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Suspended sediment in lowland rivers – towards identifying the ratios of mineral and organic components and their variation during the year

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Abstract

Concentrations of suspended sediment transported by rivers are influenced by interactions between multiple drivers that act on a range of spatial and temporal scales. Such levels vary over the year, as well as across multi-year periods. Most conventional approaches to determining suspended load are based upon analyses of total suspended sediment concentration (SSC), i.e., the sum of mineral and organic matter. This approach makes it difficult, if not impossible, to determine the impact of multiple environmental factors on changes in suspension concentration precisely. The present paper focuses on the mineral and organic components of suspended sediment with the aim of determining how our knowledge of the share of each individual component can improve interpretations of SSC fluctuations during a hydrological year. The analysis conducted (personal and other researchers' results) has shown that mineral and organic suspensions demonstrate mutually incompatible opposite trends under influence of environmental factors. This analysis of organic components identifies clear seasonal trends, which indicates that organic suspensions of autogenous origin have a strong influence on the dynamics of changes in suspension concentration; such analyses are rarely included in assessments of SSC dynamics.

Key words: suspended sediment concentration, mineral suspension, organic suspension, seasonal variability

1. Introduction

In lowland rivers across the globe, most sediment transport takes place as *suspended load* (e.g., Walling & Fang, 2003), a term that refers to all suspended material carried by a river. This load consists of two major components, viz., mineral and organic matter; these demonstrate different concentration change dynamics under the influence of natural and anthropogenic processes occurring in the river catchment. The *suspended sediment concentration* (SSC) during a hydrological year depends on meteorological, hydrological and biological factors, as well as on geomorphological and geological influences. An important role is also played by anthropogenic factors such as land use type and transformation of the catchment landscape by, *inter alia*, hydrotechnical constructions, dam reservoirs, training work carried out in the riverbed and mining. Anthropogenic activities may result in rapid positive and negative changes in suspended load across a relatively small area and in a relatively short time (Siakeu et al., 2004; Warrick & Rubin, 2007; Walling, 2008; Skolasińska & Nowak, 2018); as such, they must be considered when interpreting fluctuations in SSC.

Conventional approaches to the study of suspended load are based on determining the total SSC, i.e., the sum of mineral and organic matter. This approach makes it difficult, if not impossible, to determine the impact of multiple factors on changes in suspension concentration precisely. This may be one of the reasons why the factors that influence sediment flux variation in rivers, and the relationships between them, remain relatively poorly understood and require further research (Vercruysse et al., 2017; Peng et al., 2020; Vercruysse et al., 2020). In addition, previous research on variations in suspended sediment transport has also been found to be inadequate, as noted by Skolasińska & Nowak (2018) and Skolasińska et al. (2020).

Therefore, the present paper examines the fluctuation ranges demonstrated by mineral and organic components of suspended load, and determines how their individual differences may influence the interpretation of other data sets taken as total SSC. The research draws on the findings of an initial study of the River Warta in Poznań (western Poland) and an analysis of published results by other authors, whose findings confirm the need for a fresh interpretation of suspended load as a mixture of two components, viz., mineral and organic matter. I have not conducted systematic field research (only preliminary) on the topic of the present paper, nor is it intended to provide a complete discussion of the final research results. Rather, the aim is to emphasise the problem of qualitative differences in the composition of river suspension, not only quantitative differences in suspension concentration. This is especially important in sedimentological studies based on SSC determinations, where the conclusions on sources of the transported material, the rate of denudation processes and the general functioning of the river catchment are drawn. It is assumed that the approach proposed here will yield more accurate identification of the relationship between SSC and environmental factors, and with changes occurring in river catchments during the hydrological year. The emphasis will be on organic components and biotic processes, because these are rarely included in assessments of SSC dynamics.

2. Differences between mineral and organic components of suspended load

Suspended load consists of mineral and organic matter. The mineral component in turn comprises silty-clay particles with a diameter below 63 μm, which originate from river erosion, surface runoff and material blown in from the catchment area; its quantity is in many cases positively correlated with discharge. The organic component comprises phytoplankton and zooplankton and its concentration typically demonstrates seasonal fluctuations related to the thermal profile of the river water. However, it may be of both authigenic and allogenic origin.

