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Martin Becvar

Estimating typical sediment concentration probability density functions for European rivers

Supervisor: Prof. Sue White

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Abstract

Sediment in rivers is linked with qualitative and quantitative water problems throughout Europe. Sediment supply and transfer are part of a natural process of minimising gradients in the landscape. However, since human activities have started to affect the equilibrium, sediment supply is often out of balance with the river system. Cases of either low or high concentration often mean an instability which may cause severe problems. Therefore it is highly important to gain knowledge about sediment patterns in catchments as a part of catchment management.

This study was undertaken in order to improve sediment modelling in the GREAT-ER point source pollution river modelling package which currently uses suspended sediment concentration of 15 mg.l^{-1} for all rivers in Europe, which is an obvious oversimplification.

There are three aims for this thesis; one to investigate the range of suspended sediment yields from major European catchments (44 catchments investigated), two the verification of sediment delivery equations and three to develop a methodology to predict suspended sediment concentration from sediment yield in these rivers. Coarse sediment and bed load are not investigated in this study.

Monitored river sediment concentration data were analysed and compared to sediment yields obtained using the well established sediment delivery ratio (SDR) approach. Several SDR equations were tested. Equations where the area of the catchment was used as the sole variable provide the best results. In addition, sediment yields were estimated based on the recent PESERA soil erosion map for Europe. Annual sediment yields were finally predicted using three relationships between observed yields and catchment characteristics. A method to predict sediment concentration at different flow exceedance rates was successfully developed and provides satisfactory results. The basic principle of the method is redistribution of annual sediment yield into annual water volume using flow characteristics at the point of interest. Further investigations with an emphasis on sediment data and refining the methodology were suggested in order to improve concentration modelling.

Key words: sediment concentration, sediment yield, sediment delivery ratio, soil erosion, water quality, European catchments, GIS

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List of abbreviations

ANN	Artificial Neural Network
CEFIC	European Chemicals Industry Council
CHMI	Czech Hydrometeorological Institution
CN	Curve Number
CORINE	Coordination of Information on the Environment
DTM	Digital Terrain Model
EC	European Commission
FAO	Food and Agriculture Organisation of the United Nations
GIS	Geographical information system
GLASOD	Global Assessment of Soil Degradation
GPR	Ground Penetration Radar
GPS	Global Position System
GREAT-ER	Geography-Referenced Regional Exposure Assessment tool For European Rivers
INRA	Institut National de la Recherche Agronomique
IWE	Institute of Water and Environment
MAD	Mean Absolute Deviation
NSRI	National Soil Research Institute
PESERA	Pan-European Soil Erosion Risk Assessment
RIVM	National Institute for Public Health and the Environment
SCS	Soil Conservation Service
SDR	Sediment Delivery Ratio
SRTM	Shuttle Radar Topography Mission
SSC	Suspended Sediment Concentration
SY	Sediment Yield
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation

1 Introduction

This research M.Sc. study was undertaken in order to improve sediment modelling in the GREAT-ER river package. GREAT-ER (Feijtel *et al*., 1997; Feijtel *et al*., 1998) is a steady state river model which is used to assess the impact of chemicals from point sources in the aquatic environment. It has been developed for the European Chemicals Industry Council (CEFIC) in anticipation of new EC legislation on chemicals. GREAT-ER is run in a Monte Carlo analysis, randomly selecting different flow exceedances for each run and assigning contaminant load and sediment concentration to each flow exceedance following a set of rules for a particular river and location along its length. Currently GREAT-ER uses just one sediment concentration ($15.mg.l^{-1}$) for all rivers in Europe. This is obviously oversimplified and needs to be improved.

A simple empirical approach (Fig. A 1) used in this study introduces a methodology to estimate annual sediment yields in large European catchments and translate those yields into typical suspended sediment concentrations in rivers. Coarse sediment or bed load are not investigated in this work. The objective of this thesis is to estimate the most likely long-term range of concentrations for a river of interest, not to determine exact sediment concentration. The scale of this study is small and it is acknowledged that there are plenty of factors which strongly influence sediment patterns that have not been included. However the contribution of the study in this scientific field is certainly not insignificant as the suggested methodology (Fig. A 1) is verified against measured data and deals with sediment calculations in large catchments.

1.1 Aim

The aim of this thesis was to develop a methodology to predict sediment concentrations for large rivers in Europe from catchment sediment yields.

1.2 Objectives

- to investigate and collate available spatial and temporal pan-European data sets to include a digital terrain model (DTM), land use information, a river network layer, catchment boundaries, discharge and sediment concentration data and published information about sediment yields for European rivers. Since there was no budget for the data acquisition, only freely distributed data were searched;

- to develop or select approaches for estimation of soil erosion by water and sediment yields in the major European catchments using available data;
- to test developed approaches against available river data sets;
- to use the developed methodology to predict sediment yields in various locations and translate those sediment yields into sediment concentration for the major European rivers.

This study therefore includes collection of spatial and temporal data and a review of published papers to support the theoretical background and to gain additional information about former approaches and the overall problem. Several approaches were considered to estimate soil erosion and sediment yield for particular catchments. Later on, depending on data availability, calculated values were tested against measured values. The outcome from this testing was used to establish a methodology to calculate sediment yields and to translate them to sediment concentration. This methodology was kept simple to make it easy to use for prediction of sediment yields and sediment concentration outside the locations where measurements have been carried out. The resultant predicted sediment concentrations may be considered for use in sediment modelling in the GREAT-ER river package; however, due to the data used and the level of verification, they should still be considered as provisional at this stage.

2 Literature review

In European rivers sediment concentration is largely controlled by the supply of material to rivers rather than the ability of the river to transport sediment particles. This means that relationships between river flow and sediment concentration are often hysteretic, and a wide range of sediment concentrations can be seen at any particular flow rate for a particular point on a river. However, it is still true that sediment is moved preferentially in high flows and thus higher concentrations are seen during floods than during low flows. Therefore the following review looks at sediment supply, methods for estimating sediment loads (or sediment yield) for rivers, and relationships between concentration and flow characteristics which may be of use in estimating typical concentration rates in European rivers.

2.1 Sediment supply

2.1.1 Sediment sources

Sediment in rivers occurs as a result of complex processes acting within catchments and rivers themselves. From this point of view two major sediment sources can be identified:

1) Sediment which is generated by a river as a consequence of natural or human initialized bed-forming processes. River channel changes, both vertical and cross profile, act on flood plains by modifying the channel’s shape and adjusting its dimensions in order to comply with discharges. Remobilization of stored sediment, bank erosion, creation of pool and riffle sequences - these processes 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 cause 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. Products of soil erosion on agricultural land, consequences of construction and mining activities then represent typical sources of sediment which is supplied from surrounding areas. In fact any place where the soil is not strong enough to resist the erosive forces can be generally labelled a sediment source.

It is highly important to identify the major sediment sources and evaluate their significance for sediment patterns as a part of catchment management. Different sediment sources may dominate sediment supply, varying from place to place – this can be remobilized sediment within a river (Hupp & Phillips, 1997) or soil erosion on agricultural land which is commonly (but not necessarily) recognised as the major source (Waters, 1995). Sediment sources from land can be further divided into four categories (Waters, 1995):

Agriculture

For most areas which suffer from excessive sediment concentrations in rivers and thus negative consequences, soil erosion on agricultural land is likely to be the major source. Due to inappropriate crop management and agricultural practices, high rates of soil erosion may occur on arable land. Where intensive agriculture occurs at higher altitudes or on steeper slopes this is even more serious. Indeed, soil erosion can be particularly linked with altitude – with increasing altitude soil erosion increases, mainly due to steeper slopes (Walling & Webb, 1996). But flat areas can also be significant contributors to sediment yield. For example floodplain cultivation is one of the activities which may contribute quite significantly during floods when the water level reaches these areas (Waters, 1995). Although flooding may fertilize the land and support the growth of the plants, additional sediment may be generated through the turbulence processes and moreover chemicals may be transferred between water and soil. This can be adverse for both water and soil. Inappropriate pressure on land by cattle may result in overgrazing, and reduced plant cover which is then not sufficient to resist erosion forces. This potentially leads to severe soil erosion and excessive sediment supply. Compaction of the plough or subsoil layer due to use of heavy machinery may lead to soil infiltration capacity decrease which results in higher runoff and thus potentially higher erosion (Morgan, 1979). The influence of the whole agricultural sector is thus fairly complicated, because even when appropriate practices and management are applied just the fact that the land is used for crop production may result in soil erosion.

Forestry

Although forest is the best cover in terms of soil erosion protection, sometimes it can be also a significant source of sediment. It is again a consequence of human intervention in relatively stable natural conditions. For example, wrongly designed road networks for wood exploitation can result in high rates of erosion, and moreover it can drain surrounding areas with further impacts. Also other practices such as clear-cutting can certainly lead to high soil loss and sediment delivery (Waters 1995).

