

Sediment Load and Suspended Sediment Concentration Prediction

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Abstract: Sediment is a natural component of riverine environments and its presence in river systems is essential. However, in many ways and many places river systems and the landscape have been strongly affected by human activities which have destroyed naturally balanced sediment supply and sediment transport within catchments. As a consequence a number of severe environmental problems and failures have been identified, in particular the link between sediments and chemicals is crucial and has become a subject of major scientific interest. Sediment load and sediment concentration are therefore highly important variables that may play a key role in environment quality assessment and help to evaluate the extent of potential adverse impacts. This paper introduces a methodology to predict sediment loads and suspended sediment concentrations (SSC) in large European river basins. The methodology was developed within an MSc research study that was conducted in order to improve sediment modelling in the GREAT-ER point source pollution river modelling package. Currently GREAT-ER uses suspended sediment concentration of 15 mg/l for all rivers in Europe which is an obvious oversimplification. The basic principle of the methodology to predict sediment concentration is to estimate annual sediment load at the point of interest and the amount of water that transports it. The amount of transported material is then redistributed in that corresponding water volume (using the flow characteristic) which determines sediment concentrations. Across the continent, 44 river basins belonging to major European rivers were investigated. Suspended sediment concentration data were collected from various European basins in order to obtain observed sediment yields. These were then compared against the traditional empiric sediment yield estimators. Three good approaches for sediment yield prediction were introduced based on the comparison. The three approaches were applied to predict annual sediment yields which were consequently translated into suspended sediment concentrations. SSC were predicted at 47 locations widely distributed around Europe. The verification of the methodology was carried out using data from the Czech Republic. Observed SSC were compared against the predicted ones which validated the methodology for SSC prediction.

Keywords: sediment concentration; sediment yield; sediment delivery ratio; soil erosion; water quality; European catchments

For human society both soil and water are highly important natural resources that need to be carefully treated and every care has to be taken to sustain them. They are very closely related – at

the fundamental level sediment, consisting of solid soil particles eroded from a specific source, is transported by a medium – water. Soil and aquatic environments are thus linked together.

Via sediment, representing the connection, all components of soil may be transferred into aquatic environments. The system of sediment supply and sediment transport was naturally balanced until human society, causing pressure on both river systems and landscape, interrupted these links. Such interruption has resulted in various severe environmental problems. Soil fertility is gradually decreasing due to an excessive level of soil erosion; aquatic environments suffer from high sediment inputs, typically rich in nutrients and chemicals, which affects water quality, aquatic habitat, engineering structures, navigation and, generally, the potential to use water. Effects on water quality and related issues are probably the most significantly apparent and debated problems caused by sediment. Sediment yield and sediment concentration are therefore highly sought after elements of environmental information, providing a possibility to assess the magnitude of running processes in catchments and their potential impacts on the environment. However, the understanding of sediment concentrations, sediment supply and transfer is still not complete. Predicting sediment concentration is particularly difficult and is still challenging the scientific community as there is a high degree of uncertainty involved, and the controlling processes are rarely predictable.

This research aims to develop a methodology to predict sediment yield (SY) and suspended sediment concentrations (SSC) for a randomly selected point on a river within a catchment. A requirement for such a method was originally envisaged together with an intention to improve sediment modelling in the GREAT-ER river package. GREAT-ER (FEIJTEL *et al.* 1997) is a steady state river model which is used to assess the impact of chemicals on the aquatic environment. It has been developed for the European Chemicals Industry Council (CEFIC) in anticipation of new EC legislation on chemicals. Currently GREAT-ER uses just one sediment concentration of 15 mg/l for all rivers in Europe. This is obviously oversimplified and needed to be improved. An MSc research study (BEČVÁŘ 2005) was undertaken in order to establish a solid base for the development of a suitable methodology. The specific objectives of this research were therefore as follows:

- to investigate and collate available spatial and temporal pan-European data sets;
- to develop or select suitable European soil erosion and sediment yield estimation approaches;

- to test the performance of the traditional existing sediment yield estimators against observed sediment yield data;
- to establish good approaches as a result of the testing;
- to use the best approaches for predicting sediment yields where observed records are not available; and
- to translate predicted sediment yields into sediment concentrations where observed are not available.

