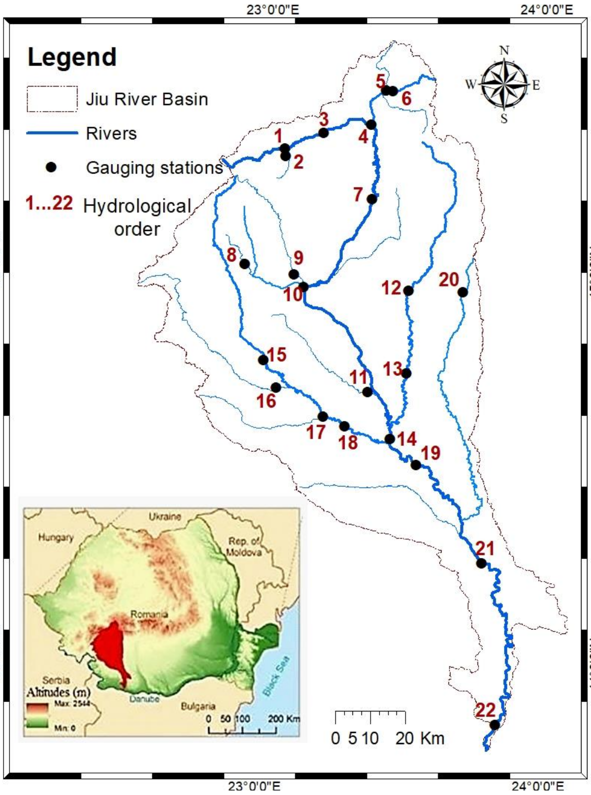

Figure 1. Study area map: Jiu River Basin and the studied stations (g.s.), numbered by hydrological order as in Table 1.

Table 1. Hydrometric stations and upstream catchments considered for the study (2001-2010)

Hydrological order	Hydrometric station	River	Upstream mean alt. (m a.s.l.)	Catchment area (km^2)	Qmed (m^3·s^{-1})
1	**Câmpu lui Neag**	Jiu	1346	159	3.21
3	**Bărbăţeni**		1263	289	6.4
4	**Iscroni**		1134	502	10.3
7	**Sadu**		1066	1255	20.3
10	**Rovinari**		697	7723	44
14	**Filiasi**		563	5239	63.6
19	**Răcari**		508	7217	76
21	**Podari**		446	9253	84.6
22	**Zăval**		417	10,070	86.8
2	**Valea de Peşti**	Valea de Peşti	1300	25	0.9
5	**Lonea**	Eastern Jiu	1206	826	2.4
6	**Lonea Taia**	Taia	1476	135	1.55
8	**Celei**	Orlea	538	61	1.83
9	**Telesti**	Bistriţa	548	270	4.2
11	**Turceni**	Jilţ	540	376	1.1
12	**Târgu Cărbuneşti**	Gilort	749	630	7.9
13	**Turburea**	Motru	590	1027	10.2
15	**Broşteni**		526	646	8.4
18	**Faţa Motrului**		384	1700	12.8
16	**Corcova**	Cosustea	482	420	3.01
17	**Strehaia**	Huşniţa	257	312	0.83
20	**Bustuchin**	Amaradia	310	37	0.09

Note: Q_{avg} (Table 1) = average liquid discharge between 1980 and 2010. The stations are organized in upstream - downstream order, river-wise.

3. METHODOLOGY

In the present study, we used data from 22 gauging stations located (g.s.) on Jiu River (9) and its main tributaries (11), at which determinations of suspended sediment concentration are performed (Table 1). The data were provided by the Jiu Water Basin Administration, and the main characteristics of the river basins upstream each considered gauging station are presented in Table 1.

The analysis is based on the liquid discharge (Q) series (mean daily water discharge) and, suspended sediment concentration (SSC) at a daily time step. The two parameters werre chosen because, in the quantitative hydrological analyses, suspended sediment concentration is the most widely examined parameter in relationship with water flow, to describe hysteretic loops (Lawler, 2006; Bača, 2008; Chen et al., 2016; Dumitriu, 2017, Moroşanu, 2020). In other studies, hysteretic relationships could be observed, as well, between the liquid flow and other parameters, such as various nutrients or water pollutants (Lloyd et al., 2015; Lloyd et al., 2016).