The movement of suspended load varies considerably over time (e.g., Jarocki, 1957; Olive & Rieger, 1992; Skolasińska et al., 2020). It shows an uneven distribution on vertical and horizontal cross-sections of the river channel and concentrations of

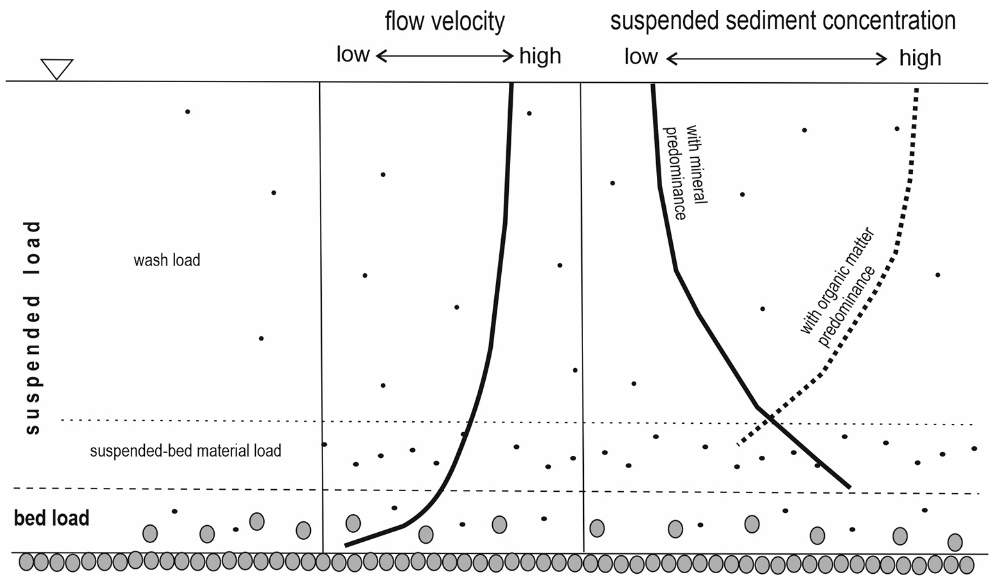

Fig. 1. Sketch for definition of the distribution of suspended solids in the vertical profile of the river (based on Shah-Fairbank & Julien, 2015, modified).

Table 1. Comparison of the two components of suspended load.

Suspended bed-material load	Wash load
periodically suspended by current turbulence	suspended permanently
contribute to bottom deposits	do not contribute to bottom deposits
positive correlation between concentration and water discharge	lack of correlation between concentration and water discharge
mainly mineral matter	mainly organic matter

both mineral and organic components tend to vary with depth in the water column, as demonstrated in Figure 1 (Shah-Fairbank & Julien, 2015). Due to the heterogeneous nature of the suspended load, some researchers have distinguished two categories: *suspended-bed material load* (or *fine sediment load*) and *wash load* (Einstein et al., 1940; Woo et al., 1986; Bettess, 1994; Yang & Simões, 2005; Khullar, 2007); the main differences between them are summarised in Table 1. Bettess (1994, p. 229) defined wash load as, "sediment that moves in suspension in the flow but is not represented in the bed of the channel" and noted that its transport was "supply dependent and [is] independent of the local flow conditions". Thus, the amount of wash load transported cannot be calculated and predicted based on the transport capacity, contrary to bed-material load.

Many researchers do not take these differences into account and therefore consider *suspended-bed material load* and *wash load* to be synonymous, which is not correct and causes confusion. The first of these terms refers mainly to silt and clay, while the second refers to that part of the total load that is washed through the channel and not found in significant quantity on the bed (Woo et al., 1986; Biedenharn et al., 2006; Khullar et al., 2010; Yuill & Gasparini, 2011). This heterogeneity in suspension material should be well understood by researchers and taken into account when analysing the functioning of the river catchment area and drawing conclusions on factors controlling the suspended sediment concentration and its dynamics.