Having such objectives, the main focus of the literature review was soil erosion, sediment supply, sediment sources and sediment transport processes. Special emphasis was paid to sediment yield estimation methods that were particularly important for the method development.

The material transported by a river stream must have a source somewhere in the catchment further upstream. Rarely is it just one source. Normally there are a number of sediment sources identified. However, generally, sediment sources can be divided into two groups:

(1) Sediment which is generated by a river itself as a consequence of natural- or human-initiated bed-forming processes. River channel changes, both vertical and cross profile, act on flood plains continually to modify the river's shape to adjusting its dimensions in order to comply with discharges. Remobilization of stored sediment, bank erosion and pool and riffle creation, for example, all generate sediment from the natural content of rivers. However, thanks to human activities these processes may be disturbed and accelerated to an excessive level, which can lead to negative impacts.

(2) Sediment which is supplied to channels from surrounding areas. In this case there are several factors which are crucial in terms of erosion risks, namely relief character, soil and climatic properties, land cover and land use in particular. Processes of soil erosion on agricultural land and the consequences of construction and mining activities are examples of significant potential sources of sediment. In fact, any location in which the soil is not strong enough to resist the erosive forces placed upon it, and where there are suitable conditions for transport of eroded material, can be labelled a sediment source

All these sources, acting in both time and space, together form an actual amount of material to be transported. However, they do not have the same

relevance. As previously stated there were two sediment sources identified to be of major importance for SSC prediction – soil erosion within the catchment and river bank erosion. These were consequently further investigated and available methods for their assessment on a European scale were examined.

In terms of soil erosion a number of projects have attempted to provide complex information about soil erosion risks at national, European and international level. Usually a map of soil erosion in Europe was produced as an outcome. Typical examples are the PESERA approach (KIRKBY *et al.* 2003), the INRA approach (LE BISSONNAIS *et al.* 2002), the USLE approach (VAN DER KNIJFF *et al.* 2000), the GLASOD approach (VAN LYNDEN 1994), the CORINE approach (CORINE 1992) and the RIVM approach (RIVM 1992). These approaches were carried out on different bases. Therefore criteria were formed in order to select an appropriate approach to be further applied for SSC prediction. Some of the main drawbacks of particular approaches were discussed by GRIMM *et al.* (2002). The criteria for rejecting an approach were, for example, too low spatial resolution, limited spatial availability of soil erosion information over large parts of the continent or a lack of soil erosion information in GIS format. The most suitable approach was thus identified to be the PESERA approach. The PESERA soil erosion approach became a fundamental data source that was relevant for testing SY and sediment delivery ratio (SDR) approaches and later also for sediment concentrations predictions.

The second source of material relevant for SSC prediction was bank erosion. Although there are methods for assessing bank erosion (Environment agency 1999) they are difficult to apply over such large areas and miscellaneous environments as investigated here. Therefore the only considered source of material was soil erosion. Certainly the original intention was to try to evaluate all the potential sediment sources, but the lack of assessment methods or essential data, meant it was only possible to deal with soil erosion. However soil erosion information alone does not indicate how much material is actively transported – sediment yield does. Sediment yield, together with the amount of water available to transport the material, also primarily determines sediment concentrations. Sediment yields can be generally estimated using either process based models or the

traditional empiric models. Process based models that take into account laws of mass and energy conservation are not usually applicable over such large study areas. The traditional sediment yield estimation methods use either direct computation from catchment parameters or a sediment delivery ratio (SDR). Sediment yield can be then calculated as follows:

$$SY = a \times X + b \times Y + c \times Z$$

where:

X, Y, Z – catchment parameters

a, b, c – regression coefficients

or the second possibility:

$$SY = \text{SOIL EROSION} \times \text{SDR}$$

Such SDR methods are also predominantly based on defining statistically significant links between observed yields and catchment parameters. The most commonly used catchment parameters are the area, relief, length (or relief-length ratio) and slope of the catchment. A number of SDR computation methods can be found in literature. Some authors have also related sediment yield to river network density (ROEHL 1962), land cover (WILLIAMS 1977), runoff (DENDY & BOLTON 1976) or soil properties (WALLING 1983). In the literature review sixteen SY estimation approaches (either direct computation or using the SDR) were reviewed (BEČVÁŘ 2005). It is presumed that these approaches produce considerably different results depending on selected parameters and conditions under which they have been developed. The intention was to use all of them and compare them against observed values to see which ones seem to be performing well. Nonetheless, essential data sources were either missing or were not accurate enough to evaluate all the parameters required for sediment yield or SDR estimation. Therefore only seven approaches were used and tested (MANER 1958; ANONYM 1971; WILLIAMS & BERNDT 1972; MCPHERSON 1975; RENFRO 1975; VANONI 1975).

Finally, current understanding of the behaviour of sediment concentration was reviewed. Generally, two types of behaviour can be distinguished. In the first case the highest sediment concentration can be observed together with high flows, unlike in the second case where it is vice versa. The highest sediment concentrations are observed in low flows. This is due to the dilution effect which

plays a role in high flows. Obviously the type of behaviour is determined by the amount of sediment supplied. The system of sediment concentrations is often hysteretic. Hysteretic loops can be observed during flood events when SSC are plotted against discharge. Although a wide range of sediment concentrations can be seen in any particular flow it can be concluded that it is still true that the majority of material is transported in high flows.

The issues reviewed above provided sufficient background and understanding in order to determine a solid knowledge base for the SSC prediction method development. In the following section the key points of the methodology development are addressed and the current state of sediment concentration prediction is described.

MATERIAL AND METHODS

The basic principle of the methodology to predict sediment concentration is to estimate annual sediment load at the point of interest and the amount of water that transports it. The amount of transported material is then redistributed in that corresponding water volume (using the flow characteristic) which determines sediment concentrations.

Hence:

$$SC \text{ (mg/l)} = \frac{\text{annually transported material (mg)}}{\text{annual water volume (l)}} \quad (i)$$

In order to obtain the first part of the equation, sediment yields methods were tested. Suspended sediment and flow data were collected from various European catchments, namely the Rhine, Mosel, Rhone, Jucar, Ebro, Elbe, Morava and Oder. Having obtained sediment concentrations and discharge data, real sediment yields were calculated using

the equation (i). Consequently sediment yield estimators (listed in previous chapter) were used to obtain calculated sediment yields at the same location where SSC data exist. This provided a great opportunity to compare both observed and calculated values. The comparison showed that results obtained using the USDA SCS (1971) SDR method correlate best with the observed yields. Therefore this method was selected to be used for sediment yield estimation. In addition, further analyses on monitored SSC were carried out in order to introduce two new relationships. Observed sediment yields were related directly to the rate of soil erosion (calculated using the PESERA approach) found in catchment delineated above the point of interest. This is shown in Figure 1.

It was discovered that sediment yield is equal to approximately one fifth of soil erosion. Another link was identified between observed sediment yield and the area of the catchment. This shows Figure 2.

These three methods were then introduced as those most suitable for sediment yield prediction and were used to calculate annually transported material – the first variable in the equation (i). The second parameter in the equation is the amount of water in which the material is transported. Since sediment yields were calculated as annual, annual water volume at the point of interest was required. That could have been easily done using the flow data, and annual mean sediment concentration could have been calculated. However this research aimed to go a little bit further than that. The intention was not to be restricted to just one value of SSC but to provide information about the variability of sediment concentrations in different flows. In order to do so, sediment concentration behaviour in different flows had to be determined.