Mining

Mining and especially surface mining always means uncovering and disturbing the land surface and thus provides a great opportunity for soil erosion processes (Waters 1995). It is not only the land disturbance that causes the sediment supply. Building soil hoppers of inappropriate extent and with steep slopes may also result in severe erosion and excessive sediment supply.

Others

Apart from the aforementioned sources there are still other potential sources. Generally at any place where, due to human activities, natural conditions or both, there is an opportunity for soil erosion processes to occur, then such a place is a potential source of sediment. This can be, for example, construction sites for all kinds of construction, where land disturbance is almost certain to happen. In urban areas there can be a large input from street wash which reaches streams without treatment. Sometimes there is a high input of suspended solids to rivers from treatment plants, which obviously depends on the level and type of waste treatment.

In general, for major European catchments there are two main sources of sediment believed to be the most important ones: soil erosion by water on agricultural land and bank erosion. Although there is not much evidence in order to support the previous statement, the two sources are very likely to be the major ones. Many studies (e.g.

recently in Matisoff *et al.*, 2002; Carter *et al.*, 2003; Evans, 2005) have recognised either stream bank erosion (due to channel instability or lack of vegetation) or soil erosion (due to land use practices) as the major sources of sediment. Although the size of the catchments was usually smaller than those investigated here, it can be assumed that these two sources also play a key role in European size catchments. This thesis does not review the erosion problem; nevertheless soil erosion by water and bank erosion are both relevant as a source of material and often the controlling factor in determining the amount of sediment supplied. Moreover, soil erosion information is crucial for sediment routing in this work, therefore some of the issues related to sediment supply and sediment concentration should be pointed out here.

2.1.1.1 Soil erosion

Soil erosion is a very complicated process with far reaching consequences. Although it is a natural process and there is no aim to stop it (Morgan, 1979), the rate of erosion observed in recent years has reached an unsustainable level and causes damage. It has adverse impacts on soil and to water sources in particular. There are a number of publications and reports published dealing with the soil erosion problem itself or in a larger sense with relation to either crop production, water environment pollution or sediment control (Fournier, 1960; Morgan, 1979; Kirkby & Morgan, 1980; Laronne & Mosley, 1982; Beasly, 1984; Hadley & Walling, 1984; Rorke, 1990; Walling *et al.*, 1992; Holy, 1994; Dostal *et al.*, 1996; Walling & Webb, 1996; Toy *et al.*, 2002; Morgan, 2004) and many others, where additional information can be found. The intention here is to provide information about soil erosion issues which are related to sediment supply. There are various soil erosion forms described in the literature (see the references given above) however they are all results of a concurrence of soil erosion factors which control the rate of erosion. A description of soil erosion factors which influence soil erosion rates is provided below. The rate of erosion in a catchment often has a crucial controlling role on sediment concentration in rivers.

Factors controlling soil erosion rates

It has been already mentioned that the process of soil erosion is determined by a concurrence of soil erosion factors. Some of these factors are more affected by human activities, some less. However, all of them are more or less affected globally by climate change (Gore, 1994) and by its consequences.

Climate

In many cases the most important climatic factor is rainfall – as indicated by rainfall erosivity, which is described as an ability to cause erosion. There are several characteristics of rain which can affect the rate of erosion. These include rainfall intensity, duration, and raindrop size distribution. Generally two types of rain are distinguished (Morgan, 1979): storm rain (with high intensity and short duration) and frontal rain (long duration, but lower intensity). The best way to describe rain in connection with soil erosion is through the kinetic energy of the rainfall. Morgan (1979) says that a critical rainfall intensity might be 10 $mm \cdot h^{-1}$. He also mentions that Wischmeier and Smith (1978) found that splash, overland and rill erosion is best related to 30 min rainfall intensity – index EI_{30}. This value is scientifically criticized, because better correlations to soil loss were found using 15 min. (Morgan, 1979) and 5 min. maximal rainfall intensity. An important issue might be the role of climate change and its impact on erosion rates. Although the role of climate change is still unclear, generally it is expected that erosion rates will increase mainly due to increased extremes in hydrological events and changes to the temporal distribution of precipitation during the year. It means that more precipitation might occur during periods when the soil is not covered with vegetation (Kos & Riha, 2000). However, conversely, it still can be expected that in certain areas erosion rates will decrease due to reduced rainfall or its intensity.

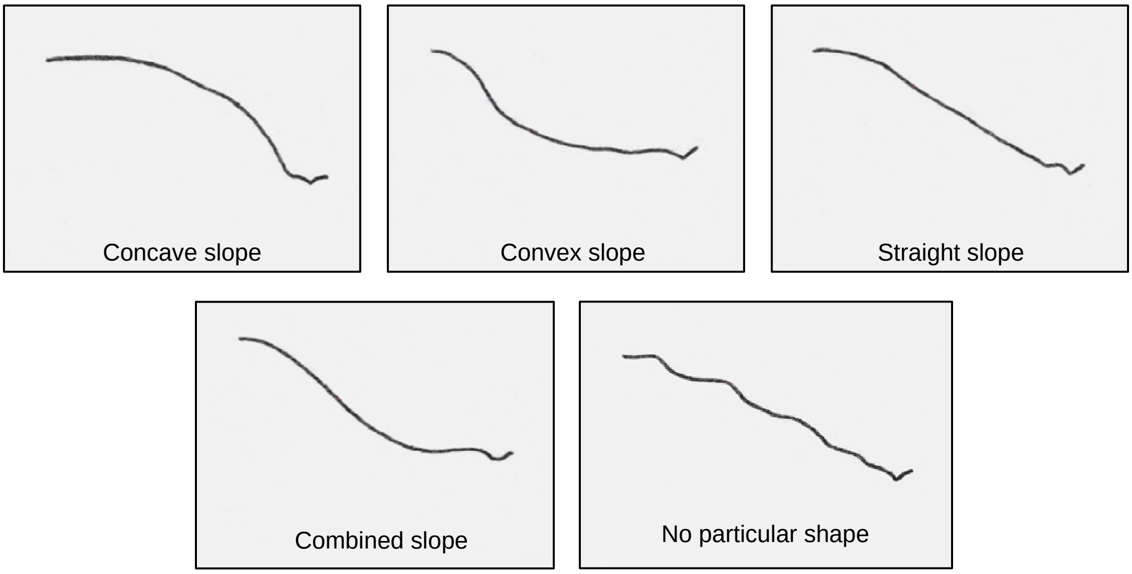
Geology and Soil

Geology determines the rate of formation of soil, primary soil properties and thus also has an initial influence on erodibility of the soil, infiltration capacity and particle distribution.

Soil erodibility is a property of soil that is defined as the resistance of soil against erosion. Generally it depends on soil texture, aggregate stability, shear strength to shear stress, infiltration capacity and organic and chemical contents (Morgan, 1979). Morgan (1979) also claims that actual infiltration capacities are much less than those indicated by field tests. This is very important, because it means that these field infiltration capacities should not be used for simulation of soil erosion processes. Soil particle size is quite important – generally large and small particles are fairly resistant because of their weight or cohesiveness respectively. The least resistant particles are silts and fine sand (Morgan, 1979).

Morphology

Morphology is a key aspect of the soil erosion process. Generally the rate of erosion depends on slope steepness, slope length, slope shape and slope aspect. Slope length is very important with regard to critical slope length (Holy, 1994). Critical slope length is the point on the slope where sheet erosion changes to rill erosion. To prevent erosion, slope length should not be longer than critical slope length, or at least some protective measures should be applied at that point to stop the overland flow.
The intensity of soil erosion is influenced also by the shape of the slope (Fig. 2.1).



Concave slope

Convex slope

Straight slope

Combined slope

No particular shape

Figure 2.1 – Typical slope shapes

In general slopes are classified as straight, convex, concave or a combination of these types. A crucial issue is how far from the beginning of the slope is the steepest part. The intensity of soil erosion is generally high when the steepest part of the slope is near the end of the slope, because both the velocity and the amount of overland flow are high (Holy, 1994).

Vegetation and land use

Type and condition of vegetation is another important factor. As a protective layer above the soil, the key role of vegetation is in reducing the kinetic energy of rain drops, although this layer also helps to keep optimal moisture conditions in the soil in order to maintain the stability of soil aggregates. Roots and parts of plants also reduce overland flow velocity and so support infiltration into the soil. The key role of the roots is also that they bind the soil. That depends very much on root and plant density (Holy, 1994). This implies that there is a high risk of erosion in early stages of plant growth when above-ground parts of plants are not fully developed. From the beginning of the growth period until harvest the risk of erosion decreases.

