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Suspended sediment transport dynamics in rivers: multi-scale drivers of temporal variation

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Abstract

Suspended sediment is a natural part of river systems and plays an essential role in structuring the landscape, creating ecological habitats and transporting nutrients. It is also a common management problem, where alterations to sediment quantity and quality negatively impact ecological communities, increase flood hazard and shorten the lifespan of infrastructure. To address these challenges and develop appropriate sustainable management strategies, we need a thorough understanding of sediment sources, pathways and transport dynamics and the drivers that underlie spatial and temporal variability in suspended sediment transport in rivers. However, research to date has not sufficiently addressed the temporal complexity of sediment transport processes, which is limiting our ability to disentangle the hydro-meteorological, catchment, channel and anthropogenic drivers of suspended sediment transport in rivers. This review critically evaluates previously published work on suspended sediment dynamics to demonstrate how the interpretation of sediment sources and pathways is influenced by the temporal scale and methodology of the study. To do this, the review (i) summarizes the main drivers of temporal variation in suspended sediment transport in rivers; (ii) critically reviews the common empirical approaches used to analyze and quantify sediment sources and loads, and their capacity to account for temporal variations; (iii) applies these findings to recent case studies to illustrate how method and timescale affect the interpretation of suspended sediment transport dynamics; and finally (iv) synthesizes the findings of the review into a set of guidelines for a multi-timescale approach to sediment regime characterization. By recognizing *a priori* that study design and temporal scale have an impact on the interpretation of SS dynamics and employing methods that address these issues, future research will be better able to identify the drivers of suspended sediment transport in rivers, improve sediment transport modelling, and propose effective, sustainable solutions to sediment management problems.

Keywords: Suspended sediment; Regime; Load; Catchment; Timescale; Drivers

1. Introduction

Suspended sediment (SS) is a natural part of river systems. It is the organic and inorganic material carried within the water column (Bridge, 2003; Fryirs and Brierley, 2013). SS plays an essential role in structuring the landscape, creating ecological habitats and transporting nutrients (Dean et al., 2016; Koiter et al., 2013b). Despite being an indispensable part of the river system, SS is also linked to a range of problems related to pollution, ecological degradation, flooding and damage to infrastructure in an increasingly built-up world (Bilotta and Brazier, 2008; Horowitz, 2009; Taylor and Owens, 2009). To develop adequate management strategies, we must be able to quantify SS transport, and link these transport dynamics to drivers both within the channel and the wider catchment in order to accurately predict SS transport in rivers over management relevant timescales (Gao, 2008; García-Ruiz et al., 2015; Taylor and Owens, 2009; Vanmaercke et al., 2011). However, despite decades of research, the spatial and temporal dimensions of the factors and process interactions underlying SS transport in rivers have not yet been fully captured and understood.

On a basic level, sediment transport through a catchment is straightforward. Fine organic and inorganic material erode from land surfaces, flow downhill to a river and are then transported downstream as suspended sediment. However, research has increasingly highlighted the stochastic and variable nature of each stage of this basic process (Phillips, 2003). In fact, it is this complexity in the field-catchment-river sediment transfer system that makes estimation of the provenance, transport and deposition of sediment in rivers so challenging (Gao, 2008; Poulenard et al., 2009; Rickson, 2014; Sun et al., 2015; Zhang et al., 2013; Zheng et al., 2012). Currently, we are unable to accurately predict SS concentrations in rivers over multiple timescales because we lack comprehensive understanding of how different drivers of SS transport interact over space and time.

Previous studies have used concepts such as 'sediment coupling', 'sediment connectivity', 'jerky conveyor belt' and 'sediment cascade' to describe the field-catchment-river sediment transfer system, all of which emphasize the variable, non-linear linkages across temporal and spatial scales that eventually determine SS transport (Bracken et al., 2015; Croke et al., 2013; De Vente et al., 2007; Ferguson, 1981; Fryirs, 2013; Hollister et al., 2008; Koiter et al., 2013a). While these conceptual frameworks have helped researchers to better comprehend the dimensions of the sediment transfer system, important gaps remain in actually linking spatial and temporal scales of SS transport in rivers. A review study on scale independencies in geomorphic systems showed that, when the amount of scales in a system increases, it becomes more difficult to transfer knowledge and relationships from one scale to another (Phillips, 2016). In other words, the challenge lies in formulating conclusions about drivers and processes of SS transport both across spatial and temporal scales.

In this context, we argue that there are two key issues, already identified in previous studies, which need to be addressed in further detail. First, the choice of timescale in many sediment studies limits *a priori* our understanding of the potential explanatory factors driving SS transport (Cao et al., 2007; Dean et al., 2016; Harvey, 2002; Sun et al., 2015; Zhang et al., 2013). In general, studies of SS transport dynamics have focused predominantly at a specific temporal scale, e.g. short-term variations in sediment concentrations during flood events (i.e. hourly timescales) (De Girolamo et al., 2015; Fang et al., 2015; Francke et al., 2014) or decadal trends in sediment loads (Belmont et al., 2011; Gao et al., 2015; Walling, 2009). As these studies are typically based on data collected at this single temporal scale, it is difficult, if not impossible, to interpret them in terms of processes and drivers over multiple timescales (Harvey, 2002; Zheng et al., 2012). When a river system is considered well or poorly connected (depending on its capacity to transmit the effects of environmental change through the system), the relative importance of drivers for geomorphic change is strongly influenced by different timescales (Harvey, 2002). Therefore, acknowledging the relative importance of these different timescales is essential to better understand and interpret SS transport dynamics.

A second and related issue is that common methods to analyze and quantify SS transport and sources are often applied without consideration of the different timescales at which SS transport occurs. Over the last few decades, a wide range of empirical approaches have been developed and applied, from single sediment rating curves to complex multivariate analysis techniques (Asselman, 2000; Francke et al., 2014; Onderka et al., 2012; Poulenard et al., 2012). A review study on understanding catchment-scale SS transport showed that the appropriate method for sampling and calculating SS loads in rivers depends on the timescale considered (Gao, 2008). Therefore, it is essential to consider to what degree sediment dynamics (both spatial and temporal) should be captured to match the specific research question of a study (Gao, 2008) and how different methods are able to represent these dynamics (Cao et al., 2007).

This review will build further on these key issues by using previously published literature to highlight the importance of evaluating and interpreting SS transport dynamics over multiple temporal scales in order to elucidate the spatial and temporal process interactions driving these dynamics. The main objectives of the review are to: (i) briefly summarize the main drivers of variation in SS transport in rivers (Section 2); (ii) review the common empirical approaches that are used to analyze and quantify site-specific SS transport and sources, with special focus on the limitations of these methods in terms of capturing temporal variability (Section 3); (iii) apply these findings to recent case studies to illustrate how method and timescale affect the interpretation of SS transport dynamics (Section 4); and finally (iv) synthesize the findings of the review into a set of guidelines for a multi-timescale approach to sediment regime characterization (Section 5).

In addition to the review on SS monitoring and modelling by Gao (2008), other excellent reviews address different aspects of SS transport, including SS sampling and determining sediment fluxes (Horowitz, 2008); human legacy effects on sediment transport (Wohl, 2015); sediment delivery at the catchment scale (Fryirs, 2013); the influence of SS on water quality and ecology (Bilotta and Brazier, 2008); and sediments in urban river basins (Taylor and Owens, 2009). This review complements these earlier reviews by linking SS transport dynamics to various drivers across timescales. It provides both an up-to-date summary of the major drivers of SS transport in rivers and practical guidance on designing SS transport and sourcing studies, which in combination will aid future research to better identify, characterize and model the scale-dependent temporal variations in SS transport in rivers.

2. Spatiotemporal complexity of suspended sediment transport

The field-catchment-river sediment transfer system is a continuum of erosion, transport and deposition. The amount of SS transport by rivers depends on the interaction of multiple drivers acting on different spatial and temporal scales (Bracken et al., 2015; Fryirs, 2013; Onderka et al., 2012; Poulenard et al., 2012; Rickson, 2014; Sear et al., 2003). In this section, we provide a concise summary of the main processes of fine sediment generation and transport on land (Section 2.1), and the factors driving spatial (Section 2.2) and temporal (Section 2.3) variability in SS transport within rivers. The total sediment load in rivers generally consists of SS and bedload. This review focusses on SS, which is the fine-grained fraction of the sediment (generally < 63 µm), transported within the water column of a river. SS is the dominant type of sediment generated within catchments and accounts for approximately 70 percent of the annual sediment delivery by rivers to the oceans (Morgan, 2005). In this review, as is common practice, SS transport will be expressed as concentration (mg/l), and the amount of SS transported over time as sediment load (tons).

2.1 Sediment generation and transport towards the river

One of the primary sources of SS in rivers is the erosion of soils. Soil erosion occurs in two phases. First, individual soil particles or small aggregates are detached from the 'in-situ' soil, as a result of various processes such as rainfall impact, running water, biological activity, geochemical and physical weathering, freeze-thaw cycling, wind and other processes that disturb the soil. Then the detached soil particles and aggregates are entrained by wind or water flow, which transports them away from their point of origin (Morgan, 2005). Soil erosion is mainly driven by: (i) the erosivity of the eroding agent; (ii) the erodibility of the soil (i.e. the susceptibility of the soil to detachment, entrainment and transport by the eroding agent), as determined by soil properties; (iii) the slope length and steepness of the land (i.e. the topography); and (iv) the nature of the surface cover, including land use and management practices (Morgan, 2005; Renard et al., 1991). Besides the erosion of soils, sediment can also originate from mass movements (such as landslides), riverbank erosion and/or anthropogenic activities and interventions in the landscape (Fryirs, 2013; Morgan, 2005). Material eroded in the catchment may be transported (e.g. by overland flow or wind) directly to the nearest channel (natural or artificial) or deposited before it reaches the channel, where it may be remobilized by other processes at a later stage (i.e. when the transporting agent is more effective at carrying the sediment). The sequence of transport, deposition and remobilization has also been described as a sediment cascade (Collins and Walling, 2004; Fryirs, 2013; Harvey, 2002). In the following sections, the spatial and temporal dimensions of the sediment cascade are further discussed.