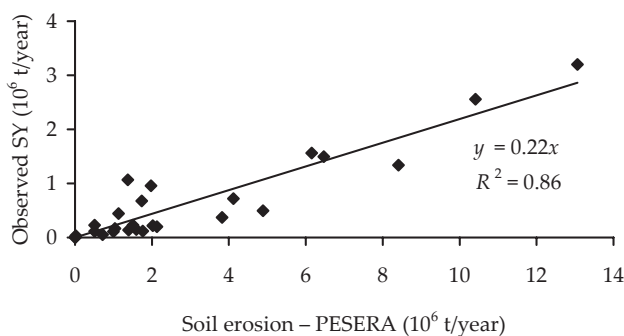


Figure 1. A link between observed sediment yields and corresponding soil erosion rates

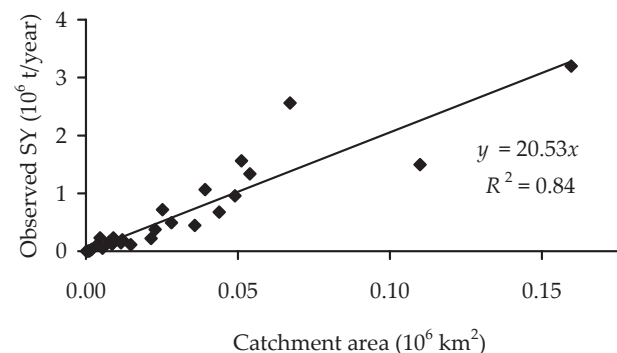


Figure 2. A link between observed sediment yields and corresponding catchment areas

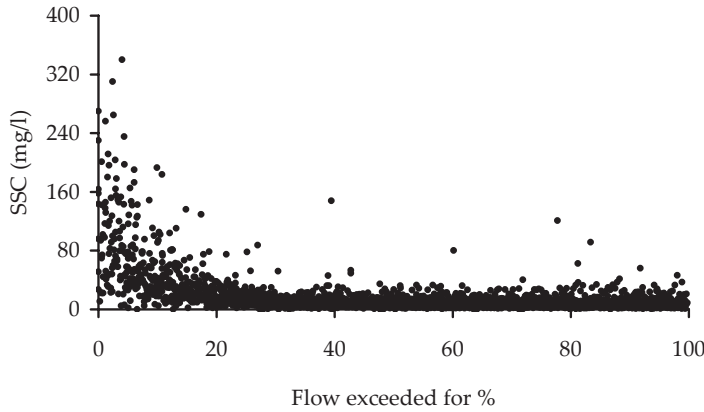


Figure 3. Sediment concentrations plotted using the flow exceedance

For that purpose the flow exceedance curve was used. However instead of plotting the discharge sediment concentration occurring in that particular discharge were plotted. In doing so, the relationship between flow exceedance and SSC could be observed. Figure 3 shows an example from the river Rhine at Koblenz in Germany.

It is quite obvious that a law can be established here. SSC behaviour can be divided into two parts. In the first part up to Q_{30} sediment concentrations remain relatively constant whereas in the second part, in flows higher than Q_{30} they change logarithmically. The SSC prediction was then also divided

into two parts according to that law. Of course, sediment yield and water volume as parameters to be utilised in the equation (i) had to be estimated separately for those two parts. By carrying out further analyses using the available SSC data it was found that flows of up to Q_{30} accounted for just 14% of total annually transported load, and thus in higher flows the remaining 86% is transported. Figure 4 shows the principle of the water volume estimation. A sum of areas over the whole data sample divided by a number of observation years determines the annual amount of water volume in flows higher than Q_{30} .