Management and Social Issues

Soil and crop management is a completely anthropogenic factor. Often, it is the main factor controlling soil erosion rates. Long-term use of heavy machinery eventually leads in compaction of plough or subsoil layer which affects infiltration velocities. The more infiltration capacity decreases the more runoff is produced and thus more erosion occurs. Another example of inappropriate management is ploughing in a non-contour direction which allows generation of runoff and thus soil erosion development. Inappropriate soil and crop management may significantly increase the soil erosion rate. On the other hand there are a number of measures for preventing soil erosion that can be applied. However, it may require additional costs for the farmers. Therefore it depends on the policy being held and the farmer’s behaviour.

On the surface, social factors may seem of little importance. Nevertheless it is an important factor which causes soil erosion problems and its further consequences. For example, higher population density means that higher pressure on the land exists and it compels farmers to produce more crops. This may force them to use inappropriate techniques or land management. In addition some farmers may be aware of the erosion problem; however they do nothing and try to get the maximum yield although it means damaging the resources.

2.1.1.2 Bank erosion

Bank erosion is a result of a natural process determined by a lateral movement of the river channel. The channel migrates across the floodplain and its shape remains often unchanged – attempts to control the bank erosion can destroy this equilibrium. Bank erosion can be understood as an adjustment of river channel size and shape to convey the discharge and sediment supplied from the surrounding land (Environment Agency, 1999). However, there are situations and places where bank erosion can cause damage. In such places society has been trying to protect this land and property using a number of different protective measures with local and short term aims. In the past these measures included massive heavy concrete, steel or stone protections. Simply, the idea was to protect banks with something heavy enough that water could not move it. One of the problems was that water energy was instead reflected to another place downstream rather than being absorbed by these measures. Nowadays a different approach is being practised – it is far more effective to work with natural forces than to work against them (Environment Agency, 1999). The change of this attitude is remarkable. The attention is now also focused on the impact of the measures on the wildlife in the stream, aesthetic impression and ecological status of the place. Such solutions are commonly termed environmental friendly solutions.

Generally the stability of the bank depends mainly on the flow regime and the strength of the bank materials (Environment Agency, 1999). Of course, there are other aspects that can be important in terms of bank erosion such as if the river is used for navigation or how seriously the river has been altered in the past.

Five main types of bank failure which cause excessive sediment supplies can be distinguished (Environment Agency, 1999):

- shallow slides
- rotational slips
- slab failures
- cantilever failures
- wet earth flows

Different types of bank failure occur under different circumstances. It is essential to understand conditions in which particular failure occurs in order to choose an appropriate protection method or combination of methods.

Sediment supply due to bank erosion is a very important source of sediment in streams. The extent of bank erosion may also indicate the quantities of sediment entering in the upper catchment. In most rivers sediment transport is limited by supply, not by the ability of the water to move sediment (Foster *et al*., 1995). Transport capacity of a water stream is finite and if exceeded then sedimentation would occur. Thus the low rate of bank erosion may suggest the capacity is already reached by sediment supplied from surrounding areas. Downs & Gregory (2004) state that the sediment system in a river is a continuum of sediment supply, transport and storage operating at a range of scales in space and time. It depends on local conditions, but in some rivers bank erosion might be the major source of the sediment. Where they are affected by human activity, rivers do not behave naturally; therefore where essential, bank erosion should be sensibly controlled by supporting the resistance of banks in order to avoid unacceptable damage. Doing so should not mean just moving the problem. Resolving the problem only locally can make the situation even worse further downstream.

For sediment concentration estimation, soil erosion by water and bank erosion were both considered as the major sources of sediment in this study. However in terms of bank erosion there has been no appropriate method found to assess the erosion at the European scale. Therefore the only major source considered in this study is soil erosion from land. This surely means introducing an error into sediment concentration predictions. The magnitude of this error for a catchment very much depends on a relevance of bank erosion as a source of material. For a catchment where bank erosion is a dominant source of material the error will be quite high. Nonetheless, the information on the magnitude of bank erosion in each catchment studied is not complete and thus the error could not be expressed. In the next section recent soil erosion approaches used to assess erosion for the European continent are reviewed.

2.1.1.3 Recent soil erosion approaches for Europe

In the past few years a number of projects have attempted to assess the risk of soil erosion at national, European and international levels (Grimm *et al*., 2002). The following section provides a brief description of some of these studies.

The CORINE approach

The CORINE soil erosion risk maps for the Mediterranean area were produced in 1992 (CORINE, 1992). It was a result of overlay analysis by GIS. The traditional Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) with certain modifications was used to assess soil erosion. The largest areas in terms of high risk of erosion were found in Spain, Portugal, Greece and Italy (Fig. 2.2). The CORINE methodology has the great advantage of simplicity, in that it provides a clear forecast for the whole of the area studied (Grimm *et al*., 2002).

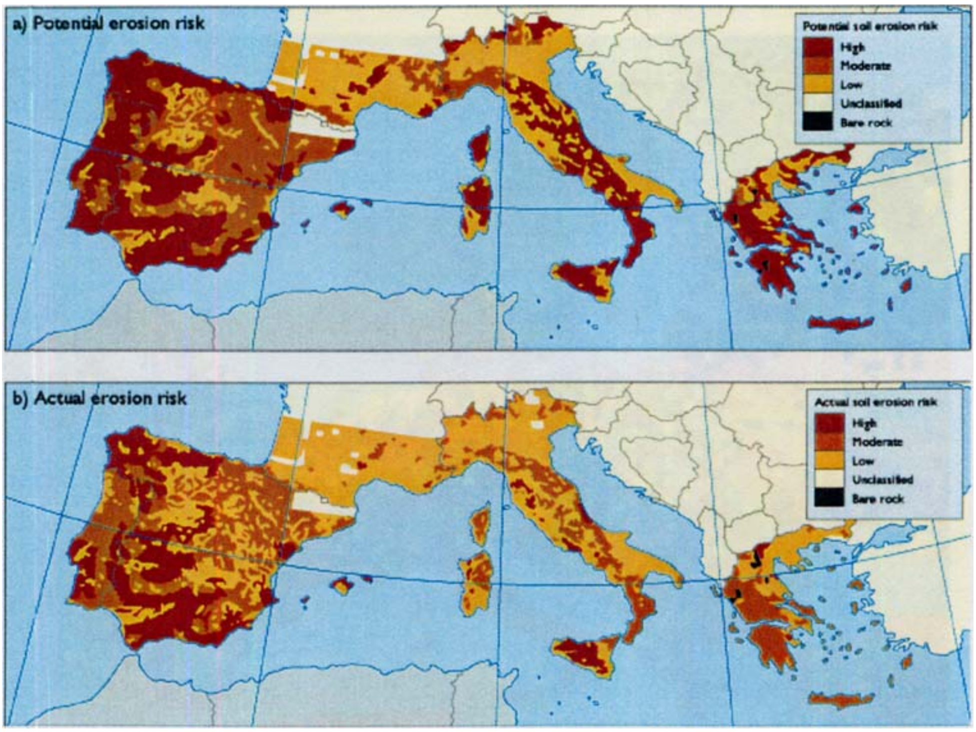


Figure 2.2 – European soil erosion risk - the CORINE approach

The RIVM approach

The RIVM assessment of water erosion was prepared as a part of a major report on strategies for the European Environment in 1990 (RIVM, 1992). This assessment of current risk was combined with climate and economic scenarios in order to generate future scenarios for 2010 and 2050. A simplified approximation of the USLE model with CORINE land cover data was used to assess soil erosion. It is available only in 50 km resolution (Fig. 2.3) so the accuracy of the information might not be sufficient when interpreting at regional scales. By all means for SSC predictions the spatial variability of the soil erosion information is too poor. Therefore this approach is not suitable for this purpose. This approach was also evaluated as too crude to support policy making process (Grimm *et al*., 2002).