Still, SSC values have the drawback of being characterized by the absence of a high temporal resolution data on Romanian rivers. While liquid discharge is calculated at a daily, even hourly pace (during important flood events), on the basis of the rating curve at each gauging station, the concentration of suspended sediments is indirectly obtained based on a few dozen samples a year, by determining their weight by the filtration method. Consequently, the solid discharge, marked with "R", is an indirect hydrological parameter calculated by integrating the liquid discharge (Q) and the suspended sediment concentration (SSC) over time. In the case of the latter, the solid component of discharge, given the fact that the suspended sediment data provided by the habilitated institutions are obtained indirectly (R), through calculations, an estimate of the direct values of the concentration (SSC), by reversing the relationship, needed to be made. Thus, starting from the solid discharge, R (m^3·s^{-1}), we went back to determine the concentration of suspended sediments. This parameter was calculated on the basis of the formula: SSC[$g \cdot m^{-3}$] = $\bar{R}$ [$kg \cdot s^{-1}$] / $\bar{Q}$ [$m^3 \cdot s^{-1}$] ·1000.

To explore the relationship between the liquid discharge and the suspended sediments concentration, we looked at the 10 most important flood events in terms of frequency – return period having occurred between 2001 – 2010. For reference, we used the most important gauging station of the Jiu River basin, Podari g.s., located at the entrance to the lower (plain) sector, where a significant proportion of the sedimentary load reaches. Floods considered to be the most significant within the 10-year observational dataset respected the following rules: the start-up discharge value exceed 20% of the baseflow, while the end was equivalent to the return value to baseflow conditions or when discharge was maintained at an almost constant value corresponding to the subsequent high water (Savin, 2001; Lloyd et al., 2016). From approximately 20 floods which complied with the imposed hydrological criteria at Podari g.s. during the analysis period, the floods with the 10 highest maximum discharge were selected for the hysteresis analysis.
Furthermore, in addition to the criteria of the highest floods in terms of maximum discharge and return periods, another parameter to be considered in choosing the floods for hysteresis analysis was their total duration (expressed in number of days). Because only one daily average value of liquid and solid discharge was used to calculate the hysteresis index, for a better estimate of it, as many values as possible were needed, thus floods that last several days (more than a week) were preferred. Therefore, as Table 1 shows, the most important floods had long and very long durations, between 9 and 20 days at the Podari g.s., downstream, where we expect a delayed response to rainfall and liquid volume contributions from tributary rivers. Obviously, the same flood upstream, at a hydrometric station that serves a smaller basin, is certainly likely to last less, so it was essential to select long-term floods from the beginning, so that they have a sufficient number of days (over 5, on average) at the gauging stations delivering for the smaller, upstream river basins.

Table 2. The selected 10 floods, with their hydrological characteristics at Podari gauging station, on Jiu River

Flood No.	First day	Last day	Duration (days)	Q_{max} ($m^3 \cdot s^{-1}$)	Return period * (years)
1	13/04/2003	25/04/2003	13	713	6.26
2	14/11/2004	26/11/2004	13	834	8.42
3	15/08/2005	3/9/2005	20	875	9.15
4	10/7/2005	20/07/2005	11	750	6.92
5	11/4/2006	19/04/2006	9	830	8.35
6	10/3/2006	21/03/2006	12	1022	32.63
7	16/11/2007	26/11/2007	11	966	19.83
8	23/10/2007	1/11/2007	10	786	7.56
9	28/01/2009	5/2/2009	9	813	8.04
10	8/11/2009	19/11/2009	12	743	6.8

Note: * The return period was previously calculated in Moroșanu (2020), using Log-Pearson Type III distribution.

In the following, we will refer to these floods considering the month and year of their production (for example, the flood of July 2005). In the analysis of the hysteretic behavior of the 10 floods, a specific focus was made on identifying the dominant fine sediment sources. To achieve this goal, a hysteresis index (HI) was computed, for the median discharge (defined as Q at 50% of the flow value range), according to the standard method proposed by Lawler et al. (2006): $Q_{mid} = k \cdot (Q_{max} - Q_{min}) + Q_{min}$. In this formula, Q_{max} represents the peak discharge of the flood, Q_{min} is the starting discharge for the event, while k is set at 0.5, being the position at which the loop breadth is investigated (the mid-point of the rising/ falling limb).
The suspended sediment concentration values relative to Q_{mid} of the rising (SSC_{RL}) and falling limbs (SSC_{FL}) of the flood hydrograph were then interpolated with an automatic linear interpolant, in order to calculate the final hysteresis index, HI_{mid}. A first classification of the two main types of positive or negative hysteresis resulted from the imposition of a bilateral conditions. If $SSC_{RL} > SSC_{L}$, the flood is characterized by a clockwise hysteresis, the following formula was applied: $HI_{mid} = (SSC_{RL}/SSC_{FL}) - 1$.