$$\text{TOTAL } Q_{0-30} = \int_{t(1)}^{t(2)} f(t)dt + \int_{t(3)}^{t(4)} f(t)dt + \dots + \int_{t(i)}^{t(i+1)} f(t)dt + \dots + \int_{t(n-1)}^{t(n)} f(t)dt = \sum_{i=1}^n \int f(t)dt$$

$$\text{MEAN ANNUAL WATER VOLUME } Q_{1-30} = \text{TOTAL } Q_{0-30} / \text{no. YEARS} \tag{ii}$$

Similarly the water volume in flows up to Q_{30} can be determined:

$$\text{TOTAL } Q_{30-100} = \text{TOTAL } Q_{0-100} - \sum_{i=1}^n \int f(t)dt$$

$$\text{MEAN ANNUAL WATER VOLUME } Q_{30-100} = \text{TOTAL } Q_{30-100} / \text{no. YEARS} \tag{iii}$$

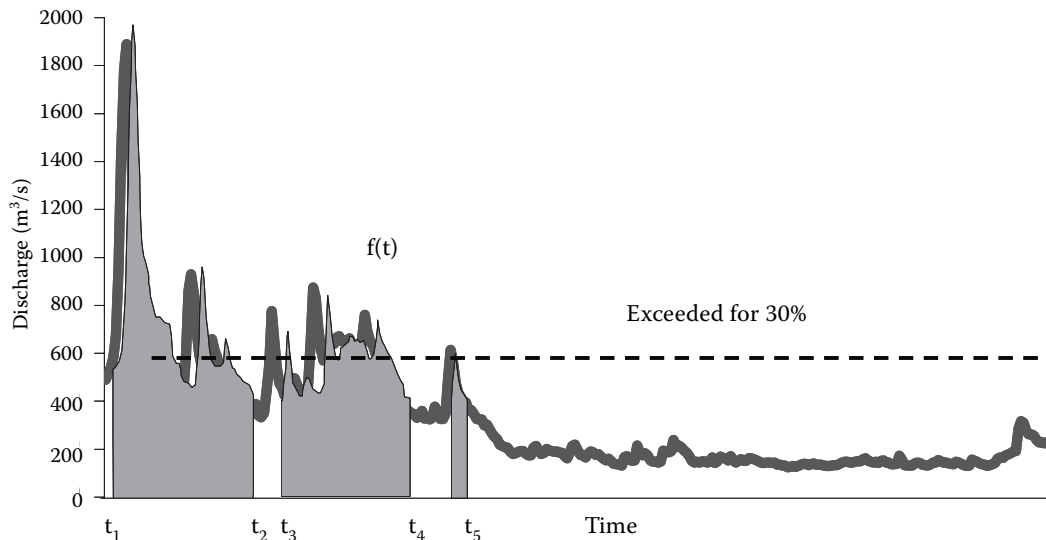


Figure 4. Water volume calculation for 30% flow exceedance

It can be written as follows ($f(t)$ is a function describing discharge in time):

Having estimated the water volume it was then fairly straightforward to calculate SSC occurring in flows up to Q_{30} using the equation. For flows higher than Q_{30} , a function describing the data had to be determined. The monitored SSC data from various European basins were analysed. The function was produced consequently:

$$SSC(Q_{30-0}) = -47.16 \ln(x) + 183.66$$

where:

x – percentage of flow exceedance

At this point the methodology seemed to be consistent and ready to be applied. However during the predictions some major imperfections were identified. Figure 5 illustrates the critical shortcoming.

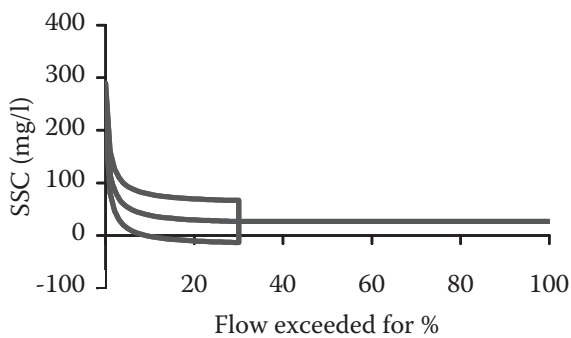


Figure 5. Shortcomings in the methodology

In some cases a step in SSC progress appeared or sediment concentrations were of negative values. In order to eliminate this, the methodology was slightly modified. Instead of producing a coher-

ent curve, showing the variations of sediment concentrations in a certain flow level, discrete values of SSC were aimed. Figure 6 shows this modification.

