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Spatial and temporal patterns of suspended sediment concentrations in the Rhine River

C A T Sutari^{1*}, M Van der Perk¹, H Middelkoop¹

¹Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands

*Corresponding author : cutayuts@gmail.com

Abstract. Suspended sediment is a natural and crucial component and plays a crucial role in the hydrological, ecological and geomorphological functioning of the river system. The main objective of this study was to understand the spatial and temporal variation of SSC in Rhine River. This study used daily data of suspended sediment concentration from 1952 to 2016 from SSC model Sutari et al. (submitted manuscript, 2019) and daily data of water discharge collected from International Commission for the Protection of the Rhine (IKSR) and Dutch Rijkswaterstaat from 1995 to 2016 to understand the change of SSC. Analyses of product images suggest that the change of SSC shows a marked increase of about 6 mg/L at Upper Rhine (km 0 to km 435), a gradual increase of about 3 mg/L at Middle Rhine (km 435 to km 735), and is relatively constant at Lower Rhine (km 735 to km 865). Turning to seasonal variation, high SSC is mostly found in winter while low SSC is mostly found in summer. However, another result shows that the SSC tend to be high in June at almost all monitoring stations where the discharge is minimum. Meanwhile, under high discharge condition, the Mosel River gives the most significant contribution of SSC to the Rhine compared to other tributaries due to having a high discharge.

1. Introduction

The total sediment in the rivers generally consists of suspended sediment and bedload. This study focuses on suspended sediment, which consists of organic and inorganic materials carried within the water column [1][2]. Suspended sediment may also facilitate the transport of nutrients and other chemical adsorbed onto the surface of solid particulates [3]. The analysis of suspended sediment is essential as the evaluation of water management programs can be costly when such water problems appear. However, despite the abundance of research, the spatial and temporal variations in suspended sediment concentrations have not yet been fully captured and understood.

The suspended sediment concentration in a river varies within a year. The amount of suspended sediment is a product of the interaction of multiple drivers that act on different spatial and temporal scales [4][5]. However, the suspended sediment concentration tends to increase during the months following the peak discharge because of a different pattern of erosion and rainfall [6]. Therefore, we need to understand how the suspended sediment can vary spatially within the catchment and how these variations in turn affect temporal variations.



A previous study by van der Perk et al calculated the annual suspended loads at the Lobith monitoring station near the Dutch-German border for the period 1952 until 2016 based on the measured discharge and suspended sediment concentrations to estimate daily sediment loads, and discussed the declining trend in suspended sediment loads [7]. In this study, daily suspended sediment concentrations were estimated based on daily discharge measurements using a rating curve method, and the estimated daily suspended sediment loads were summed for each year to obtain annual loads. However, temporally limited data sets (1952-2016) and spatial limited locations (only at the Lobith monitoring station near the Dutch-German border) made it difficult to obtain a comprehensive conclusion about the temporal and spatial patterns of the suspended sediment in response to human interventions. Since recently, estimated the suspended sediment concentrations (SSC) in the Rhine River using Landsat satellite images and corresponding SSC data from the International Commission for the Protection of the Rhine (IKSR) and Dutch Rijkswaterstaat from 1995 to 2016 [8]. The model was built using the ratio of logarithmic transformation of a red/green band and logarithmic transformation of SSC based on *in-situ* sampling measurements. The SSC model works well and shows satisfactory performance.

In this study, based on model result the suspended sediment concentration are derived for several sampling locations along the Rhine River [8]. The objective of this study is to understand the spatial and temporal patterns in the Rhine River. To understand the change of SSC, the river channel is divided into several sampling reaches, at 35 km intervals between sections, resulting in the longitudinal graph of SSC from upstream to downstream.

2. Methods

2.1. Study Area

The Rhine River is the second largest river in Europe. This river has a catchment area of 165.000 km² with the total length of the river of 1320 km, from European Alps (highest elevation 4275 masl) to the North Sea. Mean annual precipitation in the Rhine catchment ranges from ~500 mm in Rheinhessen (west-central Germany) to ~2000 mm in the Swiss Alps [9]. Maximum discharge happens during summer at the upper stream area and during winter in the downstream region. Most of the Rhine water comes from snowmelt in the southern part of the drainage basin during summer, whereas the rivers in the central part of the Rhine River contribute water to the downstream are during the winter. The discharge at Rhine River varies within Upper Rhine, Middle Rhine, and Lower Rhine. The largest discharge occurs at the Lower Rhine with maximum discharge reaching 12.000 m³/s. On the other hand, the discharge is only 267 m³/s at the Higher Rhine (lowest discharge).