2.2 Spatial variability in suspended sediment transport

SS transport in rivers is determined by the interaction between processes operating at multiple scales (Fryirs, 2013; Harvey, 2002). Therefore we need to understand how SS transport can vary spatially within a catchment and how these variations in turn affect temporal variations. The combination of geological, topographical, climatic and land cover features of a catchment determines the spatial distribution of soil erosion and sediment transfer that regulate the SS concentration at any particular point in the river (Figure 1). In this section, we briefly discuss how these catchment characteristics affect differences in (i) sediment generation, (ii) sediment transfer and (iii) sediment transport within the river.

First, the sediment load of a river is primarily determined by the availability of sediment in the catchment and the transport capacity of the erosive agent. Sediment generation can vary immensely across a river catchment depending on differences in soil susceptibility to erosion, determined by erodibility and land cover. For example, arable and horticultural lands are known to be very prone to soil erosion. The lack of a continuous vegetation cover exposes the soil to erosive agents, and field operations such as tillage disturb the natural structure and strength of the soil, which increases the vulnerability of the soil to erosion (Panagos et al., 2015; Renard et al., 1991). In addition, surface sealing and crusting due to the redeposition of fine soil particles following erosion, leads to poor water infiltration, increasing the volume and velocity of overland flow and its capacity to erode and transport large quantities of soil particles (García-Ruiz et al., 2015). Contrary to arable areas, forested areas and grasslands generate less sediment because of their permanent vegetation cover, rooting systems and higher infiltration rates, which reduce the risk of generating erosive runoff. Topographical differences within the catchment add to this spatial variability in soil erosion by generating more water runoff (and erosion) on steep slopes compared to gentler gradients. Besides sediment originating from natural surfaces such as soils and bedrock, sediment can also originate from anthropogenic sources. Fine particulate material from road construction works, roads, car parks and atmospheric pollution (e.g. from vehicle combustion and industrial sources) as well as other particles originating from anthropogenic activities, are deposited on land. Large expanses of impervious surfaces in urban areas generate higher volumes of overland flow that will transport these particles to artificial drainage networks and rivers (Horowitz, 2009; Rossi et al., 2013; Taylor and Owens, 2009).

Secondly, the amount of sediment reaching the channel depends mainly on the catchment connectivity (Brosinsky et al., 2014a; Sear et al., 2003). Fryirs (2013) developed a conceptual framework, describing catchment connectivity in terms of three different types of linkages (longitudinal, lateral and vertical) and three types of blockages (buffers, barriers and blankets). The linkages represent the relationship between the catchment and the river network, while the blockages disrupt the linkages. The (dis)connectivity of the linkages determines the total sediment load in the river. In other words, river catchments can be seen as nested hierarchies wherein subareas are connected to the river system to various degrees. Some areas within the catchment (sometimes of considerable size) can be ignored as sediment source areas because they are poorly connected to the river network, as a result of topographical blockages preventing sediment reaching the river (Fryirs and Brierley, 2013). Therefore, an analysis based only on total catchment land cover and/or geology and their influence on erosion may overestimate sediment loads (Figure 1).

Finally, once the fine sediment is delivered to the river, it will either be transported downstream as SS or deposited locally, mostly depending on the grain size of the sediment particles and the energy of the stream flow (i.e. the capacity of the river to transport fine sediments). SS can be deposited as a result of a drop in stream velocity and turbulence that both keep sediment suspended, resulting in a decrease in the capacity of the river to transport SS. Examples are the development of debris fans at a junction of a tributary with a high SS flux and the main river characterized by low stream velocities, or deposition in rivers where the channel morphology suddenly changes causing a drop in velocity (Harvey, 2002).

2.3 Temporal variability in suspended sediment transport

In this section, we outline how temporal variability in SS transport at a given location adds to the spatial complexity of SS transport described in Section 2.2 (Fryirs, 2013). The temporal variability in SS transport at a particular point in the river, otherwise called the sediment regime, is determined by the interaction of various catchment-scale drivers (Grove et al., 2015; Thompson et al., 2013), which can be classified into four main, but often strongly interlinked, categories: (i) hydro-meteorological factors (ii) sediment source variations; (iii) natural landscape disturbances; and (iv) human interventions (Figure 1).

First, hydro-meteorological conditions are dominant drivers of SS transport processes, both on long and short timescales (Horowitz et al., 2014). Precipitation and subsequent overland flow are the main agents of soil erosion and sediment transport (Perks et al., 2015; Yellen et al., 2014). Therefore, different parameters such as total discharge, peak discharge, water yield, time of rise and fall of hydrograph, total duration of a precipitation event, maximum 30-minute rainfall, mean rainfall intensity and antecedent rainfall are commonly included in models to estimate sediment transfer from the catchment to the river (e.g. Dominic et al., 2015; Duvert et al., 2010; Fang et al., 2015; Onderka et al., 2012; Seeger et al., 2004; Tena et al., 2014). In addition, snowmelt has been shown to be a dominant driver for SS transport in many parts of the world (e.g. Lana-Renault et al., 2011; Le et al., 2006; López-Tarazón and Batalla, 2014; Praskievicz, 2014). For example, in a small catchment in the subalpine belt of the Central Spanish Pyrenees, discharge and SS transport during a snowmelt period accounted for up to 50% and 60% of the respective annual values, while precipitation during this period only represented 10-13% of the annual precipitation (Lana-Renault et al., 2011).

Second, SS transport will vary as a result of changes in the dominant sediment source(s). Sediment source variations are often the result of interactions between catchment characteristics and hydro-meteorological processes, causing complex feedback mechanisms and threshold behavior (Onderka et al., 2012). Changes in vegetation cover (e.g. due to crop rotation or natural seasonal variations) can cause a shift in the dominant sediment source to the river (Belmont et al., 2011; Rovira et al., 2015; Sun et al., 2015). Furthermore, erosion hotspots such as gullies can form on fields during storm events, causing an increased contribution of sediment from a specific source. Finally, during individual precipitation events, the sediment supply from a particular source can become exhausted or diluted during persistent high discharges, or other sediment sources might become more connected to the river over time (Fan et al., 2012; Francke et al., 2014; Martínez-Carreras et al., 2010; Poulenard et al., 2012).

Third, large scale natural landscape disturbances such as mass movements and wildfires can have a significant impact on SS supply and transport in rivers over short and long term timescales. Similar to sediment source variations, complex feedback mechanisms are caused by interactions between landscape disturbances and other drivers (Owens et al., 2013). Changes in hillslope and/or river connectivity due to landslides can cause a shift in the dominant sediment source. Furthermore, landslides can either be the result of hydro-meteorological conditions (e.g. induced by typhoons (Chang et al., 2015)) or can induced by other landscape disturbances (e.g. earthquakes (Vanmaercke et al., 2016; Wang et al., 2015)). Likewise, wildfires are often considered as a factor causing an increase in SS transport. However, recent studies show that the effect of wildfires strongly depends on the specific impact of the fire and often only creates the conditions for increased soil erosion, whereby the specific hydro-meteorological conditions during recovery of the vegetation are mainly driving any changes in SS transport (Owens et al., 2013; Prosser and Williams, 1998).

Finally, SS concentrations can also be affected by human intervention. Although human intervention can cause short-term variations in SS concentration (i.e. during road construction works), most of these interventions are manifest in the sediment concentrations and loads over extended periods of time, which are called ‘legacy effects’ (Wohl, 2015). Reduction of sediment transport and deposition can occur when there is less sediment input caused by, for example, the construction of dams and reservoirs, changes to the channel dimensions due to flood alleviation schemes or by soil and water conservation measures. Increase in sediment loads can result from a greater sediment supply, e.g. as a result of soil erosion due to intensification of land use, mining and mineral exploitation or construction works (Fan et al., 2012; Fuchs et al., 2011; Gao et al., 2015; Mohr et al., 2014; Sun et al., 2015; Zhang et al., 2009).

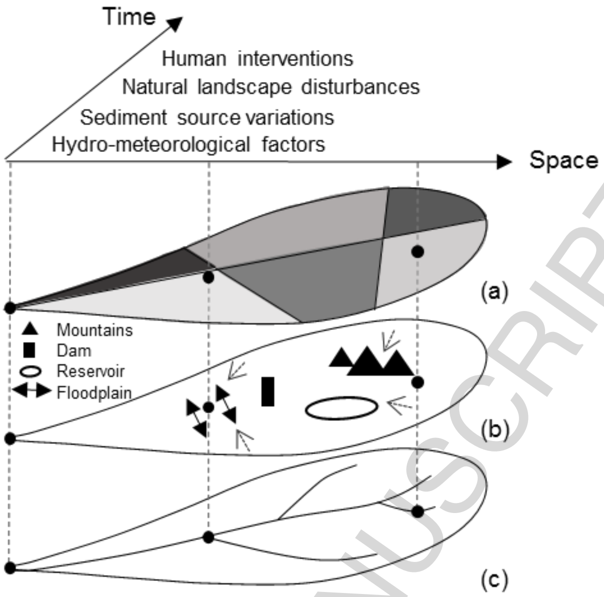

Figure 1: Visualization of the driving factors underlying SS transport at the catchment-scale. SS transport vary: (i) spatially depending on the interactions between (a) catchment characteristics (e.g. geology, land use, climate, topography), (b) catchment connectivity influenced by blockages, and (c) river transport capacity; and (ii) temporally depending on the interaction between hydro-meteorological factors, sediment source variations, natural landscape disturbances and human interventions.