In the opposite case (anticlockwise hysteresis and $TU_{RL} < TU_{FL}$), the index was obtained as follows (Lawler et al., 2006): $HI_{mid} = (-1/ (SSC_{RL}/SSC_{FL})) + 1$.

The resulting HI values for the 10 floods were analyzed according to the shape of the hysteresis loops, in order to classify the hysteresis effect in one of the 5 categories in terms of the relation between the liquid and solid fluxes: linear, direct, indirect, 8-shaped and complex.

4. RESULTS AND DISCUSSION

Depending on the available sediment sources and its geomorphology, every river basin can be characterized by a different spatial and temporal variation of suspended sediment concentration. Also, in close dependence with the slope processes, factors such as the distance between the supply sources, the presence of intermediary resuspension mechanisms of fine sediments, transport intensity and deposition sites are key elements in understanding suspended sediment behavior during flood events.

Through the results obtained after calculating the hysteresis index, we were able to investigate more closely the possible types of sediment sources upstream of the analyzed hydrometric stations. It is clear that hysteresis patterns can be observed for a number of reasons; however, it is generally assumed that clockwise hysteresis, caused by concentrations increasing more rapidly than discharge during the rising limb of the flood hydrograph, suggests a sediment source close to the hydrometric station (Lloyd et al., 2016). Conversely, anticlockwise hysteresis generally denotes a longer lag between the liquid discharge and the suspended sediment concentration peaks, meaning that the source is located further upstream (Bača, 2008; Lloyd et al., 2016).

Following the application of the hysteresis index (HI) for the 22 hydrometric stations, at the 10 extreme hydrological events investigated, the raw resulting values have been summarized in Fig. 2. Note that for some of the stations, during certain flood events, no value is displayed, for one of the two following reasons: 1) either the flood did not occur in the basin / sub-catchment in question; 2) or the flood did not have a considerable length and magnitude, to allow the calculation of the index, which requires a minimum of a few days of duration of the event, given the rather coarse time scale of a value (daily average discharge) per day computed.

Hydrological order	Gauging stations	March 2006	November 2007	August 2005	November 2004	April 2006	January 2009	October 2007	July 2005	November 2009	April 2003
1	Câmpu lui Neag		-0.07	-0.07	0.37	0.21		0.07	-0.33	-0.03	-0.06
2	Valea de Pești		-0.11	0.09	-0.25		0.29	-0.79	-0.01	-0.01	-0.01
3	Bărbăţeni		0.00		0.00		-0.01	0.61	-0.04	0.56	-0.23
4	Iscroni		0.14	-0.31	-0.29	-0.21	0.75	0.14	-0.26	0.53	-0.12
5	Lonea Taia	-0.48						0.56	0.02		
6	Lonea	-0.01	0.10	0.52	0.17	0.09			0.00		
7	Sadu		0.37	0.04	0.14	0.53	0.44	0.17	0.26	-0.17	0.29
8	Celei	-0.13	-0.08	-0.07	0.05				-0.03	-0.04	0.19
9	Telești	-0.19	0.23	-0.07	-0.03	0.20	0.26		-0.12	-0.02	-0.29
10	Rovinari	0.01	-0.05	0.06	0.08	0.00	0.01	-0.01	0.00	0.00	0.02
11	Turceni	0.16	-0.56	-0.06	0.23	-0.34					-0.05
12	Târgu Cărbunești	-0.03	-0.05	-0.09	-0.15	0.34	0.17	-0.11	0.29	0.42	0.26
13	Turburea	0.02	0.03	0.08	0.77	0.00	0.77	-0.20	0.02	0.02	0.26
14	Filiași	-0.01		0.06	0.02	0.05	-0.22		-0.03	-0.01	0.09
15	Broșteni	-0.05	-0.01	-0.19	0.11	-0.15	-0.04	0.02	-0.03	-0.02	0.08
16	Corcova		-0.20		0.01	-0.23	-0.05		-0.23	-0.06	0.31
17	Strehaia	0.54	0.41	-0.19		-0.36	-0.02	-0.06	0.31		-0.32
18	Fața Motrului	0.01	0.03	0.14	0.03	0.05	-0.01		-0.20	-0.01	0.04
19	Răcari	0.80	0.21	-0.46	0.69	-0.04	0.66	0.52	0.07	0.55	0.34
20	Bustuchin	0.53		-0.09	-0.09		-0.13		-0.08		0.28
21	Podari	0.66	0.74	-0.02	0.39	0.21	0.59	0.19	0.50	0.90	0.15
22	Zăval	0.18	0.48	0.11	0.12	0.13	0.47	0.48	-0.16	0.75	0.31