Rhine River has been progressively affected by the increasing human impact over many centuries. The population is expanding with intensive land utilization. Moreover, Rhine River has been intensively used for transportation and engineering works. In the upper catchments, people built weirs and water mills as a source of hydropower [10]. In the downstream area, embankments were constructed in a progressively greater extent and strength as permanent flood protection [11]. To date, the river is completely embanked [12]. In the 19th century, regulation of weir construction resulted in intensive bed degradation and other parts of Rhine River were channelized and protected [13]. The river was narrowed and straightened to increase the accessibility of shipping route [14]. In the 20th century, small engineering works, flood protection constructions, and many tributaries dams were built to generate power [14]. In this period, mining also influenced the subsidence of the riverbed [15]. For the shipping purpose, sediments blocked navigation were dredged and re-allocated to the river elsewhere [12]. Also, coarse materials were supplied to stabilize the riverbed and to stop bed degradation [12].

2.2. Data collection

The daily data of suspended sediment concentration from 1952 to 2016 were the result of SSC model, according to Sutari et al [8] .and based on bi-weekly to daily observations. The data of SSC and water discharge were collected from International Commission for the Protection of the Rhine (IKSR) and Dutch Rijkswaterstaat from 1995 to 2016. Fig.1 shows the locations of IKSR monitoring stations, SSC data, and discharge data.

To understand the change of SSC, the river channel was divided into several sample locations, which lie 35 km per sections. For tributaries, the sample locations of SSC are chosen at several meters before the confluence with the main channel of the Rhine River. In total, there are 35 sample locations at the main channel and 6 samplings are for the tributaries (the Neckar River, the Main River, the Nahe River, the Mosel (Moselle) River, the Sieg River, and the Ruhr River).

In the analyses section, the Rhine River is further divided into three major reaches. The first reach is the Upper Rhine, which covers kilometer 0 until kilometer 435. The major tributaries in the upper reaches are Aare and Neckar. The second is the Middle Rhine, which extends from km 435 to km 735. There are two major tributaries join in the middle reaches. Main and Mosel play an essential role in regulating the Rhine sediment discharge. The final major reach is the Lower Rhine, which lies between km 735 and Bimmen (km 865), where several small tributaries join: Ruhr and Lippe.