2.4 Conclusions: spatiotemporal complexity of SS transport

SS transport in rivers is highly non-linear in time and space, and is often characterized by threshold behavior and feedback mechanisms (Bracken et al., 2015; Onderka et al., 2012). The non-linear nature of soil erosion and transport of sediment at the catchment-scale results in spatiotemporal variations in sediment generation, transfer to the channel and transport through the river network. A point upstream in the catchment may be characterized by entirely different SS dynamics compared to the catchment outlet. These differences are especially marked in catchments with variable erosion rates due to mixed land use (e.g. urban, agriculture, grassland and woodland) or a heterogeneous topography and lithology (Zeiger and Hubbart, 2016). Furthermore, a single point in the river is often characterized by a changing sediment regime over multiple timescales caused by variations in the sediment and/or water supply over time resulting in a sediment deficit or surplus. Due to complex interactions between the different factors driving SS transport, it is often difficult to identify the dominant driver, especially when considering multiple timescales. To develop frameworks with improved spatiotemporal resolution that specify provenance and changes in SS transport along the sediment cascade (Fryirs, 2013, p. 31), comprehensive understanding is required of the capabilities and limitations of the common approaches to quantify SS transport and sources over multiple timescales.

3. Empirical approaches to analyze suspended sediment transport and sources

A range of empirical models are used to analyze and quantify SS loads and sources in rivers and evaluate the importance of different drivers (Bilotta et al., 2012; Collins and Walling, 2004; Gao, 2008). While individually these models are useful for expressing SS transport for the process and scale under question, they typically address specific parts of the sediment cascade and are relevant to particular timescales. Therefore the results of different methods are difficult to interpret in terms of drivers and processes underlying SS transport operating over multiple timescales. In the following section, four main empirical approaches are discussed: (i) sediment rating curves; (ii) hysteresis models; (iii) multivariate data-mining techniques; and (iv) sediment fingerprinting. For each approach, the main limitations and challenges are discussed, with special focus on how each deals with temporal variability in SS transport.

3.1 Sediment rating curves

The approach

One of the most commonly used approaches to estimate SS loads over time is to establish a relationship between discharge and SS concentration, i.e. sediment rating curves. In this approach, discharge is considered a proxy variable that represents the sum of all processes controlling soil (and sediment) erosion and transport to and within the river (Asselman, 2000; Horowitz, 2003). Generally sediment rating curves are represented by a power function of the following form: $S = aQ^b$, where S is the SS concentration (mg/l) and Q the river discharge (m^3/s) and a and b are regression coefficients. Sediment rating curves from different rivers demonstrate varying relationships between discharge and SS concentration over different orders of magnitude, depending on the location, as indicated in Section 2.2 (Figure 2). Sediment rating curves are popular because they are fairly simple to construct and they can be established with a discrete and relatively small dataset (Horowitz et al., 2014). In the case where only a few sediment samples are available, turbidity (calibrated with SS concentration data) can be used as a proxy variable for SS concentration to develop sediment rating curves (Bilotta and Brazier, 2008; Gao, 2008).

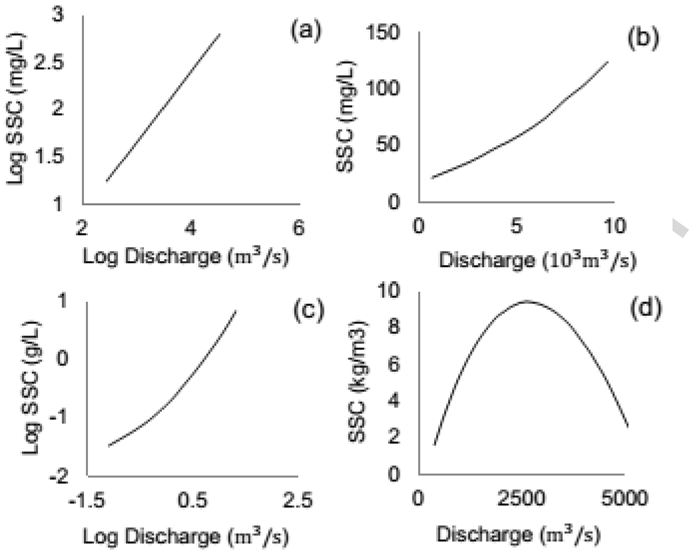

Figure 2: Examples of sediment rating curves between suspended sediment concentration (SSC) and discharge for (a) the Broad River, Georgia, USA, using linear regression (modified from Horowitz, 2003), (b) a tributary of the River Rhine, Germany, using nonlinear least squares regression (modified from Asselman, 2000) (c) the Celone River, Italy, using second-order polynomial regression (July 2010-July 2011) (modified from De Girolamo et al., 2015), (d) the Ningxia-Inner Mongolia reaches of the Yellow River using third-order polynomial regression (1969-1986) (modified from Fan et al., 2012)

Accounting for temporal variability

With the sediment rating curve approach, the relationship between SS concentration and discharge is represented by univariate mathematical formulations. However, univariate relationships do not account for the variable drivers behind SS transport (Dean et al., 2016; Kisi, 2004; Onderka et al., 2012). In other words, the method is not sufficient to explain the scatter around the relationship between SS concentration and discharge which is caused by the spatiotemporal complexity of erosion and sediment transport processes (Asselman, 2000; Horowitz, 2003; Kisi, 2004; Onderka et al., 2012; Smith and Blake, 2014).

Furthermore, the statistical approaches used in sediment rating curves can lead to considerable uncertainties with regards to time. For example, Horowitz (2008) showed that sediment rating curves tend to underestimate high and overestimate low SS concentrations because high flows are generally less common than low flows, while regression techniques tend to reduce the importance of outliers. Horowitz et al. (2014) evaluated the effects of sample numbers and sampling scheduling on the precision and accuracy of annual SS load estimations based on daily SS data from monitoring stations in the USA. Their study demonstrates that instead of sampling at fixed points in time, hydrology-based sampling (i.e. sampling during high-flow events) is the most accurate method to estimate annual SS loads with the fewest number of samples. Asselman (2000) showed that rating curves fitted by least squares regression on logarithmically transformed data underestimate long-term sediment transport rates by 10-50%. This is because sediment rating curves do not account for the scatter along the regression line caused by events with high sediment concentrations. Finally, as discussed in Section 2, the relationship between discharge and SS concentration is dynamic in nature, depending on the interaction of multiple drivers across timescales (Horowitz 2008; Tena et al. 2014). These findings imply that previously established sediment rating curves may not be representative when major changes in the river and/or catchment characteristics occur, such as the construction of dams or changes in land cover. Sediment rating curves need to be updated regularly and interpreted with caution when estimating annual SS loads. Furthermore, they are only valid for a particular timescale, depending on the data used to construct the rating curve (Bezak et al., 2016; De Girolamo et al., 2015; Francke et al., 2014; Horowitz, 2008).

Methodological challenges

Although they are the most commonly used method to estimate sediment loads at a specific location, sediment rating curves have some methodological limitations. An appropriate regression model needs to be chosen and fitted to the data. There is no consensus as to the most appropriate regression technique and the final choice mostly depends on the observed data. Most common methods are linear least squares regressions performed on log-transformed data (Figure 2a). Several studies have developed alternative approaches to construct sediment rating curves such as nonlinear least squares regression (Asselman, 2000) (Figure 2b-d) and generalized linear models (Cox et al., 2008). Furthermore, other studies subdivide calibration data into groups related to seasonality, hydrology or flood limbs to improve the outputs (Eder et al., 2010; Fang et al., 2015). As a result, studies are highly inconsistent (and difficult to interpret) in terms of the relationship between discharge and sediment dynamics (Sun et al., 2015).

3.2 Hysteresis models

The approach

Various interactions at the catchment scale between factors described in Section 2 often result in hysteresis patterns between the SS concentration and discharge, as represented in the sediment rating curve (e.g. Duvert et al., 2010; Lloyd et al., 2016; Sun et al., 2015; Tananaev, 2015). The most common patterns are anti-clockwise and clock-wise loops (Figure 3) (Horowitz et al., 2014; Williams, 1989). More complex hysteresis patterns have also been observed, such as a single line plus a loop and figure-eight patterns (Sun et al., 2015). The analysis of hysteresis patterns can provide useful insights into the presence of feedback mechanisms and thresholds determining SS transport (Eder et al., 2010; Krueger et al., 2009). While hysteresis patterns are commonly used to express SS dynamics at the event-based scale, they can also be used to visualize seasonal variations in the relationship between SS concentration and discharge (Sun et al., 2015).