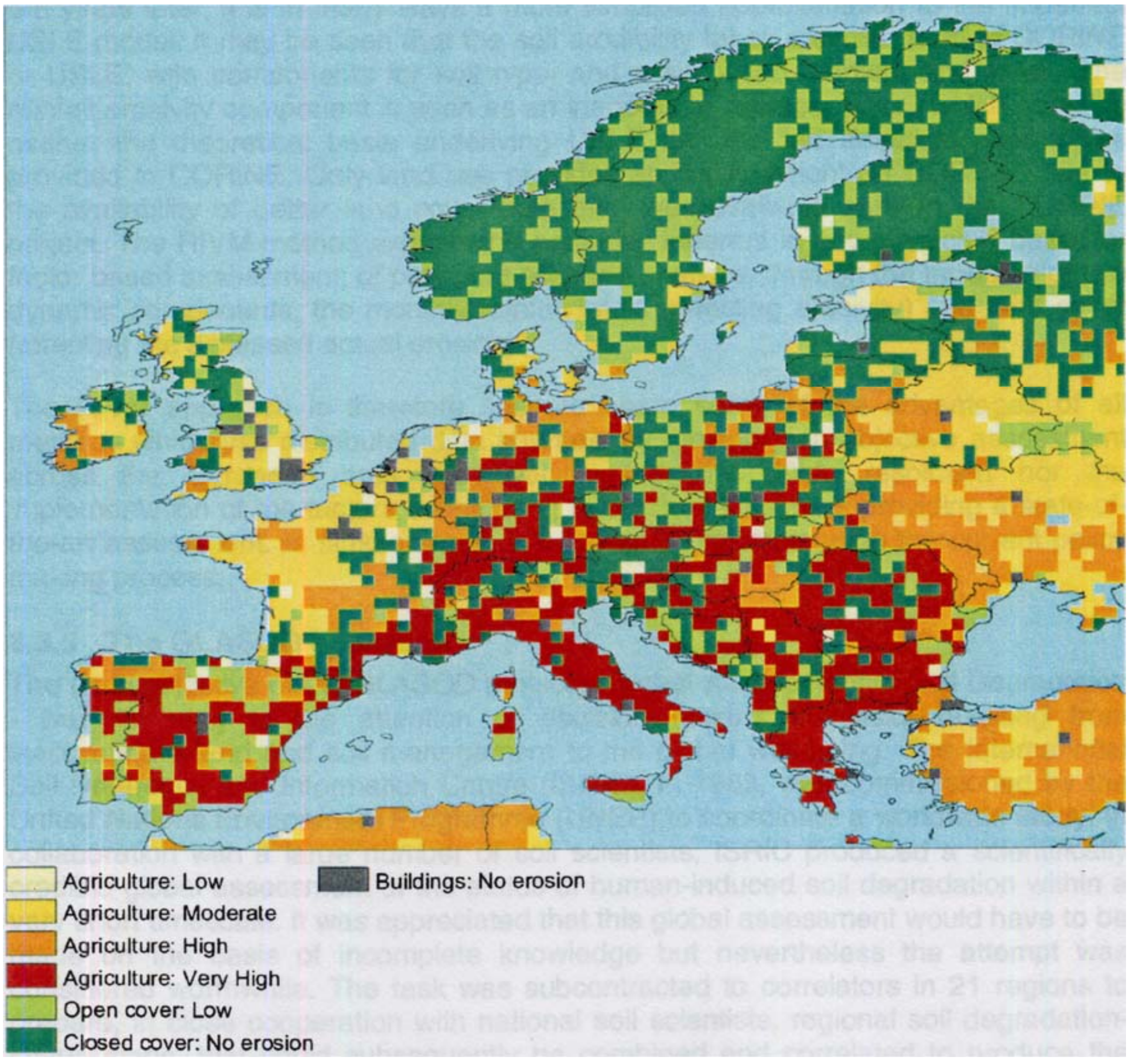


Figure 2.3 – European soil erosion - the RIVM approach

The GLASOD approach

The main objective of the GLASOD project was to bring to the attention of decision makers the risks resulting from inappropriate land and soil management. The GLASOD map of water erosion of soils in Europe was published in 1994 (Van Lynden, 1994). It was based on expert assessment - questionnaires were sent to scientific teams in each of the European countries. Experts were asked to delineate, on a standard topographic basemap, units showing a certain homogeneity of climate, vegetation, geology, soils and land use. This was then evaluated and interpreted for the degree of degradation. Maps were produced providing a minimum resolution of approximately 10 km (Fig. 2.4). The Mediterranean area was again mentioned as one of the areas with high erosion risk, Croatia and Turkey in particular (Grimm *et al*., 2002).

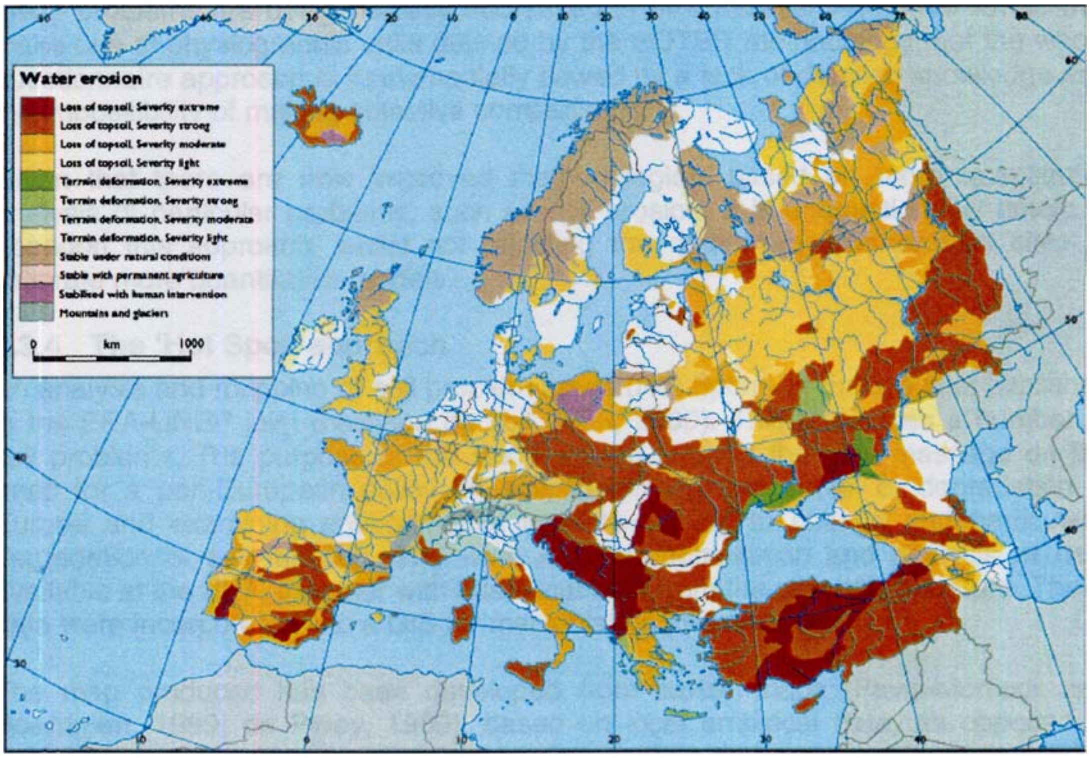


Figure 2.4 – Water erosion in Europe - the GLASOD approach

The USLE approach

The well-known USLE (Wischmeier & Smith, 1978) has been used for many research studies of soil erosion (Grimm *et al*., 2002). It is not essential to describe here the basic principles of USLE. The model is designed to estimate long-term annual erosion rates on agricultural fields. Although the equation has many shortcomings and limitations, it is widely used because of its relative simplicity and robustness. Moreover it represents a standardized approach, so results are comparable with others studies. A first attempt to produce a map of quantitative soil erosion by rill and interrill erosion for the whole continent was published in 2000 (Van der Knijff *et al.*, 2000). Two maps at 1 km grid resolution were produced: a map with current risks (Fig. 2.5) and a map with potential risks (no vegetation cover, C = 1). High rates of erosion occur mostly in the Mediterranean area once again and also in the Alps.