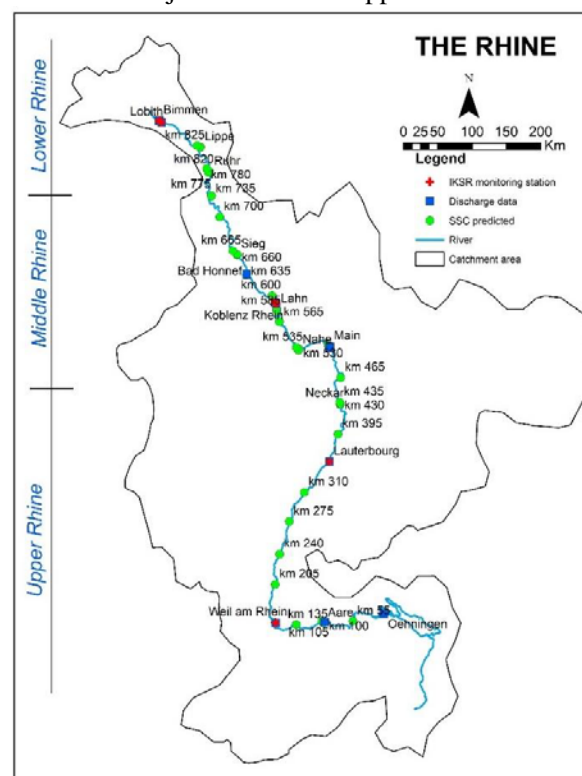


Figure 1. Locations of IKSR monitoring stations, SSC data, and discharge data

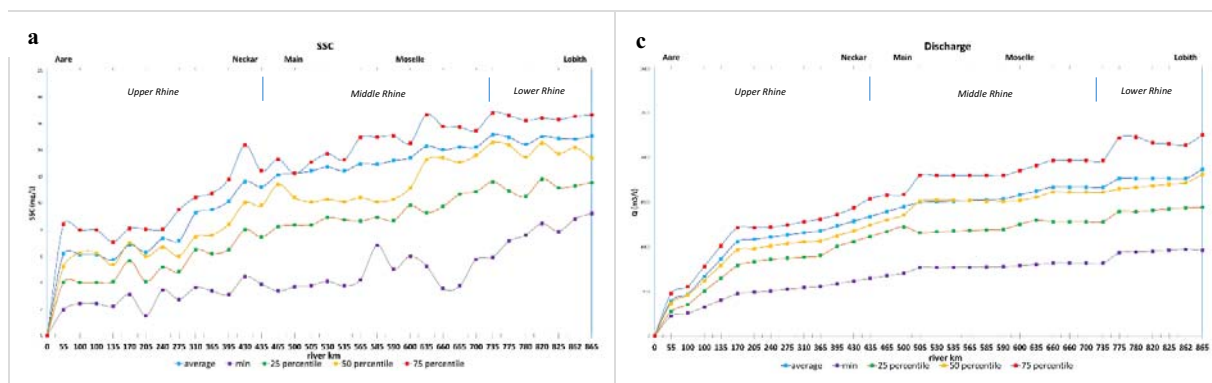
3. Result and Discussion

3.1. Spatial Pattern of SSC

The SSC shows a marked increase of about 6 mg/L at the Upper Rhine, a gradual increase of about 3 mg/L at Middle Rhine, and relative constant at the Lower Rhine on both selected dates (Fig.2a) and entire data (Fig.2b). The average SSC on selected dates and entire data are 8.5 mg/L and 10.4 mg/L at the Upper Rhine, 13.2 mg/L and 15.1 mg/L at the Middle Rhine, and 14.9 mg/L and 16.8 mg/L at Lower Rhine respectively. The minimum values of SSC show far out values in the distribution of SSC. This can be recognized as a high variation of SSC from 1995 to 2016.

SSCs increase in the downstream direction, especially after tributary confluence locations. The first sudden jump is identified at Maxau, and followed by the Neckar River at Upper reaches. There is a substantial 20% increase of SSC from Maxau (km 395) to km 430 based on both selected data and entire data calculations. Meanwhile, the Neckar River is determined to be less contributing to the increase of SSC, with only 8% calculated from the entire data and 8% of decrease from the selected date. At the Middle Rhine, the Main River increases SSC by approximately 1 mg/L for both entire and selected datasets. Meanwhile, the transport of SSC from the Mosel River increases strongly by about 10% for both datasets. Further downstream, the changes of SSC are much stable and it disappear completely after km 735, without any sudden jump at tributary confluences, where several small tributaries such as the Ruhr River, the Lippe River, and the Sieg River debouche in the Rhine River.

The SSC shows a strong correlation with discharge, as revealed by the pattern in the changes of discharge at every reach in both selected dates (Fig.2c) and entire data (Fig.2d). A 4%-fold increase of discharge (averaged over all measurements sites) leads to an 8%-fold increase of SSC change. The SSC at Rhine River increases as the discharge also increases; however, the concentration of the sediment depends on whether the discharge is increasing or decreasing and on the availability of supplies.