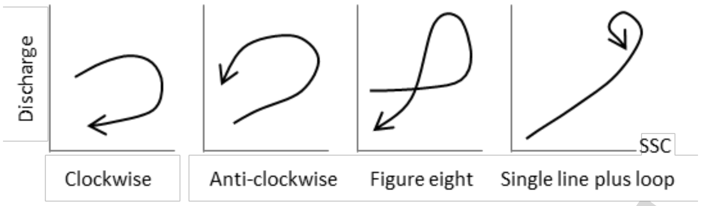

Figure 3: Hysteresis patterns between discharge and suspended sediment concentration (SSC)

Accounting for temporal variability

Hysteresis patterns express the temporal variability in SS concentration and emphasize the context-specificity of the observed processes. Krueger et al. (2009) developed empirical models of sediment event dynamics from observations at high temporal resolution in a drained and undrained, intensive grassland, field-scale experiment. Instead of a simple power law (as in the sediment ratings curve technique), an additional factor is added to account for the rate of change of river discharge: $S = aQ^b + c\ dQ/dt$, where S is the SS concentration, Q the river discharge and dQ/dt is the slope of the hydrograph. Their results showed that the model performed well in simulating small hysteresis loops, but could not account for the exhaustion of sediment sources due to the variability in sediment transport dynamics (Krueger et al., 2009). Eder et al. (2010) tested four methods to calculate instantaneous sediment concentrations in an agricultural catchment in Austria. They conclude that both general rating curves and event-specific rating curves result in considerable scatter for event specific sediment concentrations and total sediment loads. The inclusion of parameters related to the rate of change of the discharge to account for hysteresis effects, resulted in improved estimations with 0-1% deviation from the measured SS concentrations. However, the model proved to be unsuitable for high numbers of data points and for complex hysteresis patterns comprising multiple discharge and sediment peaks (Eder et al., 2010).

Methodological challenges

The main challenge related to the analysis of hysteresis patterns is their interpretation, which is strongly context driven and not straightforward (i.e. two similar hysteresis patterns can be the result of the interaction of different drivers or different timescales) (Fan et al., 2012; Smith and Blake, 2014; Smith and Dragovich, 2009). To address these issues, Smith and Dragovich (2009) developed a quantitative method to compare hysteresis patterns between nested catchments (i.e. sub-catchment versus entire catchment). The aim was to facilitate the interpretation of these patterns in terms of erosion and sediment transport processes across spatial scales. It was reasoned that similarity in response to particular rainfall and flow events might reflect spatial uniformity in the observed hysteresis patterns and the corresponding erosion processes and/or proportional sediment source contributions. Towards this end, a dimensionless ‘similarity function’ was developed, based on individual line lengths and angles formed between SS concentrations and discharge data for each sampling time (Smith and

Dragovich, 2009). Similarity in hysteresis patterns seemed to reflect uniform rainfall patterns, resulting in erosion and transport processes occurring both at the sub-catchment and catchment scale. In addition, the similarity function could also reflect consistency in the dominant sediment sources (Smith and Dragovich, 2009). Contrarily, small, local events appeared to result in less or no similarity between hysteresis patterns, indicating less uniformity in erosion and transport processes. Despite the possibilities this approach offers, its applicability is spatially limited due to strong variability in the dominant erosion and transport processes and thus variations in sediment sources (Smith and Dragovich, 2009).

3.3 Multivariate data-mining techniques

The approach

The heterogeneity of sediment transport processes in time and space require other methods besides sediment rating curves and hysteresis models to represent SS dynamics and to identify the main factors controlling them (Francke et al., 2014; Onderka et al., 2012). The increasing volume of environmental data has created opportunities to develop alternative approaches based on data-mining techniques to estimate SS concentrations at a high temporal resolution. Data-mining techniques in this context represent a range of multivariate data-analysis methods to establish relationships between SS concentration and a set of variables. For example, quantile regression forests (Francke et al., 2008; Zimmermann et al., 2012), fuzzy logic (Kisi, 2005; Lohani et al., 2007), M5′ model trees (Onderka et al., 2012), artificial neural networks (Cobaner et al., 2009), and Stepwise Multiple Discriminant Analysis (MDA) (Bilotta et al., 2012) have all been used successfully to estimate SS concentrations in various contexts. Other studies have performed more simple correlation matrices and principal component analyses (PCA) to examine the importance of different drivers that regulate SS transport (e.g. Dominic et al., 2015; Perks et al., 2015; Seeger et al., 2004; Tena et al., 2014).

Accounting for temporal variability

Over the last decade, a range of different studies have demonstrated the capability of data-mining techniques to account for the temporal variability in SS concentrations and loads, including the importance of multiple drivers of the processes involved. Numerous examples indicate that SS transport is often strongly driven by a set of catchment-specific drivers. For example, a data-driven model based on Quantile Regression Forests to estimate monthly SS loads was developed by Francke et al. (2014) for the Isabena catchment in Spain. The model included factors such as the rate of change of discharge, rainfall energy and the day of the year to account for sediment supply variations and antecedent conditions. Their results demonstrate that the variables with the most predictive power depend on the time and location, indicating the importance of local processes. Onderka et al. (2012) developed a modular data-driven model (M5’ model trees) to simulate intra-event SS concentrations in response to a range of controlling variables in a headwater catchment in Luxembourg. Hydro-meteorological variables were included in the model, as identified in Section 2.2, which defined conditions prior to and during events. Their results show that antecedent hydro-meteorological conditions are the main drivers for the amount of SS during storm events (Onderka et al., 2012). Grove et al (2015) used an MDA model based on a set of hydro-meteorological and catchment variables to predict mean annual SS concentrations based on 15 minute turbidity data collected over two years for ten reference-condition stream/river sites. They found that the mean annual SS concentration was significantly different for all the sites between the two observed years, and that this variability could be predicted reasonably well using the MDA model. Perks et al. (2015) performed a factor analysis on a range of environmental variables representing the fluvial and wider catchment conditions prior to, and during, hydrological events for grassland dominated headwater catchments. Their results also show that complex hysteresis patterns are mainly driven by antecedent hydro-meteorological conditions. Zeiger and Hubbart (2016) performed multiple linear regression analyses on a four-year SS dataset in Hinkson Creek Watershed in the Lower Missouri Mississippi River Basin, USA. They conclude that annual sediment loads are significantly correlated with total annual precipitation, but also with land use (Zeiger and Hubbart, 2016). Finally, Cobaner et al. (2009) used neuro-fuzzy computing techniques and artificial neural networks to predict SS concentrations in the River Mad catchment, USA. Similar to the conclusions in other studies, their study demonstrates that data-driven models containing hydro-meteorological data perform better in predicting SS concentrations compared to sediment rating curves.

Methodological challenges

The main limitation towards extensive use of data-mining techniques in the context of SS transport is the availability of sufficiently large (continuous) datasets of SS concentrations and other variables, over multiple timescales. Continuous sediment data (as well as data on catchment-scale variables that drive SS transport) in time and space are often scarce and collected with a range of different methods, that may not be comparable or consistent (Kettner et al., 2007; Rovira et al., 2015; Vanmaercke et al., 2011). Furthermore, large datasets require the use of complex data management techniques and advanced computational skills. As a result, many computational techniques tend to be ‘black-box’ in approach, which makes them less transparent and flexible compared to simple sediment rating curves (Kisi, 2004).

3.4 Sediment fingerprinting

The approach

A final empirical approach to gain insights into SS dynamics is to compare temporal variations in sediment source contributions to the total sediment load in the river (Brosinsky et al., 2014b; Carter et al., 2003; Cooper et al., 2014a; Fang et al., 2015; Poulenard et al., 2009). Fryirs (2013) noted that information on the preferential delivery of certain sources of sediment and the loss of other sources should be taken into account when assessing sediment delivery within a catchment, because sediment sources may vary between and during high flow events. Knowledge of sediment source variations can provide the necessary information to formulate more conclusive statements about factors driving the variations in SS transport. One approach to retrieve this kind of information is by sediment fingerprinting.

Generally, the interactions between geology, climate, hydrology, land cover, weathering processes and anthropogenic activities define the composition of soil and sediment (Koiter et al., 2013b). Sediment from a particular source can therefore be characterized by a "fingerprint", i.e. a combination of biogeochemical and/or physically-based properties specific to their origin within the river catchment. It is assumed that these properties behave conservatively (meaning that they do not change with time) and thus allow a direct comparison between the primary source material and the SS (Koiter et al., 2013b; Walling, 2013). The fingerprints are used to develop statistical models to estimate the relative contributions of sediment sources to the SS (Davis et al., 2009; Walling, 2013).

Accounting for temporal variability

Since the 1970s, sediment fingerprinting has been successfully applied as a tool to gain insights into sediment dynamics at a river basin scale in catchments all over the world (Mukundan et al., 2012). Despite its widespread use, most studies report the dominant sediment source, but do not consider possible source variations over time (e.g. Vale et al., 2016). However, recent sediment fingerprinting studies have demonstrated significant variations in sediment sources on a decadal scale (e.g. Belmont et al., 2011; Chen et al., 2016) and during individual events (e.g. Cooper et al., 2014a; Evrard et al., 2013; Poulenard et al., 2012). Therefore, applying sediment fingerprinting on multiple timescales can provide information on possible variations and shifts in the dominant sediment source over short to long term timescales, which can help to better understand the interactions between the factors underlying SS transport.