It is fairly self-explanatory – for each ten percent of flow exceedance a representative SSC was estimated. The numbers reflect how much of the annual sediment yield is transported in this particular part of the flow.

The methodology was verified using data from the Czech Republic. The Czech Hydrometeorological Institute provided high quality data (daily SSC) at three locations: the Elbe at Děčín, the Morava at Strážnice and the Oder at Bohumín. Predicted SSCs were compared with the observed ones. The following Figures 7–9 show the comparisons.

RESULTS AND DISCUSSION

The result of this research was a successful development of a methodology to predict sediment concentration. The method was applied and used for SSC prediction at 47 locations. Figure 10 shows an example of predicted sediment concentration using the three sediment yield estimators.

Although the verification proved the methodology performs well, there are several issues that need to be further discussed. The study area includes 44 basins that cover almost the entire continent. Therefore, as well as natural boundaries (such as the catchment ones) there are also political boundaries which make any modelling particularly difficult. Especially important is the fact that some parameters and typically involved processes have an inherently high level of uncertainty, such as sediment yields and sediment concentrations. Different environmental policies and land management practices may significantly influence

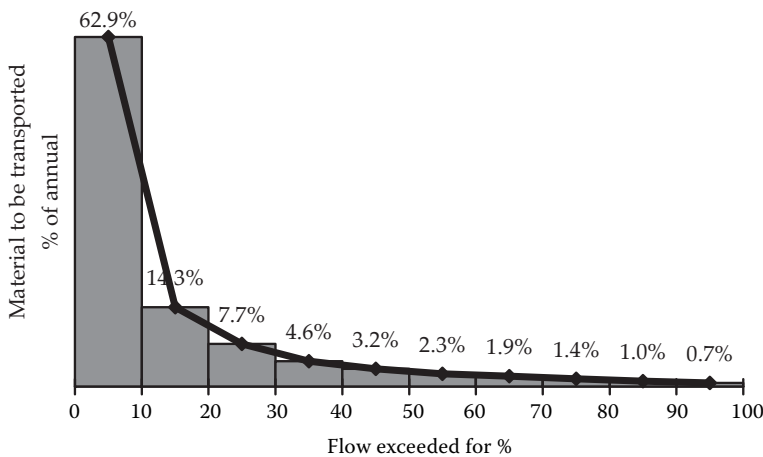


Figure 6. Modification of the methodology

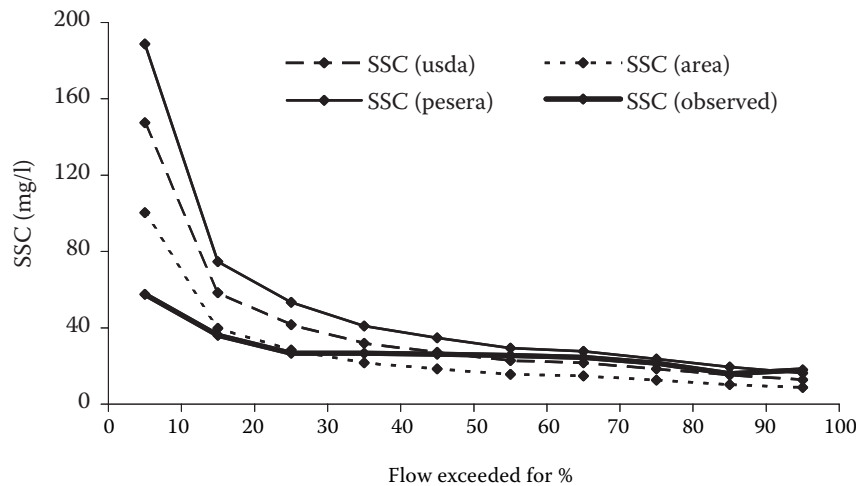


Figure 7. Verification: calculated SSC vs. observed, the Elbe at Děčín

sediment patterns even within one catchment. Nevertheless even this would not be a major issue if good quality data existed. Data availability was perhaps the main limiting factor in the methodology development. The fact that suspended sediment concentration data were not collected from all the catchments was to a certain extent limiting to the development of a methodology, and moreover even the collected ones were not of the same quality. The data were from different sources with temporal resolution varying from daily to monthly (or even longer) sampling periods. In terms of SSC predictions the main weakness lies in the fact that it does not take local conditions into account. Local conditions may significantly influence sediment concentration; however, no available method could be applied over such large areas as investigated here in order to take them

into account. Therefore actual suspended sediment concentration may differ in orders of magnitude (reservoir trap efficiency or additional sediment sources may play a key role). The error on SSC prediction when all the other sediment sources were omitted also needs to be further investigated. Nonetheless the values obtained by applying the methodology can be considered for use in the GREAT-ER river package. The mean suspended sediment concentration extracted from all the available monitored SSC data was 23 mg/l. The mean from all the predicted ones was 50 mg/l whereas GREAT-ER uses just 15 mg/l. That means that the amounts of chemicals, associated in GREAT-ER with the particular sediment concentration, may be underestimated.

At the moment however, the sediment concentrations must still be treated as provisional ones