In practice, during field measurements, it is not possible to separate the two categories because they are sampled simultaneously. Standard direct measurements are based on point measurements (from a certain depth); briefly, a water sample of a certain volume is taken for laboratory analysis, in which the total concentration of suspended particles in the water is determined using filters: the direct weight method. The methodologies of such field work and laboratory analysis are always developed to minimise errors (for instance, in Poland: Brański, 1967, 1968; Pasławski, 1973).

The present hypothesis is that the mineral and organic components of suspended load demonstrate different (discordant) content variability during the hydrological year; as such, when analysed as a combined sample, the results may not accurately reflect the range of factors that can potentially affect the suspended sediment concentration.

3. Pilot (initial) research in the River Warta at Poznań during a drought

Pilot measurements of SSC were performed in the middle course of the River Warta at Poznań (western Poland), a lowland meandering river with a mean gradient of 0.46‰ and ~0.27‰ near Poznań. From the nineteenth century until the 1970s, the river was here subjected to artificial regulations aimed at flood protection. The width and depth of the regulated channel at Poznań are dependent of water level and range from 40 to 50 m and from 1.5 to 3.0 m, respectively. The average discharge is 111 m^3/s (average high: 356 m^3/s and average low: 41m^3/s); the average water level is 268 cm (average high: 484 cm and average low: 164 cm) (based on the period 1961-1990; Kaniecki, 2004). High-water stages typically occur from February to May, whereas low-water stages are observed from June to September, unless a rainfall-triggered high-water stage occurs. In recent years, however, this has changed under the influence of global warming (Ptak et al., 2019).

The measurements were taken in early September 2015 during a drought that led to a significant decrease in water level of all the main rivers in Poland, including the River Warta (Fig. 2A). Water samples were collected at the Lech Bridge (Fig. 2A) with a 'TOŃ 2' bathometer with a capacity of 5 litres, which was released on a rope from the bridge into the river (Fig. 2B). The water sample collection procedure is shown in Figure 2C, i.e., from the shallow subsurface zone (s) and from a deeper one (d). The SSC was determined in *c.* 3 litre samples using paper filters, using the direct weight method. The water samples from early September (i.e., the ongoing drought) identified a very high SSC, about 80 g/m^3 (Fig. 3); the suspension was primarily composed of organic matter, as based on observation with a binocular. The SSC test results indicate higher SSC at the banks than in the middle of the river, and lower

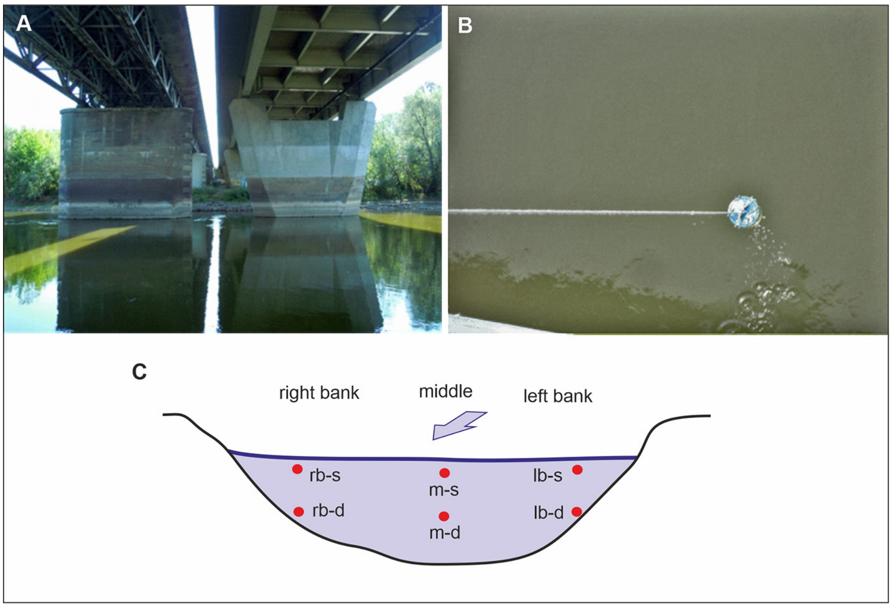

Fig. 2. The sampling of the river water taken on 1st September, 2015 during a drought. **A –** The River Warta – the Lech Bridge at Poznań; **B –** Water sampling using a five-litre bathometer (type 'TOŃ 2'); **C –** Direction of sampling (s – near surface, d – deeper).