Methodological challenges

When applying sediment fingerprinting to provide insights into the spatial and temporal complexities of SS transport, there are three major challenges. The first one is accounting for sediment pathways from source to sink. As indicated in Section 2, materials can be eroded and subsequently deposited before they finally reach the river (Cooper et al., 2014a; Vale et al., 2016). In sediment fingerprinting, only the primary sediment source is identified, without providing information about sediment transport rates and the complexity of the pathways (i.e. locations and duration of intermediate sediment storage in the catchment and in the river) (Cooper et al., 2014a; Koiter et al., 2013b; Poulenard et al., 2009). This problem is clearly illustrated by a hydromorphological assessment study of the River Frome (UK) (Grabowski and Gurnell, 2016). Previous studies showed that erosion from agriculture was the dominant sediment source in the River Frome, while changes in the river planform over time suggest that this contribution could be dated back to the post-WWII agricultural expansion in the UK. While the use of fallout radionuclides in sediment fingerprinting has helped to assess the time passed since the sediment eroded (residence time) (e.g. Palazón et al., 2015; Smith and Blake, 2014; Wilkinson et al., 2015), it remains a challenge to interpret patterns in sediment source contributions in terms of catchment erosion processes.

Second, some geochemical sediment properties (even though considered conservative) significantly change as a result of variability in particle size distribution and organic matter content, as well as biological, geochemical and physical transformations over multiple scales during sediment generation and transport in the catchment and in the river (Koiter et al., 2013b; Smith and Blake, 2014). Therefore, caution needs to be taken when identifying the sources of sediment based on geochemical properties.

Finally, traditional sediment fingerprinting approaches based on geochemical analysis techniques are very time- and cost-consuming, limiting the use of the technique at a high temporal resolution (Brosinsky et al., 2014a; Cooper et al., 2014a; Poulenard et al., 2012). Recently, studies have demonstrated the promise of spectral reflectance-based (visible and (near) infrared) fingerprinting methods as a quicker and less costly alternative for sediment source apportionment, with considerable potential to expand the temporal resolution of sediment fingerprinting analyses during high-flow events (e.g. Cooper et al., 2014a, 2014b; Evrard et al., 2013; Martínez-Carreras et al., 2010; Poulenard et al., 2009; Tiecher et al., 2015).

3.5 Conclusions: analyzing and quantifying SS transport over multiple timescales

Different empirical methods exist to analyze and quantify sediment sources and SS transport dynamics over multiple timescales, ranging from simple sediment rating curves to more complex approaches that can assess the relative importance of various drivers. In summary, sediment rating curves are an appropriate method to provide a first explorative characterization of the sediment regime of a river (i.e. to estimate sediment loads over a certain period), but they are not sufficient to capture the temporal variation caused by the interactions of drivers and feedback mechanisms. By including additional catchment-scale variables, multivariate methods are better able to represent the multiple interactions between hydrological and geomorphological processes that drive temporal variation in SS transport, especially at short to medium timescales (i.e. individual high flow events to seasonal). Sediment fingerprinting is a complementary method to provide information on sediment source variations over multiple timescales. However, given the high spatiotemporal complexity of SS dynamics, interpretation of the results of different methods in terms of drivers over multiple timescales and the selection of appropriate methods remains challenging.

4. Interpretation of suspended sediment transport dynamics

While a wide range of empirical techniques have been used to analyze and quantify SS concentrations and loads, the majority of studies have applied these techniques to a single timescale, generating a snapshot of sediment transport with which they deduce variations in the drivers of SS transport. The problem is that the quantification of sediment concentrations and loads and their variability over time is dependent on the scale at which the system is studied (Horowitz et al., 2014). If data are collected at a resolution appropriate for analysis for a single timescale, it limits *a priori* the potential to identify the explanatory factors driving SS transport (Cao et al., 2007; Sun et al., 2015; Zheng et al., 2012). While this is not a problem if the study is interested in a single timescale (for example, land cover change at a decadal scale and the resultant changes in sediment loads), it makes it difficult to investigate the process interactions and feedbacks between different drivers across timescales. A lack of understanding of these drivers and interactions makes the accurate prediction of sediment concentrations or loads at management-relevant timescales an impossible goal at present (Cao et al., 2007; Harvey, 2002). To illustrate how timescale could affect our understanding of processes, examples of SS transport studies from around the world are presented and their results interpreted at three different timescales in this section (Figure 4). Furthermore, we demonstrate how the combination of different methods presented in Section 3 provides better insights into multiple drivers of SS transport and their mutual interactions.

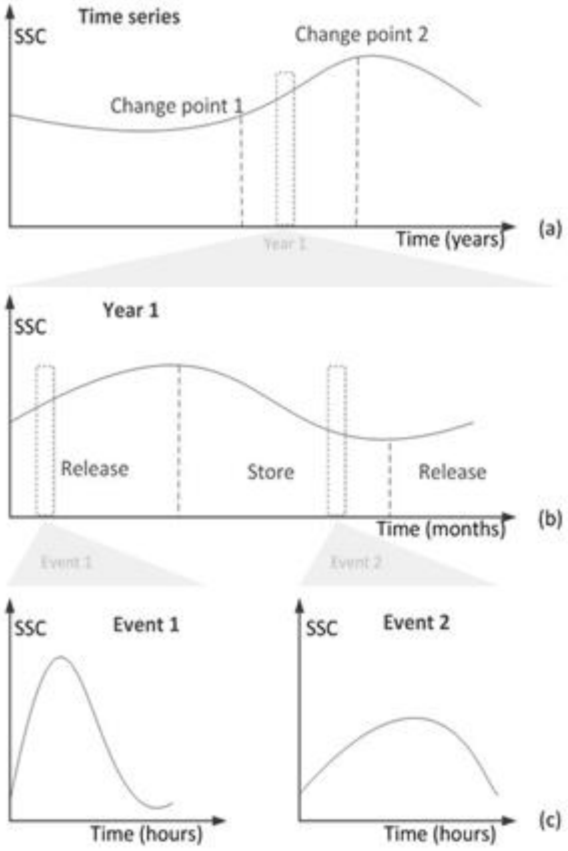

Figure 4: Temporal scales of suspended sediment concentration (SSC) in rivers; (a) inter-annual: indicating change points and/or trends defined as a result of drastic changes in one or more of the drivers, (b) seasonal: indicating the capacity of the catchment to store sediments, and (c) event-based dynamics: indicating the impact of individual events and feedback mechanisms.

4.1 Inter-annual variation

Suspended sediment loads vary over long timescales (i.e. decades and centuries) due to natural and anthropogenic forces. Long term SS dynamics can therefore indicate change points and/or trends in water and/or sediment supply in the catchment. Change points are abrupt alterations in the sediment regime caused by drastic changes in one or more of the drivers that affect sediment production and transport (Huang et al., 2013; Wohl, 2015). Therefore, assessing long-term sediment regime alterations not only provides insights into the impact of climatic changes on discharge and corresponding sediment loads, but also into the impact of human interventions (Fan et al., 2012; Francke et al., 2008; Horowitz, 2008; Smith and Blake, 2014; Stone et al., 2015; Sun et al., 2015).

Drivers

As discussed in Section 2.2, hydro-meteorological factors such as rainfall and river discharge are major drivers of SS transport. Over long timescales, discharge or water yield (i.e. amount of water per unit of time) is often a good predictor of mean sediment loads (Horowitz, 2008; Rovira et al., 2015). Changes in rainfall patterns and amounts (e.g. as associated with climate change) can cause significant changes in long-term SS loads (Kettner et al., 2007; Rovira et al., 2015; Walling, 2009). Furthermore, a shift in sediment source(s) can cause variable sediment loads under similar (constant) hydro-meteorological conditions. Land cover changes (e.g. conversion of forested land to arable agriculture) and catchment connectivity changes (e.g. as a result of tectonic activity or mass movements) can cause a (permanent) shift in the sediment supply (Bracken et al., 2015; Foerster et al., 2014; Fryirs, 2013). In addition, human interventions along the river network such as dam construction, flood alleviation schemes and soil and water conservation techniques can cause long-term legacy effects on the sediment supply to the river and/or the sediment transport capacity of the river (Chen et al., 2016; Rovira et al., 2015; Sun et al., 2015; Verstraeten et al., 2002; Wohl, 2015).

Interpretation

The impact of dam construction on SS transport has been well documented for several rivers, and provides a good example of legacy effects on long-term patterns. For example, Huang et al. (2013) assessed alterations in the sediment load in the upper Yangtze River in China between 1950 and 2008. Two change points were identified in 1986 and 2003 (Figure 5a). The decrease in the sediment load after 1986 was attributed to a set of dams constructed in the tributaries and the Gezhouba Dam in the main river, upstream of the monitoring site. In addition, land cover changes may have played a contributing role in changing the sediment regime, as grassland areas increased to cover more than 50% of the catchment. The further decrease in SS load after 2003 was mainly attributed to the construction of the Three Gorges Reservoir, which traps large amounts of sediment in the reservoir (Huang et al., 2013). Similarly, Fan et al. (2012) showed that dam construction along the Ningxia-Inner Mongolia reaches of the Upper Yellow River played an important role in the long-term decrease in SS concentration between 1952 and 1968.