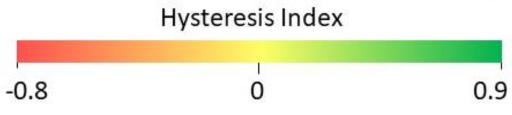

Figure 2. Gross hysteresis index (HI) results for the analyzed floods. The color gradient indicates the development of the loop (or the extent of the lag time) and whether the relationship between liquid discharge and suspended sediments load was positive (green), synchronous (yellow), or negative (orange – red).

For the characterization of the type of hysteresis of each flood at each station, we visually analysed all the hysteresis loops, in order to classify the hysteresis effect (lag time) in one of the 5 categories (Table 2).

Table 2. The type of hysteresis in the solid - liquid discharge relationship (after Moroșanu, 2020)

Hydro Order	Hydrometric station	Mar-06	Nov-07	Aug-05	Nov-04	Apr-06	Jan-09	Oct-07	Jul-05	Nov-09	Apr-03
1	Câmpu lui Neag		‖	‖	⊕	⊕		‖	⊕	‖	∞
2	Valea de Pești		∞	‖	⊕		⟳	⟲	‖	‖	‖
3	Bărbățeni		‖		⊕		‖	⟳	‖	⟳	⟲
4	Iscroni		∞	∞	⊕	⊕	⊕	⟳	⊕	⊕	∞
5	Lonea	‖	‖	⊕	⊕	‖			‖		
6	Lonea Taia	⟲						⟳	‖		
7	Sadu		∞	⊕	⊕	⟳	⟳	⟳	⊕	⟲	⊕
8	Celei	‖	‖	‖	‖				⊕	‖	⟳
9	Telești	⊕	∞	‖	⊕	⊕	⟳		⊕	‖	⊕
10	Rovinari	‖	‖	‖	⊕	‖	‖	‖	‖	‖	‖
11	Turceni	⟳	⟲	⊕	⊕	⟲					‖
12	Târgu Cărbunești	‖	‖	‖	⊕	⊕	∞	‖	∞	⟳	⊕
13	Turburea	⊕	‖	‖	⟳	‖	⟳	⟲	‖	⟳	⟳
14	Filiași	‖		⊕	‖	‖	⊕		⊕	‖	⊕
15	Broșteni	‖	‖	∞	⊕	∞	‖	‖	‖	‖	‖
16	Corcova		‖	⟲	⊕	⊕	‖		⟳	‖	⊕
17	Strehaia	⟳	⟳	⊕		⟲	‖	‖	⊕		⟲
18	Fața Motrului	‖	‖	⊕	‖	‖	‖		⟲	‖	∞
19	Răcari	⟳	⊕	⊕	⊕	‖	⊕	∞	⊕	⟳	⊕
20	Bustuchin	⟳		‖	⊕		⟲		‖		⊕
21	Podari	⟳	⟳	⊕	⊕	⟳	⟳	∞	⊕	⊕	⟳
22	Zăval	⟳	⟳	⊕	⊕	⊕	⟳	‖	⊕	⟳	⊕

In the Figure 2 and the Table 2, the cases where no symbol is presented are those of the hydrometric stations where the flood was not felt (we were unable to calculate the HI since the discharge did not increase).

The 5 categories used to classify the hysteresis pattern were: A. Linear (no hysteresis, where the HI is very close to 0 and the peak of the solid flow is almost coincident with that of the liquid flow); B. Direct (clockwise, when the HI is moderately positive → nearby sediment sources); C. indirect (counter clockwise, when the HI is moderately negative → more distant sediment sources); D. The shape of 8 (combination of types B and C → sources from different areas, both bed and slopes); E. Complex (with several hysteresis loops, typically during long-term floods with several peaks). According to these criteria, we attributed the hysteresis effects during the 10 floods studied at the 22 hydrometric stations to one of the 5 categories symbolized with: A.‖ - the linear relationship between liquid and solid discharge; B. ⟳ - direct relationship; C. ⟲ - indirect relationship; D. ∞ - "Number 8" relationship; and E. ⊕ - complex relationship.