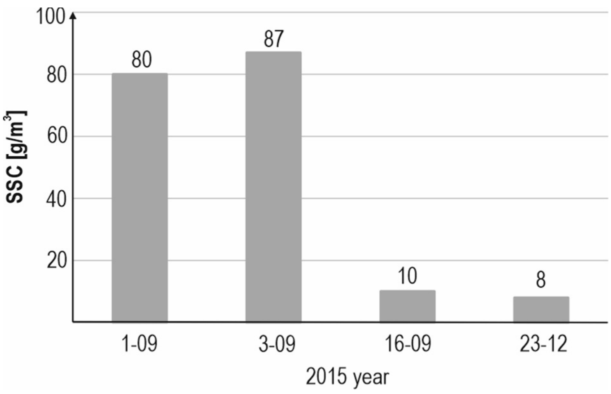

Fig. 3. The SSC (average of six measuring points) observed in the River Warta at Poznań on selected days in 2015

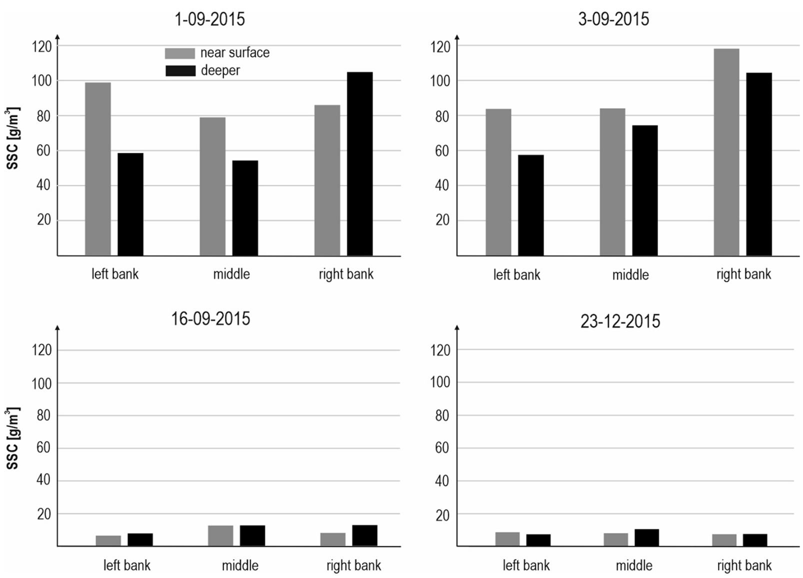

Fig. 4. The SSC observed in the River Warta at Poznań, at specific measuring points on selected days.

SSC at deeper levels than at the surface under conditions of higher water temperature (23°C) and very low water level (118 cm) (Fig. 4). These results differ from the typical graphs (Fig. 1) of mineral suspended sediment, indicating that SSC is lowest at river banks and highest at the bottom (approximately three times more than near the water surface). In addition, higher SSC has been observed during periods characterised by low flow and high water temperature, rather than during periods of high flow. This clearly indicates the need for further research including regular observations of SSC and its composition in lowland river sites to understand better the influences of the origin of particle suspension (mineral or organic) on fluctuations during the year.

4. A review of relationships observed between SSC fluctuations and selected environmental factors in lowland rivers

Analysis of SSC data often focuses on the variation in SSC in relation to changes in discharge. It is widely recognised that SSC correlates positively with discharge during isolated hydrological events, such as floods, resulting in a variety of hysteresis loops (Williams, 1989; Pagano et al., 2020). Previous studies on the River Warta, based on data taken between 1960 and 1980 (Skolasińska & Nowak, 2018; Skolasińska et al., 2020) did not find any clear relationship between discharge and suspension concentration. The findings also indicate that during flooding, when discharge increases, SSC decreases; however, in some years, high SSC was observed in summer periods with low discharge. Previous studies of perennial lowland rivers, such as the River Elbe in Germany (observation period 1964-2015) (Hillebrand et al., 2018), the River Berounka in the Czech Republic (observation period 2002-2007) (Desortova & Puncochar, 2011) and those in Slovenia (observation period 1955-2006) (Bezak et al., 2016) demonstrate that the correlation between SSC and discharge is not distinct and unequivocal.