However, clear trends and/or change points are not always present, especially when different factors operate simultaneously, and the interpretation of the observed patterns becomes less straightforward. Sun et al. (2015) analyzed SS dynamics in the Loushui River in South-Central China from 1966 to 1985 and 2007 to 2011. They found that the SS-discharge relationship changed considerably between decades, with no clear change points or trends (Figure 5b). Instead, four stages were identified with a sharp rise in SS load between 1966 and 1970, a slow decrease in 1971-1978, a strong increase in 1979-1985 and again a decrease after 2007. No overall explanation was given, but the change was attributed to climate (rainfall pattern and intensity) and human interventions (mining, forest cutting and road construction works). A case where the effect of dam construction on the sediment load is muted by other factors is given by Geeraert et al. (2015) for the Tana River (Kenya). Analysis of monitored SS data in combination with historical data suggests that upland dam construction in the 1960s and 1980s decreased the SS concentration just downstream of the dams, but did not greatly affect the annual sediment load in the lower Tana River. The authors hypothesize that autogenic processes, namely river bed dynamics and bank erosion downstream of the dams, mobilize large quantities of sediment stored in the alluvial plain, and thus overwhelm any possible changes caused by the dams in the lower reaches of the river (Geeraert et al., 2015).

In the previous examples, water yields and other hydro-meteorological variables are not always sufficient to explain the variation in SS transport. Additional information about the impact of different drivers is required to interpret the observed patterns correctly. One way of obtaining more information is by sediment fingerprinting as discussed in Section 3.4. Chen et al. (2016) used sediment fingerprinting to assess the impact of land use changes in the Green-for-Green Project in the Loess Plateau of China, a nationwide conservation program launched in 1999 involving reforestation to reduce soil erosion in cropland. Their results, based on deposited sediment cores, showed that as the planted forest matured with time, the sediment contribution from those catchments steadily decreased. The gradual shift is attributed to changes in soil characteristics and surface hydrological response over time; the previously cultivated soils have developed vertical structure that facilitates infiltration and have become covered by several layers of leaves, protecting the soil against erosion (Chen et al., 2016). Another study by Belmont et al. (2011) used sediment fingerprinting and geomorphic change detection techniques to characterize the sediment regime in Lake Pepin on the Mississippi River over the previous 150 years. Other studies in the area have shown that the sediment supply increased 10-fold during this period, but the combination of approaches used in Belmont et al.'s study allowed the authors to identify the drivers that are likely to be responsible for this increase. The sediment fingerprinting analysis indicated that the dominant sediment source shifted from agricultural soil erosion to erosion of stream banks, and the geomorphic analysis linked the accelerated erosion of streambanks to a combination of changes in precipitation and large scale changes to the drainage network (e.g. installation of agricultural ditches and subsurface tile drains) (Belmont et al., 2011). In addition, by analyzing sediment cores of deposited sediment, historic SS yields can be reconstructed and combined with sediment fingerprinting to assess the impact of different drivers. Walling et al. (2003) used sediment cores from small lakes and reservoirs to reconstruct SS yields and sources in the catchments of the Rivers Ouse and Tweed in the UK over the last 100-150 years. Their findings suggest that there was considerable temporal variability in the SS load throughout this period. The reconstructed SS load and sources were explained by major changes in land use and management (e.g. afforestation, conversion from pasture to arable), and the changes did not show a significant correlation with climate change (Walling et al., 2003). Similarly, a study from the Waipaoa River system in New Zealand used sediment cores in combination with a hydrological model to construct SS transport during the last 3000 years. The study shows that historic land use changes had a profound impact on the SS load in the rivers, inducing a permanent shift in the sediment regime, while the climatic impact was more muted and restricted to individual events (Kettner et al., 2007).

In conclusion, long-term observations are essential to demonstrate the interactions between the catchment and the river (Gao et al., 2013). Long term data on sediment loads can indicate change points and/or trends within the catchment. However, the interpretation of the patterns is not straightforward and requires additional information such as sediment source contributions and insights into the interactions of drivers to make definitive conclusions about the dominant factors driving SS transport on the long term.

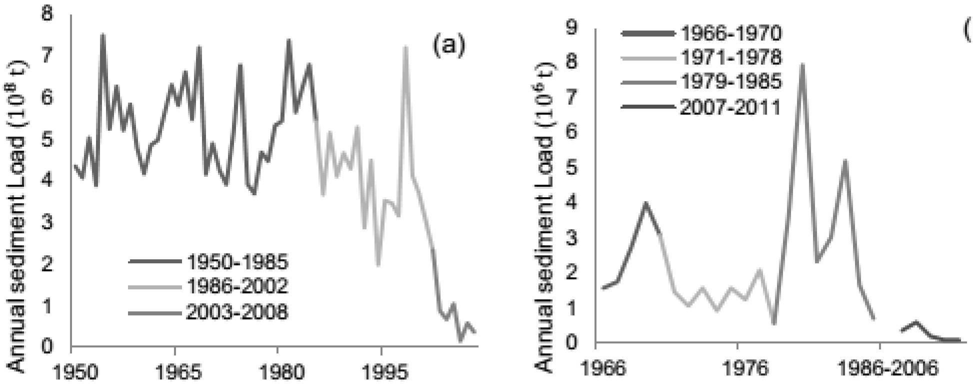

Figure 5: Annual sediment loads indicating (a) three change points in the upper Yangtze River, China (modified from Huang et al., 2013) and (b) more complex patterns in the Loushui River, China (modified from Sun et al., 2015)

4.2 Seasonal variation

In most regions of the world, sediment loads vary significantly throughout the year. This variability is often related to seasonal patterns in rainfall, snowmelt and storm events, but precipitation events of similar magnitudes during different times of the year can also result in different sediment-discharge relationships, suggesting a more complex set of drivers and interactions (Lloyd et al., 2016). Therefore, understanding the behavior of the catchment in terms of sediment generation and storage is crucial to assess the annual cycling of SS transport, which is especially important for the development of targeted soil and water conservation strategies.

Drivers

As discussed in Section 2, interactions between land use, rainfall patterns, soil moisture and hydrology cause variations in SS transport. Especially on a seasonal scale, changes in rainfall and hydrology across the year often cause marked variations in SS transport in rivers, for which the impact is often magnified by land cover changes in both natural (e.g. loss of leaf cover in a deciduous forest during winter) and agricultural systems (e.g. bare soil due to cropping patterns). For example in the lower Ebro River in Spain, a Pearson correlation matrix and PCA was performed on different variables to explain SS dynamics during flushing flows (i.e. controlled water releases). The results showed that the dominant drivers considerably varied according to season and the location within the catchment (Tena et al., 2014). Furthermore, in (sub)tropical catchments, there is often a marked difference between factors controlling SS transport in the dry seasons compared to the wet seasons (Dominic et al., 2015; Franz et al., 2014; Omengo et al., 2016). A PCA applied in two tropical sub-catchments of the Klang River (Malaysia) shows that total rainfall and rainfall intensity are strongly related to SS hysteresis patterns in the dry season, while soil moisture plays a more important role in determining SS hysteresis patterns during the wet season (Dominic et al., 2015). Finally, episodic events on a seasonal basis such as snowmelt are also important in causing variation in SS transport (Lana-Renault et al., 2011).

Interpretation

The interactions between drivers result in different patterns in SS transport, which have been visualized in changing hysteresis patterns over the course of the year. For example, Alexandrov et al. (2007) studied SS concentrations during flood events between 1991 and 2001 in the semi-arid northern Negev, Israel. The authors demonstrated that high intensity, convective rain storms during autumn and spring flush out sediment within the channel at the start of the event, resulting in clockwise hysteresis patterns. On the other hand, frontal storms common in winter generally produce anti-clockwise or no hysteresis patterns, with no signs of sediment flushing.

Besides different responses during individual events across the year, larger seasonal patterns in SS transport can also be observed that provide better insights into the cycling of sediment production and transport. Sun et al. (2015) showed that SS loads in the Loushui River in China are highest in summer, indicating that sediment produced by erosion, weathering and human activities is stored during the dry winter and spring, while the sediment is released during the summer and early autumn floods (Figure 6a-b). A reverse pattern was demonstrated by another study on the Ebro River in Spain. It showed a clockwise loop in the SS loads at the seasonal scale, which demonstrates the flushing of sediment during the wetter months in autumn and the progressive exhaustion of the sediment supply throughout the winter until the sediment load is very low during the drier summer (Rovira et al., 2015) (Figure 6a-c). Similar conclusions were drawn from a study by Park and Latrubesse (2014) who used field measurements of SS concentrations in the Amazon River to calibrate MODIS data to model SS distribution patterns over space and time. The results of this study showed clear seasonal variability in SS concentrations in the main channel, with low concentrations during the peak to falling water stages (May to October) and high concentrations during the first half of the rainy season (Park and Latrubesse, 2014).

These findings can also be supported by the results of sediment fingerprinting studies. For example, a fingerprinting study based on fallout radionuclides performed in an agricultural catchment in Wisconsin (USA) by Huisman et al. (2013) revealed that upland areas were the dominant source of SS, whereby the SS during spring was found to be generated (eroded) more recently prior to mobilization compared to SS in the wetter autumn months. These results indicate the relative importance of bed sediment remobilization during periods when rainfall and discharges are higher (Huisman et al., 2013).

The above examples suggest that seasonal SS loads are an indication of the presence of store-release processes within the catchment, i.e. periods when sediment is produced due to weathering and erosion, and stored within the catchment, and periods when this sediment is then transported towards and within the river (Harvey, 2002; Sun et al., 2015). These conclusions provide a clear illustration of the interactions of drivers discussed in Section 2. Insights into seasonal SS dynamics are useful to assess the connectivity of the catchment and the capacity of the catchment to store sediments at different times of the year, which are both essential to develop adequate soil and water conservation strategies.