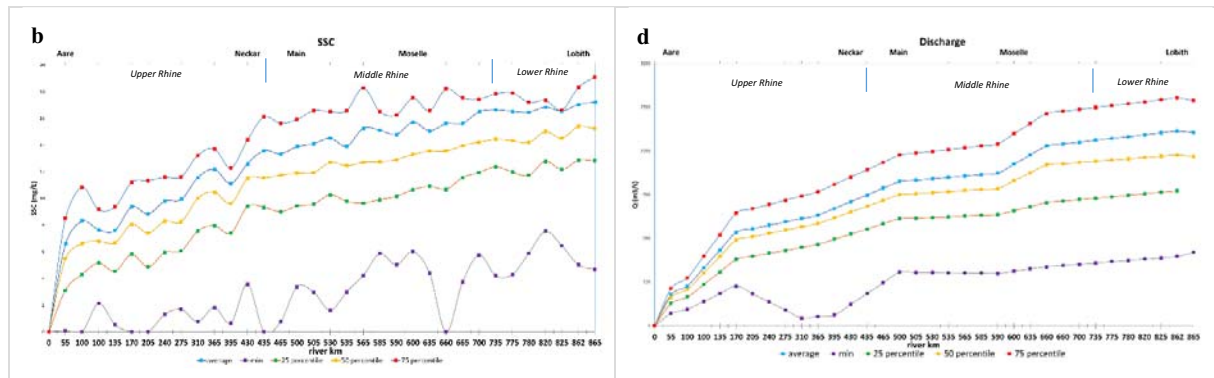


Figure 2. Spatial variation of suspended sediment and discharge in the Rhine River. The changes in SSC are presented as daily averages. In this study, the averages of SSC at Upper Rhine, Middle Rhine, and Lower Rhine are composed of 28 dates, 31 dates, and 32 dates, respectively. SSC is also presented by five other statistical parameters, which are minimum, 25th perc., 50th perc., and 75th perc. These statistics are calculated from the average SSC from all data.

3.2. Tributaries characteristics

Among tributaries, the daily average SSC series revealed that the highest contribution of SSC occurs at the Nahe River (19.2 mg/L), the Main River (18.5 mg/L), and the Neckar River (17 mg/L). In contrast, the Mosel River is recognized as the lowest SSC (13.2 mg/L). A closer inspection of SSC and discharge relation of tributaries particularly manifests at low discharges. Fig 3.2 a-b-c implies higher SSC at the Nahe River, the Sieg River, and the Ruhr River corresponds for low discharge and low SSC at the Mosel River corresponds for high discharge. However, the high variability in SSC led to the analysis on longer timescales and stratification of data to attempt to describe the high and low SSC values. Meanwhile, under high discharge condition, the Mosel River gives the most significant contribution of SSC to the Rhine compared to other tributaries due to owing a high discharge.