Long-term studies have demonstrated that SSC correlates positively with water temperature more closely than with discharge. In addition, SSC has been found to correlate with chlorophyll *a* level, indicating that the main component of the suspension is organic matter (Desertova & Puncochar, 2011) (see Fig. 5). Generally speaking, in lowland rivers, fluctuations in SSC result mainly from seasonal changes, with the level rapidly increasing in SSC during the spring, peaking in the summer, falling from the beginning of the autumn and reaching its lowest level during the winter. High flow rates do not usually increase SSC levels, and the low ones that are characteristic of the summer period increase water retention time in the river, favouring the development of phytoplankton and a shift towards organic SSC.

5. Discussion

In lowland rivers across the globe, most sediment transport takes place as suspended load (Walling, 2008). As this load is also an important medium for the transport of pollutants, it needs to be considered in water quality assessments, especially in times of increasing anthropopressure and stricter legal regulations regarding environmental protection. The importance of such monitoring is further emphasised by the increasing rates of change observed in the natural environment of river valleys due to urbanisation.

Studies performed by the monitoring network operated by state institutions typically determine the total suspension in water. However, studies have confirmed that accurate recognition of the catchment and evaluation of measured data, such as during assessment of water quality in catchment management plans, requires an accurate under-

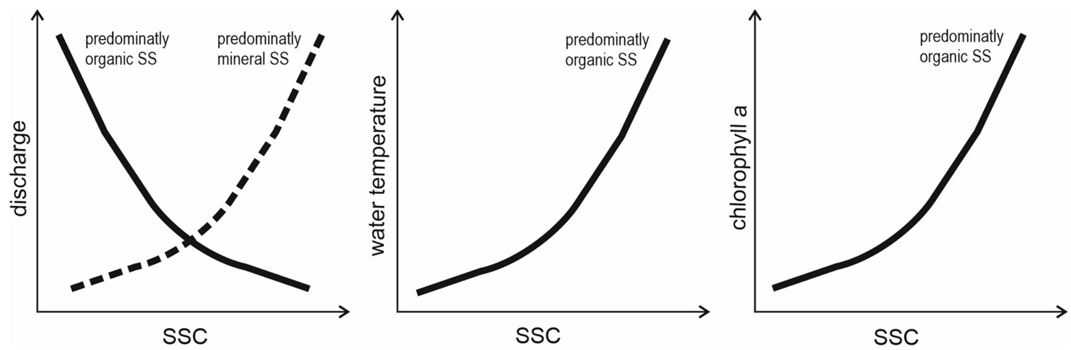

Fig. 5. General trends between SSC and selected parameters resulting from measurements in lowland rivers.

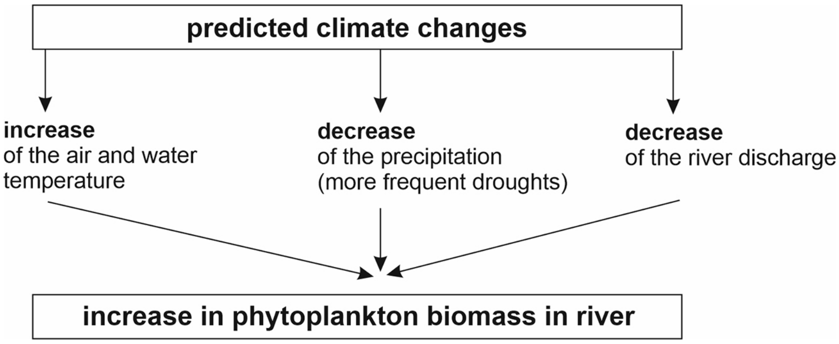

Fig. 6. Effects of climate change in rivers.