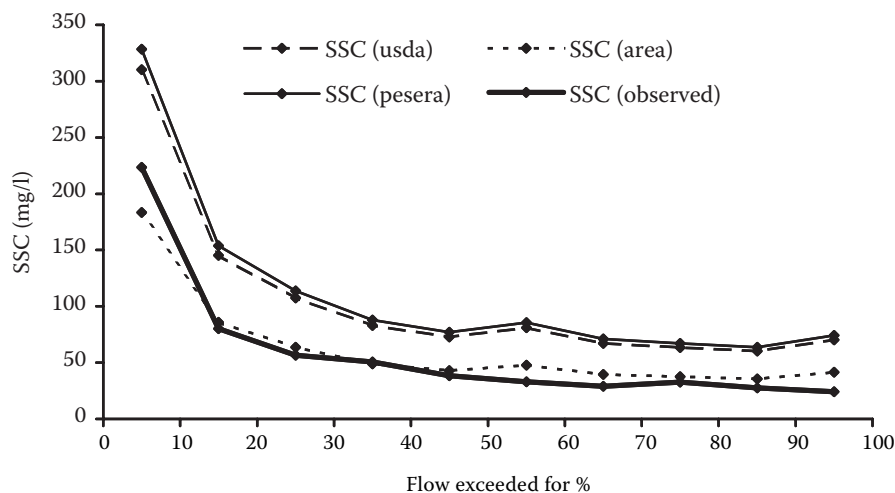


Figure 8. Verification: calculated SSC vs. observed, the Morava at Strážnice

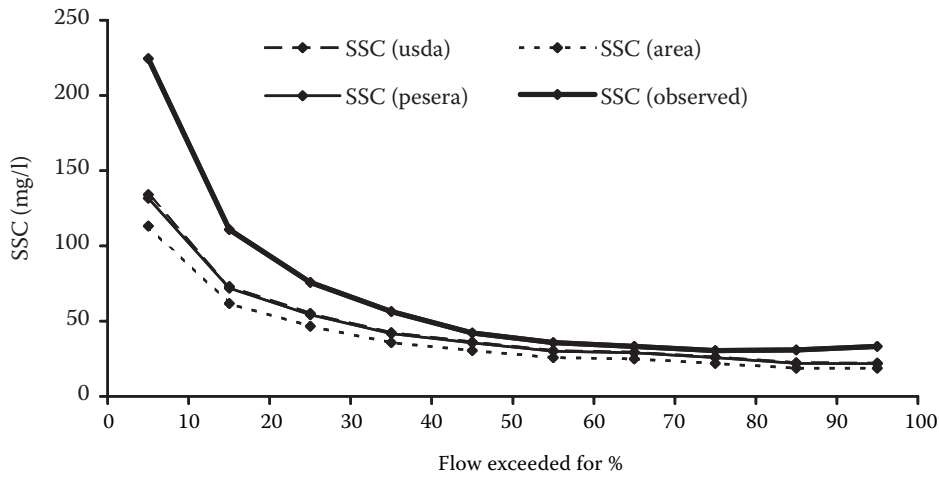


Figure 9. Verification: calculated SSC vs. observed, the Oder at Bohumín

due to the relatively crude estimations used during the prediction. The methodology currently has its shortcomings and drawbacks; nevertheless another study with an objective to eliminate them is currently underway. A PhD study entitled “Study of erosion and sediment transport in the Elbe catchment in the Czech Republic” aims to focus on the main shortcomings of the methodology. The scale of the forthcoming study is much bigger and good quality data have been obtained so far. Thus it provides a great opportunity to continue this research and further develop and refine the methodology. It is expected then that other relevant knowledge