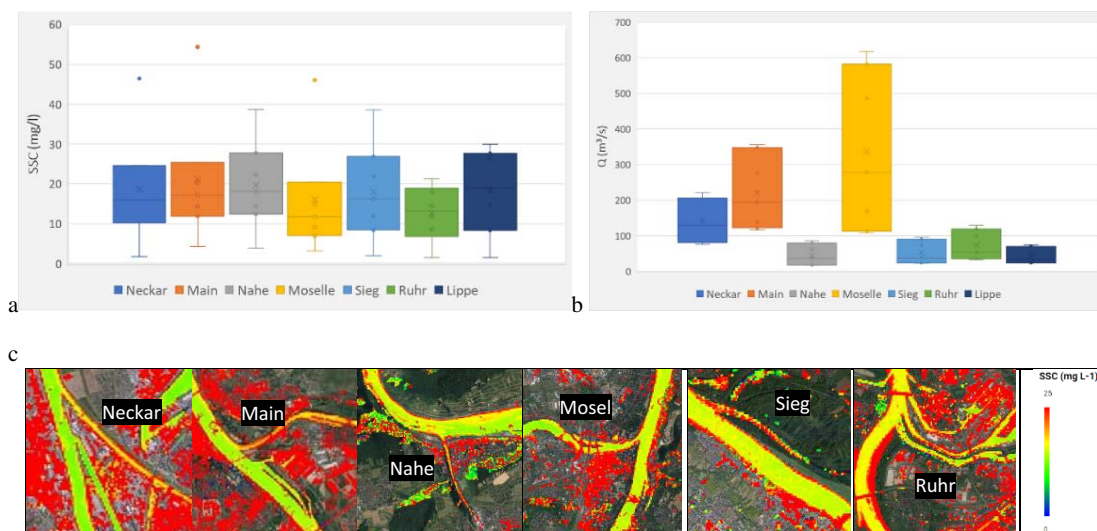
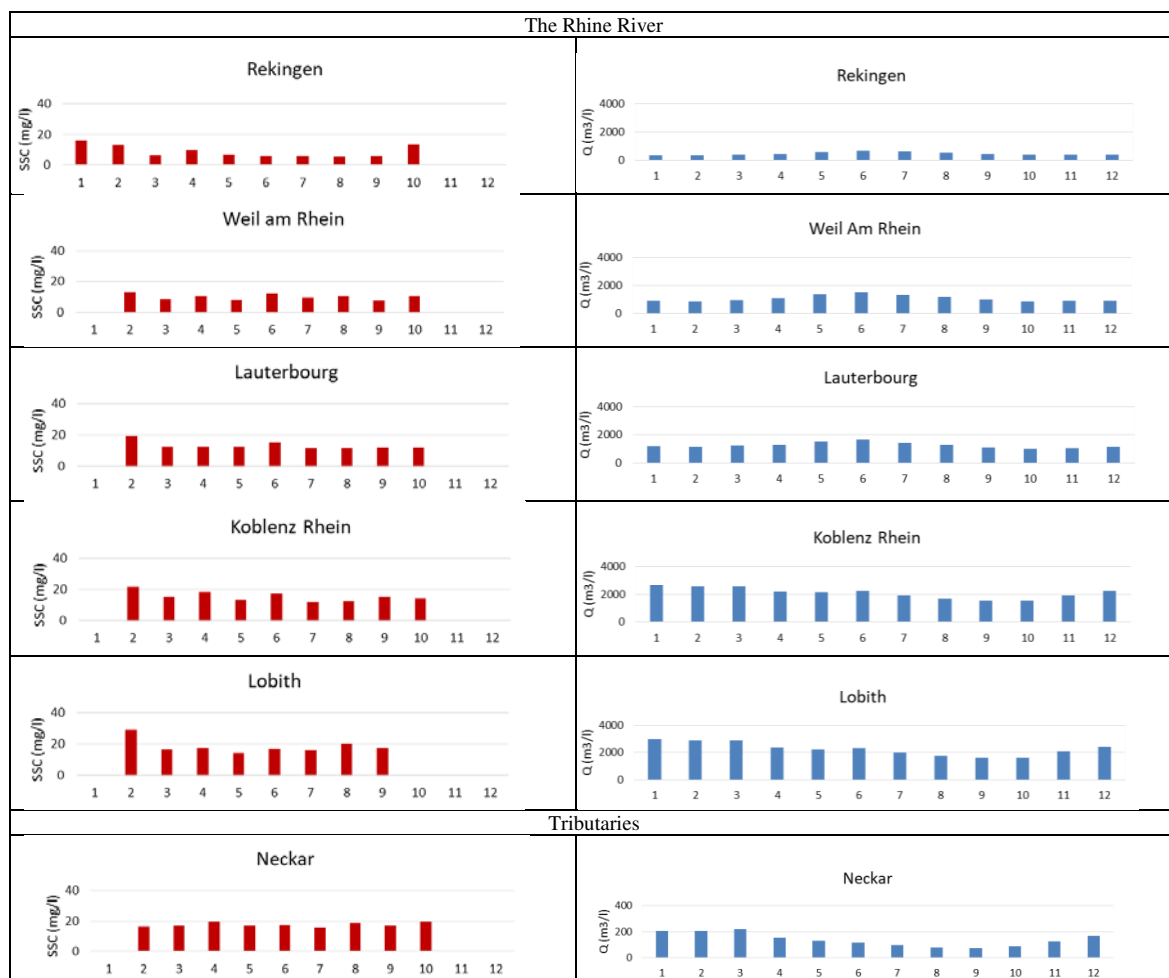


Figure 3 a,c, Average of SSC at Rhine tributaries. The SSC is calculated from the model using data from 1995 to 2016, b, Average of discharge at Rhine tributaries

3.3. Seasonal changes

As a whole basin, the SSC in the Rhine River monitoring stations shows the same characteristic of seasonal variation, except Rekingen (Fig.4). The monitoring stations Weil Am Rhein, Lauterbourg, Koblenz Rhein, and Lobith show high SSC in winter and low SSC in summer. This can be attributed to the increased sediment supply during the wet hydrological conditions in winter. However, another result shows that the SSC tends to be high in June at almost all monitoring stations where the discharge is minimum. Accordingly, this was probably a result of the primary production of organic matter.

Looking further at tributaries, SSC is higher in the winter and lower in the summer at the Aare River, the Neckar River, the Main River, and the Mosel River. The differences in SSC are insignificant for each month at the Mosel River. This is potentially due to the construction of weirs and locks in the Mosel River channel. SSC data are missing for November to December because of the higher cloud cover in winter resulting in fewer available acquisitions.