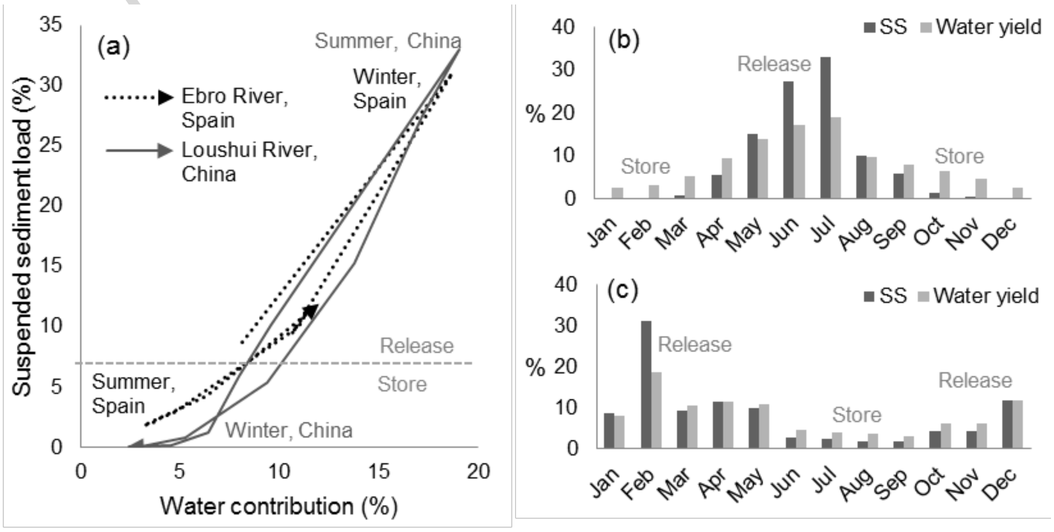

Figure 6: (a) Seasonal variation in suspended sediment and water contributions to the annual loads illustrating a phase of sediment build-up (storage) and a subsequent sediment release-phase for (b) the Loushui River in South-Central China (1966-2011) (modified from Sun et al., 2015); and (c) the Ebro River in Spain (modified from Rovira et al., 2015).

4.3 Event-based variation

In most cases, the sediment regime of a river is not characterized by a constant sediment supply, but rather by the episodic occurrence of rainfall events and/or snowmelt and subsequent high river flows. High-flow events generate a large proportion of the total annual SS load in rivers (Fang et al., 2015; Horowitz, 2009; Lloyd et al., 2016; Pulley et al., 2015). Consequently, disentangling the factors that drive event-based SS dynamics is essential to improve our understanding of longer term SS trends, the importance of episodic events on those trends, and the impact of SS on ecology, geomorphology and infrastructure.

Drivers

During a single rainfall event, there is considerable variation in SS concentration in the river, and these variations have been associated with numerous drivers (Lloyd et al., 2016; Smith and Blake, 2014). Compared to long-term patterns in SS transport, more specific hydro-meteorological factors need to be taken into account to explain the variations in SS transport during events. In recent data-mining studies, a range of significant variables have been identified, including antecedent rainfall, duration of the rainfall event, maximum rainfall over 30-minutes, mean rainfall intensity of the event, time of rise and fall of the hydrograph, runoff duration, peak discharge and total runoff (e.g. Dominic et al., 2015; Duvert et al., 2010; Fang et al., 2015; Perks et al., 2015; Seeger et al., 2004; Tena et al., 2014). Furthermore, the succession of multiple rainfall events has proved to be a good explaining factor for SS concentration (Onderka et al., 2012; Perks et al., 2015).

In addition, sediment sources can also change over short timescales. Persistent high discharge in the river can for example cause banks to collapse, resulting in a sudden increase in sediment supply (Carter et al., 2003; De Girolamo et al., 2015; Onderka et al., 2012; Yellen et al., 2014). Sudden connectivity changes within the catchment (e.g. by landslides or gully formation) can act both as a blockage to sediment movement or as an additional sediment source. Contrarily, sediment concentrations in the river can also decrease during an event when the sediment supply gets exhausted or when dilution occurs as a result of persistent high river discharges (Bracken et al., 2015; Croke et al., 2013; Fryirs, 2013). Finally, human activities can also have an impact on the SS concentration during events, especially in urban areas. For example, it is argued that street sweeping or reducing air pollution can limit the contribution of street dust to the sediment load in urban rivers (Marsalek and Viklander, 2010; Selbig et al., 2013; Taylor and Owens, 2009). However, little is known about the actual pathways of urban sediments to streams and the effect of mitigation strategies such as the frequency of street sweeping (Taylor and Owens, 2009).

Interpretation

Patterns in event-based SS transport are extremely difficult to interpret because of feedback mechanisms and interactions between multiple drivers. In general, clockwise hysteresis patterns are attributed to a fast response system (short distances between sediment source and receptor), because the peak in SS concentration typically precedes the maximum discharge of the event. Fast response systems are characterized by rapid sediment flushing and depletion in the river network, because of a limited supply of readily-available material for transport (De Girolamo et al., 2015; Fan et al., 2012; Fang et al., 2015; Francke et al., 2014; Sun et al., 2015; Tena et al., 2014). In contrast, anti-clockwise hysteresis patterns, in which the increase in sediment concentration is delayed, are typically explained by sediment being supplied from more distant sources (associated with extended travel times), channel bed erosion or prolonged erosion processes during extended storm events (De Girolamo et al., 2015; Fan et al., 2012; Fang et al., 2015; Francke et al., 2014; Sun et al., 2015; Tena et al., 2014). However, these general conclusions are by no means uniformly agreed upon.

Lag times between peak SS concentration and discharge have also been explained by spatial differences in rainfall pattern and intensity within the catchment (Poulenard et al., 2012; Smith and Blake, 2014; Sun et al., 2015). High intensity events and corresponding runoff generation generally lead to a rapid increase in sediment concentration (clockwise hysteresis patterns), while prolonged events result in the supply of more distant sources (anti-clockwise patterns) (De Girolamo et al., 2015). Furthermore, clockwise patterns have also been attributed to rainfall of long duration and low intensity, high total runoff and high initial soil moisture. In the latter case, the event is characterized by a first flush of nearby sediment sources, but then rainfall causes an increasing area of the catchment to contribute to the total sediment load, while nearby sources are exhausted (Eder et al., 2010).

The interaction of drivers and the importance of antecedent conditions becomes apparent when attempting to explain SS concentrations during events with more complex hysteresis patterns (Fan et al., 2012; Francke et al., 2014; Onderka et al., 2012; Poulenard et al., 2012; Smith and Blake, 2014; Sun et al., 2015; Tena et al., 2014). For example, a figure-eight pattern characterized by a clockwise loop at high discharges and an anti-clockwise loop at low discharges indicates that the sediment concentration continues to be high after an initial drop, while the discharge decreases. This type of pattern has been attributed to a second pulse of sediment input caused by, for example, bank failure or river bed erosion (Fan et al., 2012). A pattern defined by an anti-clockwise loop at high discharges and a clockwise loop at low discharges means that the sediment concentration decreases strongly when discharge decreases. Possible explanations for this pattern are (i) sediment exhaustion, (ii) delayed contribution of a sub-catchment (due to initial poor connectivity for example), (iii) storage in small basins and their subsequent connection after filling, or (iv) overbank flooding resulting in a drop of the streamflow velocity which causes a decrease of flow transport capacity (Eder et al., 2010; Fan et al., 2012). Patterns that consist of multiple figure-eight loops are usually caused by the succession of different events and peak flows.

The above examples illustrate that hysteresis patterns can be interpreted differently depending on the spatial and temporal scale and context. Therefore other information must be included to make more conclusive statements about the drivers of SS transport (Smith and Dragovich, 2009). Poulenard et al. (2012) used an infrared-based sediment fingerprinting technique to identify sediment contributions from three geological zones characterized by black marls, marly-limestone and molasses, during flood events in a mountainous catchment in the Southern French Alps. During a flood with an anti-clockwise hysteresis pattern recorded in August 2008, they found that black marls were the dominant source of the first sediment flush, while marly-limestones were the main supply of sediment during the peak discharge (Figure 7a). These results were explained by the vicinity and high erodibility of the black marls and the distance of marly-limestone sources from the sampling point. However, an earlier anti-clockwise event in November 2007 had a different cause. In this event, molasses sediment was more dominant during the first stage of the event (Figure 7), even though it was the most distant sediment source in the catchment. The authors argue that this material originated from sediment deposited on the riverbed, and which was resuspended during the first flush (Poulenard et al., 2012).

These different explanations for event-based SS patterns can be linked back to the findings in Section 4.2, and the seasonal differences in the amount of material available for mobilization. A sediment fingerprinting study in a rural catchment in Luxembourg found that during an event with a clockwise SS hysteresis pattern, the sediment source changed from cultivated topsoil at the beginning of the event, to grassland topsoil during the peak discharges. The findings show that the initially readily-available material from cultivated topsoil becomes supply-limited. The authors attribute the limited supply to the presence of artificial drains on the edges of the arable fields which disconnect the cultivated topsoils from the river network (Martínez-Carreras et al., 2010). A recent fingerprinting study by Cooper et al. (2014a) defined sediment sources by erosion processes (i.e. surface versus subsurface soils) in the catchment of the River Wensum (UK). The study shows that during precipitation events, the contribution of surface soils to the SS in the river is dominant, indicating surface erosion from arable fields. On the other hand, during lower river flows, SS originates mostly from subsurface erosion associated with channel banks and field drains characterized by Mid-Pleistocene chalky boulder clays, with limited contribution from surface sources (Cooper et al., 2014a).