will be gained that will support the understanding of the behaviour of sediment concentrations and improve their prediction. Sediment concentration is a critical parameter with highly indicative value that provides an opportunity to evaluate the seriousness of potential environmental impacts. Its prediction is therefore desirable.

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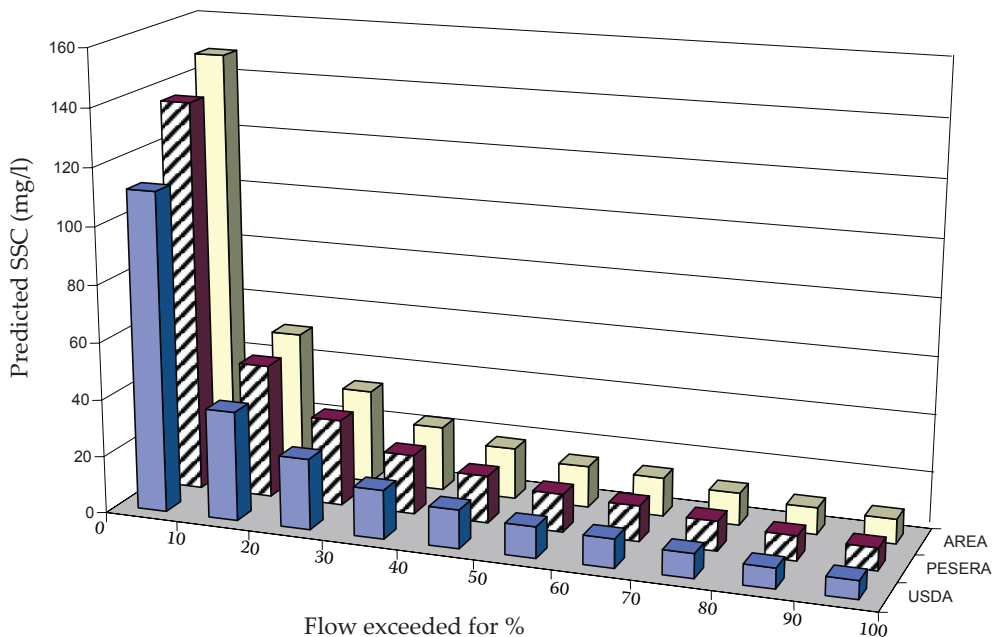


Figure 10. An example of predicted sediment concentration using the three sediment yield estimators

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Received for publication December 14, 2005

Accepted January 9, 2006

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