Counterclockwise loops (Fig. 3 a) are usually the most common hysteretic patterns to be observed, at gauging stations more likely to be located far from the sediment sources (generated on slopes), which provide material deposited and then resuspended at a slower rate after the critical point where the slope decreases. There are only 11 such cases of hysteretic patterns in river reaches, within small and medium-sized sub-catchments, which function as sinks and slowdown passages for the sediment rising and falling limbs (Fig. 3 e). Most of them could be seen at Turceni g.s., Corcova g.s., Turburea g.s., described in hydrological literature as very turbid (Moroșanu, 2016; Savin, 2003; Savin, 2005; Moroșanu, 2020), with fine sediments arriving mostly from production zones located farther upstream.

Linear relationship was the most commonly encountered pattern, with 62 cases of flood events among the 22 gauging stations (Fig. 3 b). This behavior implies a continuous supply with sediment when there is enough water to carry it, so the liquid flow is always in phase with the concentration of suspended matter (Dumitriu, 2017). This hysteretic type is thus indicated by the fact that the graphs of the liquid flow rate and the concentration of suspended matter record peaks at the same time (Fig. 3 f). They show a similar distribution on the time axis of the rising part and the falling part of the flood hydrograph. These situations are generally rarely observed in other studies; near-coincident Q ~ SSC events are typical in most small basins, due to the slow downstream translation of sediment and associated water waves (Lawler et al., 2006). We note in this category in particular the s.h. Rovinari on the Jiu River, where the increase and decrease in liquid and solid discharge occur at the same time. The simultaneous character of the two fluxes (which translates into a line, no-loop pattern) can be explained by the constant supply of sediment depending on the liquid flow, in the conditions of lack of sources far from the slopes (the only possible contributions are the rivers Tismana and Amaradia Pietroasă (with more coarse than fine suspended), while the upstream Jiu River does not contribute as much because of the Târgu Jiu and Vădeni reservoirs, which store the sediments a few kilometers upstream. Only in the case of a flood with a strong sediment input, a large proportion of it is evacuated downstream of the dams, a situation that can be confirmed with the flood of November 2004, the only one during which the relationship Q ~ SSC was of complex type.

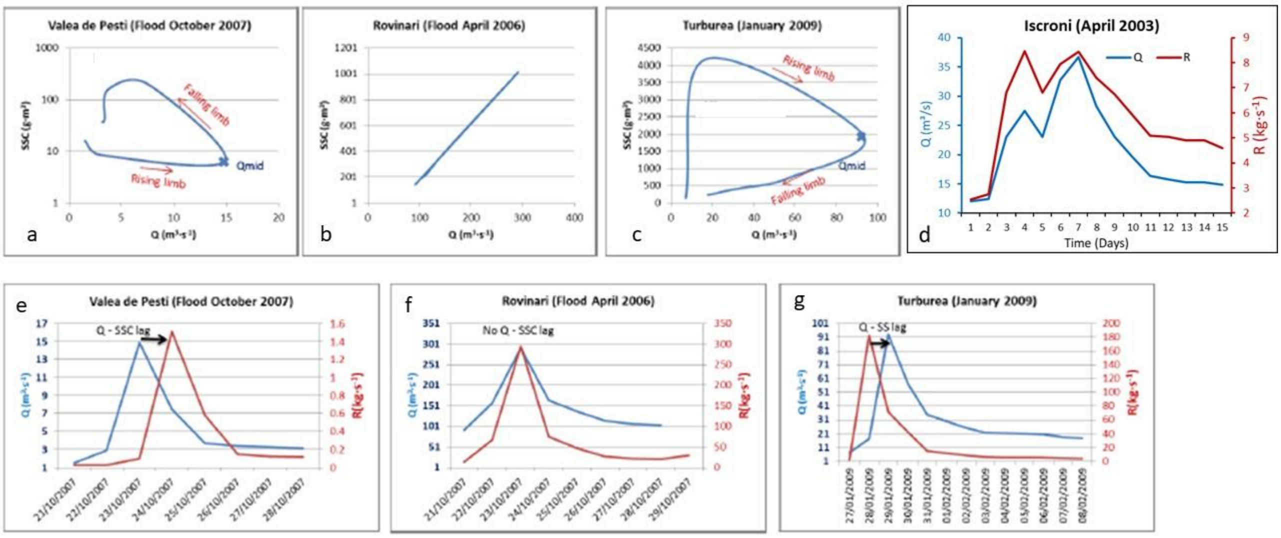

Figure 3. Types of hysteretic loops on Jiu River and some of its tributaries. Figures a-c represent models of hysteretic loops (with Q and SSC [g/l] on the axes) and figures d – g depict flood chronicles (with Q and R[$kg \cdot s^{-1}$] on the axes)