The fingerprinting examples demonstrate that an analysis based on a single method (such as hysteresis patterns or rating curve) does not provide sufficient insights into the drivers of SS transport and might lead to oversimplified conclusions. In conclusion, event-based sediment dynamics provide insights into the conditions under which SS is transported in rivers. Knowing these conditions provides a better understanding of the importance of individual storm events in defining the longer term SS trends, and on catchment-scale sediment loads in terms of location, magnitude, frequency and their sequencing over space and time (Gao, 2008; Smith and Blake, 2014).

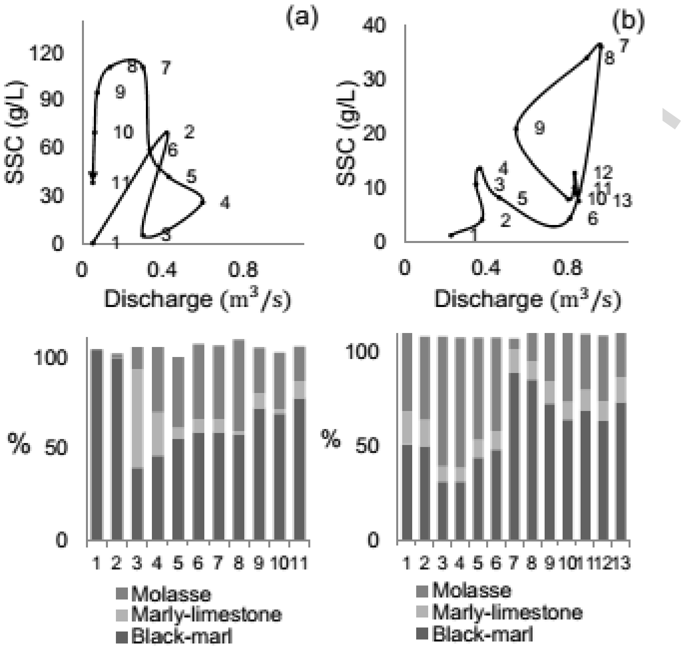

Figure 7: Discharge, suspended sediment concentration (SSC) and sediment source contributions for two flood events in the Calabre River catchment, Southern French Alps (a) 12/13 August 2008 and (b) 21/26 November 2007 (modified from Poulenard et al., 2012)

4.4 Conclusions: interpreting SS dynamics in terms of multi-timescale drivers

The interactions between hydro-meteorological factors, sediment sources, landscape disturbances and human interactions result in variable SS concentrations over short (high-flow events) and longer (monthly, annual) timescales (Sun et al., 2015; Zhang et al., 2013). The examples discussed in this section illustrate that sediment dynamics on one temporal scale are driven by a different set of processes to those at other temporal scales (Harvey, 2002). Long-term sediment transport variations are related to inter-annual climatic cycles, but also reveal change points caused by abrupt or steady changes in one or more of the catchment-scale drivers of SS transport. However, long-term SS dynamics give no information about the processes operating at smaller timescales and do not help to make conclusions about the episodic nature of SS transport. Seasonal sediment transport variations demonstrate the capacity of the catchment to store sediments and the subsequent transport of those sediments to and by the river system as a function of various drivers. Finally, event-based SS transport variations demonstrate the impact of single high-flow events on the total sediment load and the specific conditions and feedback mechanisms underlying SS transport. The case studies emphasize that a single hysteresis pattern or rating curve based on one temporal scale does not adequately represent the entire sediment regime and the corresponding geomorphic responses of a river catchment (Dean et al., 2016).

5. Guidelines for a multi-timescale approach to sediment regime characterization

From both a scientific and a management perspective, it is often important to characterize the sediment regime of a river, i.e. to quantify the SS load in rivers and understand over which timescale and under which conditions most of the SS is actually transported. Towards this end, a thorough understanding of the processes and interactions underlying SS transport is essential. The findings of this review emphasize the importance of considering the spatial and temporal scales of SS transport in order to infer conclusions about dominant drivers and processes. A main outcome of this study is a call for future multi-timescale SS studies that structurally combine different analysis techniques to fully capture SS transport patterns, sources and underlying drivers.

SS transport dynamics can be expressed over multiple timescales, for which different dominant drivers are operating. This scale-dependency has important modelling and management implications. For example, when a catchment is characterized as having problematically high sediment loads, annual sediment loads will not provide the appropriate information to develop targeted management strategies if most sediment is transported during a specific part of the year (e.g. wet season or snowmelt). Furthermore, when assessing the SS dynamics of a river to assess possible changes in the sediment regime as a result of future dam construction, it is not sufficient to rely on long-term sediment load data. While this type of data provides useful information about how SS transport interacts with certain changes within the catchment (e.g. land use change or climatic change), it does not provide in-depth information about the specific flow conditions of SS transport, and thus the potential impact of flow alterations on the sediment load of a river (Geeraert et al., 2015). Similarly, for ecological purposes and the establishment of water quality guidelines and thresholds of acceptable SS concentrations, it is important to understand how long-term SS loads and mean concentrations relate to the short-term episodic flushing of sediment during flood events at a specific location in the river (Grove et al., 2015). These considerations emphasize the importance of event-based sediment sampling, as already emphasized in more detailed review studies on SS sampling and modelling (e.g. Gao, 2008; Horowitz, 2008).

To assist in the design of future studies, we have summarized the main empirical methods described in the review, what type of information they can generally provide, and how this information can be interpreted in terms of underlying processes and drivers over multiple timescales at a single point in the river (Table 1). The aim of Table 1 is to serve as a guideline for scientists, practitioners and policy makers who are concerned about SS sediment transport in a particular river and want to better identify, characterize and model the scale-dependent variations in SS transport in rivers. The guidelines provided here will aid future research to structurally analyze existing SS datasets and/or develop time-integrated SS monitoring/assessment programs.

Table 1: Key aspects of an empirical multi-timescale approach to sediment regime characterization

	Inter-annual data	**Seasonal data**	**Event-based data**
Resolution	Monthly to annual	Daily to monthly	Minutes to daily
Data type	SSC*/turbidity/cores	SSC*/turbidity	SSC*/turbidity

Method and output			
Sediment rating curves	Calculate annual sediment loads, identify climatic cycling, trends and/or change points	Calculate seasonal sediment loads, assess possible seasonal variation in SS loads	Calculate event-based sediment loads, assess possible variation in event specific SS loads
Sediment fingerprinting	Identify possible shift in dominant sediment source	Identify possible seasonal variation in sediment sources	Identify possible event-based variation in sediment sources
Hysteresis analysis		Assess variable relationship between discharge and SS transport	Assess variable relationship between discharge and SS transport
Multivariate data-analysis			Assess importance of multiple factors as potential drivers
Drivers and processes	Impact of climatic and/or land use changes, major landscape disturbances and human interventions	Presence of store-release phases of sediment due to seasonal variations in hydro-meteorological conditions and sediment availability	Feedback-mechanisms between hydro-meteorological conditions, sediment availability, landscape disturbance and human factors
Management relevance	• Quantify mean SS concentrations and annual loads • Assess impact of historical changes	• Assess relative impact of natural/ anthropogenic vegetation changes and/or hydro-meteorological seasonality on sediment transport • Developing soil and water conservation strategies	• Identify conditions for sediment transport • Assess importance of events relative to annual SSC • Assess impact of future changes in flow conditions • Develop acceptable SSC thresholds for ecology

*** Suspended sediment concentration (SSC)**

6. Conclusions

Linking SS transport dynamics to the underlying drivers across timescales and unravelling the process interactions between them is essential to the accurate prediction of SS concentrations and loads in rivers and the development of sustainable solutions to sediment-related challenges such as soil erosion, sedimentation and pollution in streams. However, we are currently unable to fully capture the spatial and temporal dimensions of the factors and catchment scale sediment transport processes that drive SS concentrations in rivers. This review used previously published literature to highlight the importance of evaluating and interpreting SS transport dynamics in rivers across multiple temporal scales to gain better insights into the interactions of the factors driving these dynamics. The main objectives of the review were to: (i) briefly summarize the main drivers for variation in SS transport in rivers; (ii) review the common empirical approaches that are used to analyze and quantify SS transport and sources, with special focus on the limitations of these methods in terms of capturing temporal variability; a (iii) apply these findings to recent case studies to illustrate how method and timescale affect the interpretation of suspended sediment transport dynamics; and finally (iv) synthesize the findings of the review into a concrete set of guidelines for a multi-timescale approach to sediment regime characterization.

Sediment transport processes in rivers are highly non-linear over time and space and are characterized by threshold behavior and feedback mechanisms (Bracken et al., 2015; Onderka et al., 2012). These processes are driven by a wide range of factors which determine changes in sediment transport over short and long timescales. Over the past few decades, research on estimating and evaluating SS transport dynamics has shifted from single sediment rating curves to complex data-mining techniques and sediment fingerprinting methods. However, these methods have often been applied without consideration of the temporal scale of the processes. This has limited our capacity to interpret and fully understand sediment transport patterns and drivers over different timescales. The insights and guidelines provided in this review will hopefully contribute to a more consistent design of SS studies and a more comprehensive understanding of SS dynamics and associated driving factors. By recognizing *a priori* that study design and temporal scale have an impact on the interpretation of SS dynamics and employing methods that address these issues, future research will be better able to identify the drivers of suspended sediment transport in rivers, improve sediment transport modelling, and propose effective, sustainable solutions to sediment management problems.

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