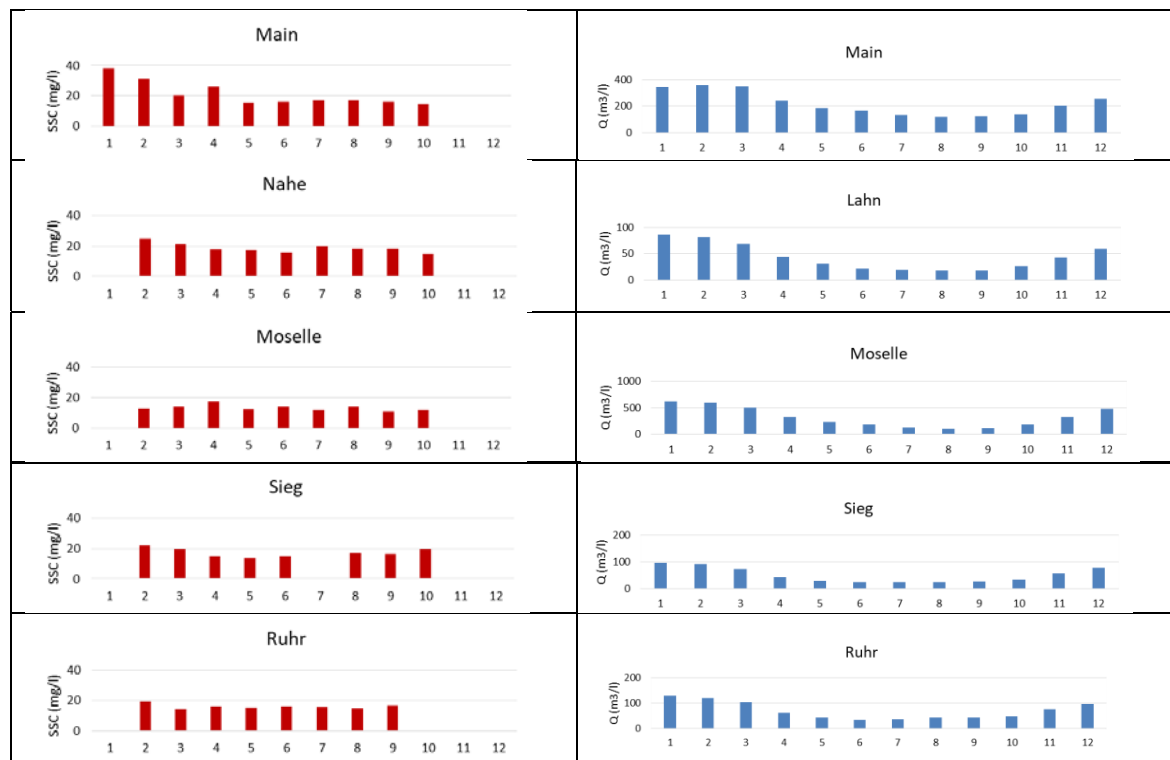


Figure 4. Seasonal variation of SSC in Rhine River average monthly SSC for the 1995 -2016 period

4. Conclusion

The SSC show have a marked increase in the Upper Rhine, followed by the Middle Rhine, whereas SSC remain relatively constant in the Lower Rhine. SSC generally increase in the downstream direction, especially at tributary confluence locations. Further downstream of km 735, SSC show less variation, without sudden jumps at the small tributaries of the Ruhr River, the Lippe River, and the Sieg River. The lack of change in suspended sediment is probably due to small contribution of SSC from small tributaries and an equivalent amount of SSC from tributaries as the Rhine River. Monitoring stations such as Weil Am Rhein, Lauterbourg, Koblenz Rhein, and Lobith show high SSC in winter and low SSC in summer. This suggests that the SSC strongly correlates with discharge, since in winter, the wet hydrological conditions cause increased sediment supply to the river. However, the SSC tends to be high in June at almost all monitoring stations although the discharge is minimum. This is probably due to the primary production of organic matter. A change in the relation between SSC and discharge in the tributaries becomes particularly evident at low discharges. The Nahe River, the Main River, and the Neckar River contribute to the change of SSC in a low discharge condition. Meanwhile, under high discharge condition, the Mosel River gives the most significant contribution to SSC to the Rhine compared to other tributaries.

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