The "clockwise" or "direct" relationship was observed for 23 of the cases, notably at the Sadu, Podari, on Jiu River, and Turburea (on Gilort River) gauging stations (Fig. 3 c). This situation shows that the transport of sediment during floods is faster than the water wave celerity. The strongest clockwise hysteretic behavior was observed on the Jiu River, upstream and also downstream, caused by the rapid remobilization of the sediments stored in the minor bed and in the alluvial plain. In the third case, on the Gilort River, there is probably an alluvium stock in the minor and major bed which suspends very quickly, leading to a wait for the solid maximum before that of the liquid flow (Fig. 3 g).

The relationship in the form of the number "8" (Fig. 3 d) or infinity-shape is a combination of clockwise and counter clockwise loops, when different types of sources (both bed, bank and slope) compete to provide fine sediment (Dumitriu, 2017). This type of relationship is as rare as that of anti-clockwise loops (9 cases) and was mainly observed in Târgu Cărbunești and Iscroni gauging stations.

The complex relationship characterizes 42 of the cases and has been observed in particular for floods with multiple peaks, at downstream stations, near confluences, or located in areas of change in morphometry. The longer the duration of the flood (15 - 20 days), the more the multiple sources of sediment can activate and complicate the hysteretic relationship.

5. CONCLUSIONS

In this research, we sought to answer two main questions: i) How does the mobilization and contribution of sediment sources influence the hysteretic behavior during floods between the suspended sediment concentration and liquid discharge?; and ii) Are there any sub-catchments showing hysteretic patterns, depending on their proximity to the source of the sediments/ erosive areas?

To answer those questions, the use of the hysteresis index (HI_{mid}), the calculation of which being adapted after the method of Lawler et al. (2006) allowed to determine the approximate domain of origin of the suspended sediments within the Jiu River Basin. The hysteretic patterns were investigated at 22 gauging stations, both on Jiu River (9) and on 11 of its tributaries (13 gauging stations). The daily liquid discharge at Podari g.s. on the Jiu River and the frequency analysis of the maximum values served to select the most important 10 floods within the river basin, having occurred in the decade 2001 – 2010, upon availability of the hydrological data.

While for most of the flood events at the 22 gauging stations under study, it was possible to explore the hysteresis patterns between liquid and solid fluxes, for 38 of the cases, the length or the magnitude of the discharge were not enough to allow the calculation of the hysteresis index.

For the effective flood events, the hysteresis index results show, for the Jiu watershed, a rather predominant linear relationship (no or very little, imperceptible at the daily time scale, lag time between the liquid and the solid fluxes), accounting for nearly 43% of cases. This pattern was followed by the complex relationship (almost 29% of cases), during floods which lasted for more than a week, in river basins where there is a mix of remote and nearby sediment sources. This pattern, along with the ”8” – shaped one (6%), occur when there are floods with multiple peaks. Most of the gauging stations where those two types occurred are located in the lower sectors of the river basins. The clockwise, or direct relationship, was found at almost 15% of cases, denoting available fine sediments storages in the riverbed, not far from the gauging stations. In a few cases (7.5%), the counterclockwise pattern suggested that suspended solids concentrations reach the peak value slower than the liquid discharge, thus confirming in some cases the existence of remote sediment sources on the slopes, further upstream of the river basins.

For most of the events, the small sub-catchments appear to be largely controlled by the sediment storages available on the slopes (as sediment is supplied by geomorphic processes and alluvial fans), whereas in the largest sub-basins, the accumulation forms (islets and sand beaches) in the riverbeds increase, through resuspension, the suspended sediment concentration recorded at the downstream gaging stations.

The analysis of the hysteretic behavior of liquid flow and suspended sediment load opens up a new research path, emphasizing the relationship between the two fluxes and the contribution of different alluvial sources (located closer or farther to the riverbed) to the delivery of sediments.

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