standing of the composition of suspended particles and their origin, i.e., whether they derive from allochthonous or authigenic sources (e.g., Hillebrand et al., 2018). My present findings demonstrate that any such monitoring should evaluate the mineral and organic components of the suspension as separate parameters, and the assessment should reflect the impact of environmental factors (precipitation, water temperature, discharge, sun exposure, land use and anthropopressure) on their concentration and composition. Organic components and biotic processes in particular are rarely included in assessments of river dynamics of suspended sediment loads. However, as high concentrations of such organic suspensions may have a negative impact on the ecological status of rivers (Hilton et al., 2006), there is a strong need to identify the driving forces behind variation in suspended sediment load, as well as their contributions.

Although such research into the ecological status of rivers under conditions of observed climate change has already been carried out in central European countries, including the Czech Republic (Desertova & Puncochar, 2011), Germany (Zwolsman & Van Bokhoven, 2007; Van Vliet & Zwolsman, 2008; Hillebrand et al., 2018) and Slovenia (Bezak et al., 2016), no such studies have been published in Poland to date. Such research is needed in Poland, as the country is located in an area that is poor in water and particularly sensitive to ongoing and predicted climate change. Over the course of the next 50 or even 100 years, a clear reduction in water resources is to be expected, coupled with increasing water deficits, particularly in lowland areas, as a result of an increase in field evaporation (see Jokiel, 2004; Kundzewicz et al., 2018). In addition, one potential negative effect of global warming is the increase in the proportion of suspended particles in rivers. The expected increase in air and water temperatures over the coming years is predicted to result in more frequent and longer periods of drought, and thus greater phytoplankton biomasses in rivers (Fig. 6). There is therefore a clear need for more research in this area, all the more so considering that biomass is a key element in assessments of the ecological status of surface water bodies according to the Water Framework Directive (WFD 2000/60/ EC).

Although measured records of SSC levels are vital in supporting water management activities, the available time series are often incomplete and, as such, not suitable for some analyses. Currently, in the river monitoring network in Poland, SSC testing is typically performed six to twelve times a year at selected sites; however, this does not allow for any analysis of short-term fluctuations in concentration. In addition, while incomplete data series can be interpolated by various models (Cisty et al., 2021), their precision is limited by the small amount of input data. An understanding of the ratio of mineral and organic forms of suspended sediment and its temporal fluctuation in lowland rivers will not only fill an existing gap in our knowledge, but will also improve the calibration of models and allow more precise scenario analyses.

Finally, SSC data are a key component in estimates of the denudation rate in catchments, and these estimates may be subject to considerable errors if SSC data are not analysed in parallel with the supply from anthropogenic sources, which often provide high quantities of SSC and are responsible for "unnatural" fluctuations. In addition, errors may occur if the organic suspension is the dominant component of the SSC: the formation of phytoplankton in the river *in situ* periodically results in an increase in SSC, and while not related in any way to denudation in the catchment area, this exaggerated value can distort the results of the analysis.

6. Conclusions

Based on a review of the literature, inclusive of some pilot measurements by myself, the following conclusions can be drawn:

– Suspended load may have different origin, both allogenic and authigenic, and may consist of mineral and organic components.
– Mineral and organic suspensions demonstrate different fluctuation patterns (incompatible, inverse trends) under the influence of environmental factors during the hydrological year.
– By analysing the organic suspensions as separate components, clear seasonal trends will be obtained, and these trends will indicate that organic suspensions of authigenic origin have a strong influence on the dynamics of changes in suspension concentration.
– Generally, in lowland rivers, the highest SSCs are typically recorded during the summer, i.e., at lowest discharges. The SSC decreases during floods; this feature is an important difference with upland or mountain rivers.
– It is necessary to distinguish between organic and mineral suspension in order to draw correct conclusions on the functioning of the river catchment studied.

The topic of suspended load in lowland rivers is still open-ended. Further research is needed, with the emphasis on qualitative analysis, particularly that which addresses the composition of the suspension, broken down into mineral and organic components and their quantitative ratios.

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