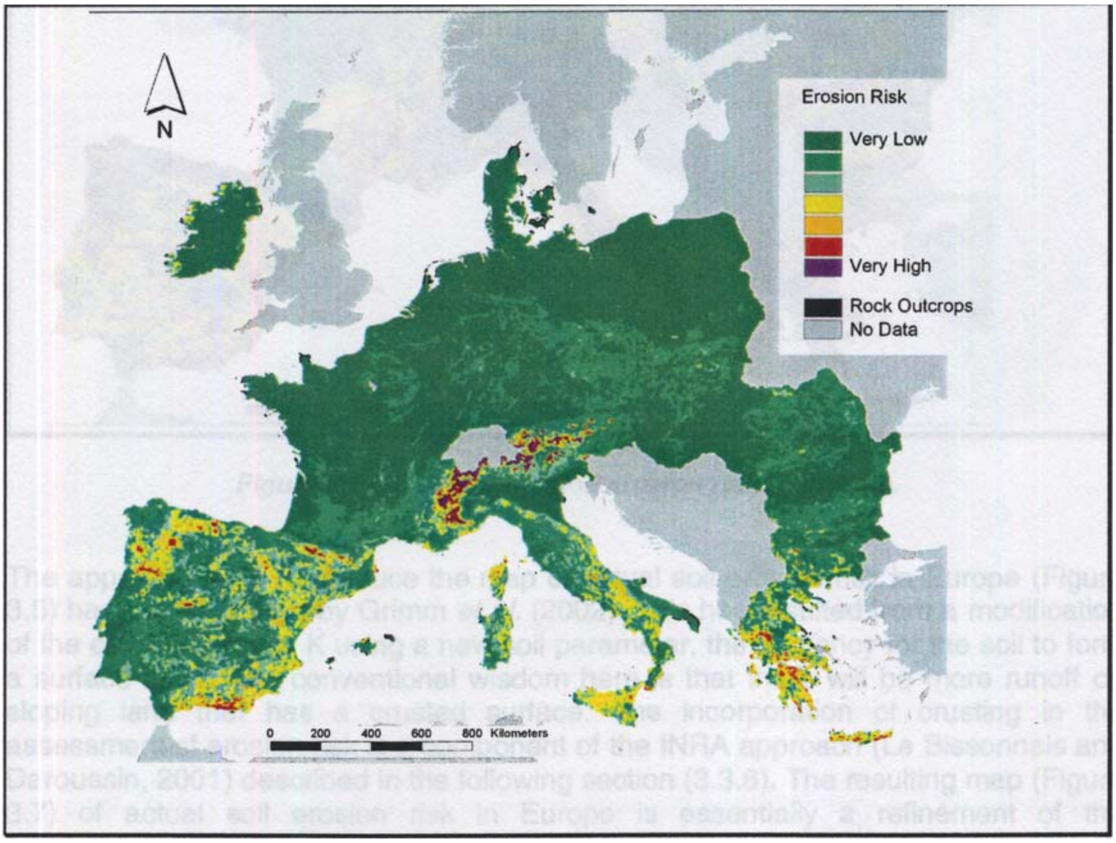


Figure 2.5 – European erosion risk - the USLE approach

<u>The INRA approach</u>

The goal of this project was to develop and apply a methodology based on present knowledge and available data for the assessment of soil erosion risk at the European scale. Soil erosion risk (Fig. 2.6) is assessed taking into account information on land use (CORINE 9 classes), crust formation (4 classes), slope (8 classes) and soil erodibility (3 classes). For details on the exact procedures used see Le Bissonnais *et al.* (2002). There are certain limitations within this model – for example a 1 km x 1 km grid resolution for the DTM does not result in accurate assessment of slope values in areas of gentle relief or short hill slopes (Grimm *et al*., 2002).

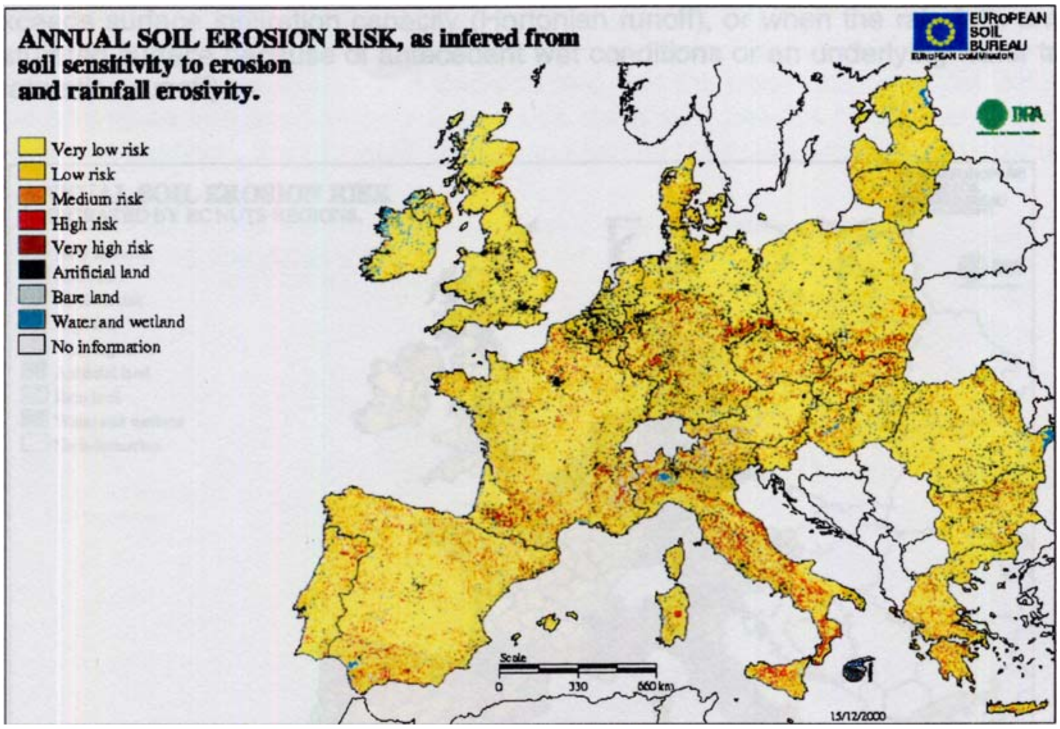


Figure 2.6 – European soil erosion risk - the INRA approach

<u>The PESERA approach</u>

This project is the latest (Kirkby *et al*., 2003) in terms of soil erosion assessments for Europe. Erosion is here a combination of the four natural parameters: land use, topography, soil and climate.

The overall objectives of the project were (Grimm *et al*., 2002):

- to develop a physically based and spatially distributed model for quantifying soil erosion and assess its risk across Europe, attach a prediction error to the model output, and calibrate the model with existing information on soil erosion rate measurements;
- to validate the developed model across different agro-ecological zones at catchment, country and pan-European level, and compare the model output to other methods for erosion risk assessment;

- to ensure the relevance of the approach to end-users through multiple applications and demonstrations, impact assessment, scenario analysis, and development of a user-friendly model.

The PESERA erosion map (Fig. 2.7) is used as a base for this M.Sc. project. All soil erosion computations were based on soil losses determined from the PESERA map for Europe. Reasons for choosing the PESERA approach include its relatively easily accessible GIS format and its innovative approach in soil erosion estimation. It includes physical modelling of soil erosion process and vegetation growth model. Thus it is not just an overlay of GIS layers representing soil erosion factors.

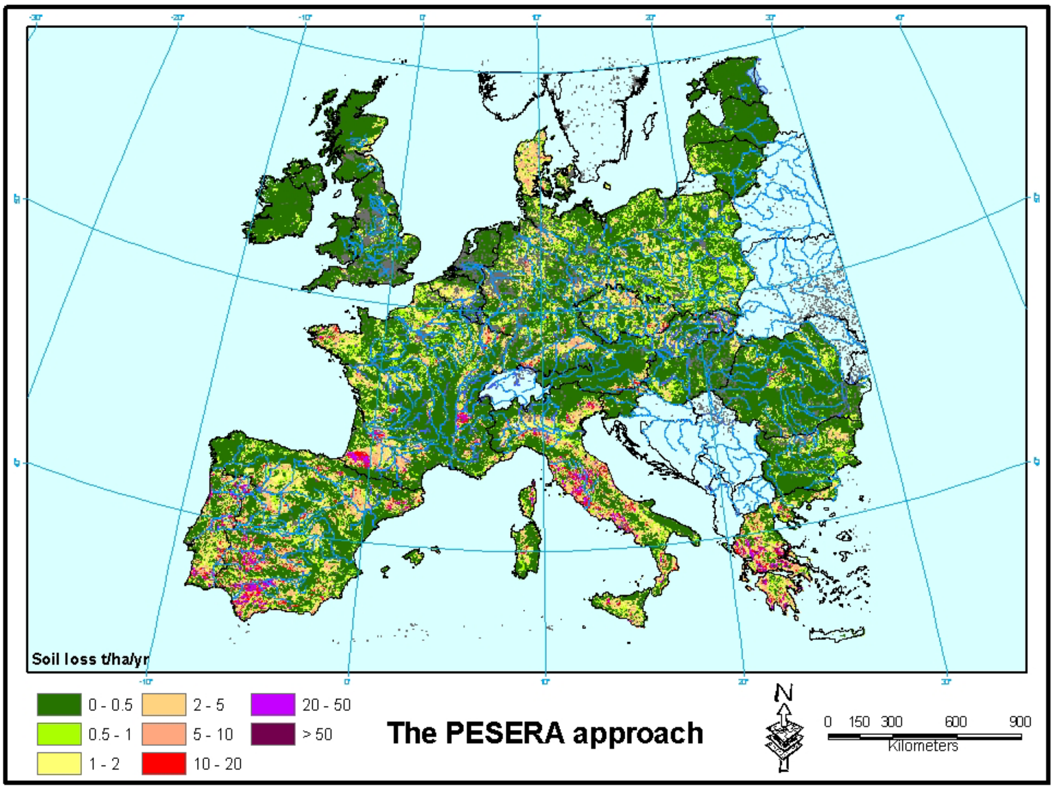


Figure 2.7 – European erosion - the PESERA approach

Figure 2.7 demonstrates quite clearly that the most significant problems with soil erosion can be identified in southern parts of Europe. Spain, the south of France, Italy and Greece in particular belong to the most endangered areas. These parts are particularly prone to erosion because they are exposed to long dry periods followed by heavy bursts of erosive rainfall, falling on steep slopes with fragile soils, resulting in considerable amounts of erosion (Grimm *et al*., 2002). In parts of the Mediterranean region, erosion has reached a stage of irreversibility and in some places erosion has practically ceased because there is no more soil left. With a very slow rate of soil formation, any soil loss of more than 1 $t \cdot ha^{-1} \cdot yr^{-1}$ can be considered as irreversible within a time span of 50 – 100 years (Grimm *et al*., 2002). Soil erosion has become a widespread problem and is significant throughout the continent.

2.2 Sediment delivery

2.2.1 Sediment delivery process

Sediment delivery is a complicated process which is influenced by a huge number of factors. Understanding this process requires deep multi-disciplinary knowledge. It is affected by a variety of processes, where the knowledge is still not complete which makes the modelling particularly difficult. Robinson (1977) states that the amount of sediment delivered at some point in a stream or river system is, amongst other things, a function of the soils; total land use (including construction and surface mining), conservation practices; ability of the flow to transport the material; density of stream channels; and stream bank stability or instability. It is essential to say that finding the links between erosion and sediment concentrations is still a major research aim within this field. Knowledge of sediment delivery from land to rivers in catchments is very important for predicting potential inputs of nutrients and chemicals to water courses and thus potential risk in terms of water quality.

Total sediment yield depends on various catchment characteristics. One such factor is river network density which as it increases means better opportunities for sediment to move from land to water bodies (Roehl, 1962). Furthermore, the river network density may suggest that the soil in that catchment might be fairly impermeable and thus more prone to erosion. A rich river network indicates that there is a high stream creation potential which suggest water is leaving the catchment as an overland flow rather than being infiltrated and leaving as a base flow. The more water on the surface the higher is the risk of erosion. Therefore the river network density is also an important indicator.

Generally the failure to produce widely valid relationships between soil erosion and suspended sediment in streams is due to the high uncertainty involved in the sediment delivery process (Walling, 1983). In addition sediment delivery processes vary in time and space. Even identical precipitation events may cause different sediment yields which will differ by orders of magnitude. That is simply because yield depends also on current land use, the crops being cultivated and previous conditions such as moisture of the soil. It is still not absolutely clear which of the factors is dominant in terms of the sediment delivery process. Syvitski (2003) claims that land use is probably the dominant factor, whereas, for example, Walling and Webb (1996) state that climate and relief are the most likely dominant ones. However it can be agreed that perhaps the most relevant is a combination of those factors. Therefore, all aspects of the sediment delivery process may be considered important. However the main problem is that it is impossible to say exactly how they concur together and how much they contribute to the process under different circumstances. Maybe that is why a widely applicable general relationship, which would produce reasonable results, has not yet been produced. It is likely that it is perhaps even impossible to produce one and it is more likely that more than one relationship will be produced with respect to particular geographical areas and with regard to local conditions.

A relationship between gross erosion and sediment yield can be described very simply using a ratio which has been termed the sediment delivery ratio. It can be written as follows (Brune, 1953; Williams, 1977):

$$SDR = \frac{SY}{E}$$

where

SDR is sediment delivery ratio varying from 0 to 1

SY is the sediment yield

E is gross erosion per unit area above a measuring point

Several authors have attempted to link observed sediment yields and soil erosion estimation. The product of such attempts was usually a sediment delivery expression.

The equations are valid only in the area where they have been developed although some authors have attempted to produce more general relationships by collecting sediment data from around the world. A review of available sediment delivery ratio formulae and sediment yield estimation methods can be found in section 2.2.3.

Sediment delivery to streams from surrounding areas can be relatively easily controlled. The main task is to protect streams from sediment input. This can be achieved by enhancing catchment roughness. Terraces, ditches and all the protective measures help to keep sediment trapped in terrain depressions within a catchment and thus it is not supplied to streams. Creating and maintaining buffer zones alongside streams significantly reduces the sediment amounts supplied to streams (Vrana *et al.*, 1998). It all depends on the particular environmental policy (how much attention is paid to the problem and whether protective measures are supported by authorities) and a farmer's behaviour. However sediment management should be an activity upon which considerable emphasis is placed within any catchment.

2.2.2 Sediment yield estimation

Various papers have been published dealing with the sediment delivery process, SY and their evaluation, leading to a wide range of methods and conclusions. Kirkby and Morgan (1980) suggest three categories of procedures to estimate sediment yield – with a subtle modification of these three categories, three general methods for sediment yield estimation can be introduced:

1) Using predictive, empirically-based equations (either using equations with direct prediction of sediment yield or equations with sediment delivery ratio which is defined as a fraction of gross soil erosion that is actively transported). It should be noted here that sediment delivery estimation using the classical approach is based solely on estimates of erosion – there are certainly ways to measure soil erosion (using caesium-137, pins, experimental areas) but these cannot be applied over such large areas as investigated here.

2) Mathematical modelling of erosion and sediment delivery processes. Such modelling is generally difficult to apply over large areas. The main problem is as the

modelled area increases, the number of additional local issues influencing the modelled processes rapidly increases. In large areas, all of the local influences might not be possible to consider thus the advantages of physical modelling are vanishing. Furthermore physical models should be calibrated prior to use and often require relatively precise data which may not be accessible or its acquisition may be expensive. Formerly there was also an HW issue but nowadays there is no problem in that respect.

3) Sediment concentration and discharge measurements or reservoir sediment deposition measurements. Kirkby and Morgan (1980) claim that direct measurement is the best way to obtain sediment yield; nowadays this may still be the most accurate method, using modern non-contact methods in particular (such as geophysical methods of GPR – ground penetration radar or sonar, used for example by Moorman, 2001). Perhaps the most accurate method is a long-term measurement of sediment concentration (including bed load) and discharge. Sediment concentration (representing a certain time unit depending on the sampling frequency) multiplied by the amount of water per that time unit gives a value of transported sediment. However these cannot really be used for future sediment yield prediction and results from any particular estimation are not transferable outside the measured location.

This chapter is rather focused on empirical approaches for sediment delivery ratio estimation with emphasis on those which should be valid for large catchments. As described above in point two, deterministic models based on the mathematical description of physical processes of sediment delivery are (for above given reasons) often excluded from application in large catchments (Grimm *et al.*, 2002). Usually, the larger the area the less appropriate is the use of deterministic models.

The process of decision making about the most appropriate method to estimate sediment yield in a particular case depends very much on the purpose of the estimate. Different methods would be used to assess how much sediment has to be removed from the storage volume of a reservoir (where a relatively accurate estimation is required in order to calculate the costs) as compared with general landscape planning which needs just a gross estimate and where there is no need for applying time-consuming modelling.

A method, surveying sediment depositions in reservoirs, has been widely used in several studies (Bis, 1999; Dostal *et al.*, 2002; Dostal *et al.*, 2003; Becvar, 2004a) in the Czech Republic. The method has been used for estimation of sediment deposition mainly in ponds and small reservoirs. Several cross-profiles are made and the depth of sediment is measured with a scaled stave alongside each profile. GPS is used to obtain the coordinates. A digital model of sediment is then created and total sediment volume is extracted. Another example is a case study (Zarris *et al.*, 2002) carried out in Greece where a combination of hydrographic surveying in a reservoir at the catchment outlet with a combination of USLE and GIS was used. The model of USLE for soil erosion estimation within a GIS is widespread and USLE is still a good model to use (Quinton, 2004). This is a commonly used and relatively simple method. Notwithstanding the fact that USLE is an empirical approach it still provides relatively acceptable results (Becvar, 2004a).

Another approach would be to collect sediment yield data and consequently link this information with catchment characteristics. This approach may be transferable and may be used in similar environments where the developed relationship could potentially be successful.

To summarise it can be said that for precise sediment yield estimation either measured data (suspended sediment concentration and discharge or reservoir sediment deposition) or a calibrated simulation model with sufficient amounts of input and validation data, are required.

2.2.3 Review of sediment yield and sediment delivery ratio equations

This section reviews the most commonly used equations for SDR estimation or SY computation. Equations developed for single event SDR estimation were omitted from the review because they lie beyond the interest of this work. Many of the following equations have limitations in their parameters. The limitation is always determined by the physical limits of the environment where the equations have been derived (e.g. area of the catchment). In a few cases the information about limitations and data used is incomplete. This is due to current unavailability of particular papers or lack of information in the paper.

1) Fournier's equation (Fournier, 1960)

Fournier (1960) is considered as a classic monograph (Walling & Webb, 1996) and gives an equation for annual suspended sediment yield:

$$\log(E) = 2.65\log\left(p^2 P^{-1}\right) + 0.46H\tan\phi - 1.56$$

where

E = suspended sediment yield (t·km^{-2}·yr^{-1})
p = precipitation in month of maximum precipitation (mm)
P = mean annual precipitation (mm)
H = mean altitude of basin (m)
Φ = mean basin slope (°)

Fournier's method for the determination of suspended sediment yield is based on field measurements made in many parts of the world for drainage basins of varying magnitude. This equation has also been tested in temperate alpine catchments by Slaymaker (1977) where it has been shown to be inappropriate, as it makes no allowance for precipitation in the form of snow.

2) Jansen and Painter's equation (Jansen & Painter, 1974)

$$\begin{aligned}\log(S) &= -2.032 + 0.100\log(D) - 0.314\log(A) + 0.750\log(H) + \\ &+ 1.104\log(P) + 0.368\log(T) - 2.324\log(V) + 0.786\log(G)\end{aligned}$$

where

S = suspended sediment yield (t·km^{-2}·yr^{-1})
H = altitude (m)
P = mean annual precipitation (mm)
V = measure of vegetation cover
G = estimate of proneness to erosion (depends on soil type)
R = relief-length ration (m·km^{-1})
T = average annual temperature (°C)

A = basin area (km^2)

D = no description of this factor in the paper ($10^3 m^3 \cdot km^2$)

This equation has been derived from sediment yield data from 79 catchments greater than 5000 km^2 across the world. Catchments were categorised into four climatic groups. Within each climatic group, sediment yield was assumed to be a function of the eight parameters. For each climatic group one equation has been provided. For all climates the overall equation is given above. Jansen & Painter (1974) state that this equation could be sensibly used to predict the scale of the sediment problem in rivers for which no sediment records exist.

3) McPherson's equation (McPherson, 1975)

$$\log(TSE) = 0.8797\log(\Phi) - 0.690\log(D) + 0.6462\log(L) + 1.1035$$

where

TSE = suspended plus dissolved sediment yield ($t \cdot mi^{-2} \cdot yr^{-1}$)

Φ = mean land slope (°)

D = basin diameter (mi)

L = main channel length (mi)

This equation has been derived from 36 catchments in southern Alberta in Canada varying in size from 30 to 551 mi^2.

4) Williams's equation (Williams, 1977)

$$DR = 1.366 \cdot 10^{-11} (DA)^{-0.0998} (ZL)^{0.3629} (CN)^{5.444}$$

where

DR = delivery ratio

DA = drainage area (km^2)

ZL = relief-length ratio ($m \cdot km^{-1}$)

CN = average SSC curve number for a catchment

This equation has been developed based on 15 catchments near Aubrey, Texas with catchment areas of up to 65 km^2. Williams (1977) suggests that this equation should be useful for predicting delivery ratios for nearby basins that have characteristics fairly similar to those where it has been developed. In this case R^2 = 0.93.

5) Renfro’s equation (Renfro, 1975)

$$\log(DR) = 1.87680 - 0.14191\log(10A)$$

where

DR = sediment delivery ratio in percent of annual erosion
A = sediment contributing area (mi^2)

Renfro (1975) developed this equation based on the Blackland Prairie study in Texas. For this study annual sediment yield data were available from 14 basins ranging in size from 0.43 to 97.4 mi^2. The coefficient of curvilinear correlation (nonlinear correlation, correlation in which the rates of change of the variables is not constant) is 0.96.

6) Renfro’s equation (Renfro, 1975)

$$\log(DR) = 2.94259 - 0.82362co\log(R/L)$$

where

DR = estimated sediment delivery rate in percent of annual gross erosion
R/L = relief-length ratio
colog (R/L) = log (L/R)

This equation has been published in the same paper as equation 5. This formula has come from a study in the Red Hills in Oklahoma and Texas. The method results from statistical analyses of 25 records of basin sediment delivery rates. The coefficient of curvilinear correlation between variables is 0.987. In this case relief and channel length are given in feet.

7) Williams and Berndt's equation (Williams & Berndt, 1972)

$$SDR = 0.627(SLP)^{0.403}$$

where

SDR = sediment delivery ratio

SLP = slope of main stream channel (%)

This equation has been derived from sediment data from five small catchments in the Blacklands of Texas. The authors recommend calculating SLP in segments; however one segment may also be used. In the latter case, SLP is the difference in elevation divided by the channel distance between the river basin outlet and the most distant point in the basin. The standard estimate of error of the above equation was about 1 % of the mean delivery ratio.

8) Walling's equation (Walling, 1983)

$$DR = C_{soil} / C_{sed}$$

where

DR = sediment delivery ratio (%)

C_{soil} = proportion of clay in the soil

C_{sed} = proportion of clay in the sediment

Walling (1983) assumes here that all clay-sized particles move through the conveyance system without deposition. Sediment data (on-site rates of erosion) have been obtained from four small catchments (area up to 2.66 km^2) in the USA.

9) Vanoni's equation (Vanoni, 1975)

$$SDR = 0.42(A)^{-0.125}$$

where

SDR = sediment delivery ratio
A = drainage area (mi^2)

This model is considered a more generalized one to estimate SDR mainly because Vanoni (1975) used the sediment data from 300 catchments throughout the world to develop this power function.

10) USDA SCS equation (USDA SCS, 1971)

$$SDR = 0.51(A)^{-0.11}$$

where

SDR = sediment delivery ratio
A = drainage area (mi^2)

This SDR model has been developed by the USDA SCS (1971) based on data from the Blackland Prairie, Texas.

11) Dendy and Bolton's equation (Dendy & Bolton, 1976)

$S = 1280(Q)^{0.46}(1.43 - 0.26\log(A))$ for areas where runoff is less than 2 in.

$S = 1958(e)^{-0.055}Q(1.43 - 0.26\log(A))$ for other areas

where

S = sediment yield ($t \cdot mi^2 \cdot yr^{-1}$)
Q = runoff (in.)

A = watershed area (mi^2)

12) Maner's equation (Maner, 1958)

$$\log(DR) = 2.962 + 0.869\log(R) - 0.854\log(L)$$

where

DR = delivery ratio
R = relief of the catchment (ft)
L = length of the catchment (ft)

13) Roehl's equation (Roehl, 1962)

$$\log(DR) = 4.50047 - 0.23043\log(10W) - 0.51022co\log(R/L) - 2.78594\log(BR)$$

where

DR = sediment delivery ratio (%)
W = watershed area (mi^2)
R/L = relief-length ratio
BR = bifurcation ratio

This relationship has been developed with respect to various characteristics such as relief, area, stream order, bifurcation ratio and drainage density. Sediment data from 38 catchments from various places in the USA with size from 0.55 to 28.8 square mile have been used. The multiple correlation coefficient was 0.961 in this case. This relationship may be reasonable to use because it combines area and relief-length ratio which are variables used by the other authors and in addition, there is a bifurcation ratio. The bifurcation ratio describes the river network density which influences the amount of sediment supplied and thus is relevant for SDR determination.

14) Mutchler and Bowie's equation (Mutchler & Bowie, 1976)

$$DR = 0.448 - 0.006A + 0.010RO$$

where

DR = sediment delivery ratio

A = basin area (ha)

RO = annual runoff (cm)

Mutchler and Bowie (1976) used sediment data from two sub-basins in the Pigeon Roost Creek river basin in northern Mississippi in order to compute SDR for each year of a 15-year period (1958-1972). The total area of the river basin is 303 km^2. For estimation of gross erosion the USLE (Wischmeier & Smith, 1978) has been used.

15) Mou and Meng's equation (Mou & Meng, 1980)

$$DR = 1.29 + 1.37\ln(R_c) - 0.025\ln(A)$$

where

DR = sediment delivery ratio

R_c = gully density

A = basin area (km^2)

16) Dickinson's equation (Dickinson *et al.*, 1986)

$$DR = \alpha\left(\frac{H_c \cdot S^{1/2}}{n \cdot L}\right)^{\beta}$$

where

DR = delivery ratio

H_c = a hydrologic coefficient expressing the ability of a certain area to generate surface runoff (estimated using the SCS CN method)

S = slope (%)
L = distance between sediment source and channel (m)
n = roughness coefficient that depends on the type of land use
α, β = empirical parameters, being 9.53 and 0.79 respectively

Some of the equations described above were used and compared in a study carried out by Quyang (Quyang & Bartholic, 1997). The objective of this study was to find suitable SDR equation which would perform well in the Saginaw Bay (Lake Huron, Michigan, USA) basin. Sediment yields obtained from gauging stations were compared to yields calculated using sediment delivery ratios. Quyang and Bartholic, (1997) state that empirical equations relating SDR with one or more factors were still useful tools to estimate sediment delivery. Renfro's (1975) equation had the highest SDR while Vanoni's (1975) resulted in the lower SDR. Finally it was concluded that the USDA SCS (1971) and SWAT-SDR (Arnold *et al.*, 1996) (a single event model) gave a reasonable accuracy of sediment yield estimation and therefore were good models for use in the Saginaw Bay basin.

It is fairly obvious from the above review that the majority of SDR and SY estimation methods are predominantly based on defining statistically significant links between observed yields and catchment parameters. They are mostly multiple regression equations and thus rarely dimensionally balanced. The most common catchment characteristics related with SY are area of the catchment, relief, length or relief-length ratio. It can be than concluded that perhaps morphology is likely to be the dominant control factor on sediment delivery. However other authors also relate SY to river network density, soil properties, vegetation cover or a runoff height. Since all these play a role in sediment delivery process the key task in order to estimate sediment yield is to evaluate the significance of these factors and describe how they concur together to result in a certain SY value.

2.3 Sediment concentration prediction

There has been a lot of work and research carried out about soil erosion and sediment delivery processes. Considerably less work has been completed on sediment concentration prediction methods. High variability involved in the processes and incomplete knowledge has resulted in a lack of simple empirical methods.

Formerly an estimation of likely SSC was needed, for example, in the design of open channels. An assumption that channels that carry water with high sediment concentrations can withstand higher velocity flows than those channels that carry water with low concentration meant that sediment concentration was important information for the channel design. For that purpose a methodology was introduced in which sediment concentrations are determined as a ratio of the weight of sediment to the weight of water (Porterfield, 1972). Another traditional method that has been widely used (Walling, 1977; Crawford, 1991) is the sediment rating curve method. After sufficient sediment and discharge data were collected they can be used for developing a sediment rating curve. It describes the statistical relationship between suspended sediment concentration and discharge and is normally given as:

$$C_S = {}_a Q^b$$

where

C_S is the instantaneous sediment concentration ($\mathrm{mg.l^{-1}}$)

Q is the instantaneous discharge ($\mathrm{m^3 \cdot s^{-1}}$)

a, b are the sediment rating coefficient and exponent

The relationship between discharge and suspended sediment concentration is most commonly accepted as a base for sediment concentration prediction methods. However some authors claim (Lewis and Eads, 1996) that a better relationship can be found between the turbidity and SSC. Nonetheless, turbidity measurements are less likely to be collected than discharge. Discharge is much more accessible information and thus the methods to predict SSC predominantly rely on the relationship between discharge and SSC.

The relationship is however somewhat ambiguous. There are locations with a strong positive correlation but also locations with negative correlation as shown in a study by Gomez *et al.* (1995). The positive or negative correlation is very much determined by the availability of material during rainfall. If there was just a very little sediment supplied during a storm or rain event there would be a dilution effect observed and measured sediment concentrations may therefore be lower in high flows.

A common behaviour observed during a storm or rain event is the anti-clockwise hysteresis loop effect in SSC progression in time. Figure 2.8 (Ongley, 1996) demonstrates the behaviour during a storm or rain event. A series of discharge measurements and water samples were taken at intervals throughout a storm event.

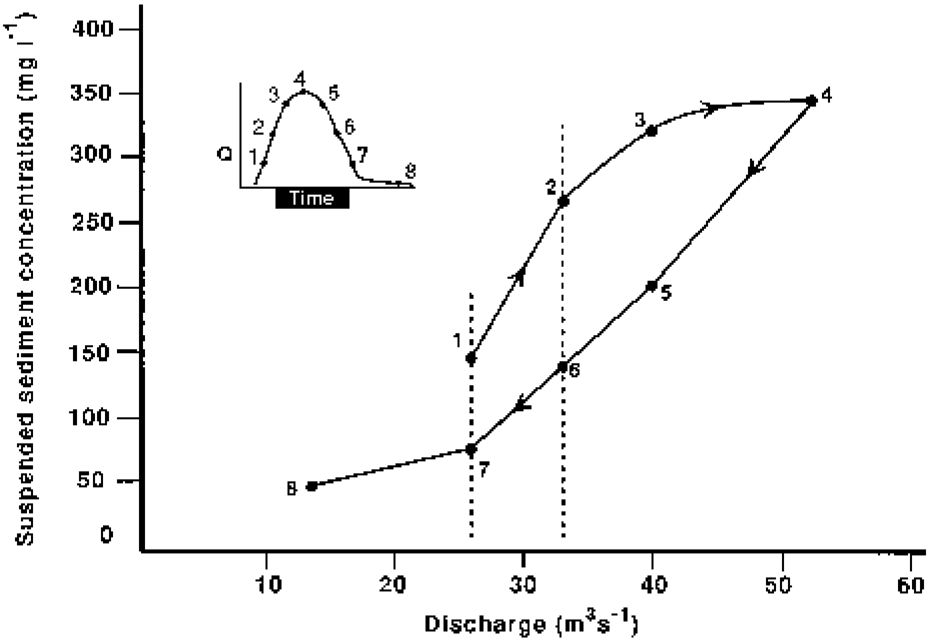


Figure 2.8 – Typical hysteresis effect observed during a storm or rain event

Another way of looking at SSC and discharge is through the artificial neural networks (ANN) (Zekai, 2004). Using this method assumes that monitored discharge and SSC data is available. The data are used for training the ANN and once has enough experience it can be used for SSC predictions. Further techniques for sediment concentration estimation may be found in the literature (Einstein, 1950; Ackers & White, 1973; Engelund & Fredsoe, 1976), however many of them have been developed from laboratory rather than river studies. They thus are more representative of a river's ability to transport sediment than the combined supply and transport process seen in natural rivers.

Such methods are not suitable for use in this study. Having a big study area and collected data of varying quality from various locations it can be agreed that a simple method for SSC would be appropriate. Hence the SSC prediction will be based on similar method as introduced by Porterfield (1972).

2.4 GIS role in erosion and hydrological modelling

GIS has become an essential tool for catchment hydrology and erosion modelling (Becvar, 2004b). The catchment is regarded as a fundamental unit geomorphologically, hydraulically and also environmentally and ecologically (Foster *et al.*, 1995). It is a logical unit to calculate water balance and soil erosion which often can be in conflict with political boundaries. GIS is a very powerful tool generally used for data management, logical and mathematical operations between layers and preparing data for deterministic models. At present a lot of commonly used modules for hydrology and catchment operations are incorporated in GIS. For this work GIS was essential to manage all the data and to carry out all the calculations. Therefore finding the best solutions and the most appropriate GIS techniques was also the subject of the literature review. The big advantage of GIS packages lies in having an effective way to automate sequences of various operations in macros and scripts. Another undeniable quality is in the possibility to present results as graphical outputs – as maps, charts and others which can be very powerful.

3 Study area

The aim of this study is to cover the entire European continent. The intention to cover the entire continent will be reviewed once available data have been assessed. Essential data might be missing or unavailable and thus the extent of the study area might slightly change. A crucial factor is the level of spatial resolution of the study. Many thousand, if not more, catchments may be found in Europe, but obviously it would not be feasible to carry out the study for all of these. Therefore from the original GIS catchment layer (Fig. 3.1) just 44 catchments (Fig. 3.2) belonging to the major European rivers were delineated. The catchment layers both result from a project called "Deriving drainage networks and catchment boundaries at the European scale" (Colombo *et al.*, 2001) where catchment boundaries were produced at different scales.

The European continent is heterogeneous in terms of vegetation, environment and biodiversity in general. In both directions north-south and west-east the environment changes. For example, from north to south the environment changes from arctic, through temperate to the Mediterranean. Of course this variability causes major problems in modelling. The more the environment differs the harder it is to generalize. This is particularly true for soil erosion and sediment process modelling, because these processes are influenced by a number of factors which differ significantly across the continent. Another factor whose significance is considerable is that Europe is not fully unified. This may be seemingly far from a modelling concern, but it has to be taken into account that each country has different environmental policy, agriculture policy, land use patterns and water management for instance, so besides natural boundaries like catchments, there are also political boundaries which make the continent even more heterogeneous. This is even more obvious when the headwater of a river is in a different country to the river mouth and the river flows through yet further countries. The influence of policy in a country whose natural characteristics could be considered as prone to erosion may result in lower erosion than expected and *vice versa*.

Figure 3.1 – Original European catchments layer

Figure 3.2 – Final European catchments defining the study area

4 Available data

The area of study under investigation in this work represents the entire European continent. Data acquisition for such a large study area was a relatively difficult and time-consuming part of this work. Since there was no budget for the data, the quality of the data is only as good as the quality of data which was obtainable free of charge. To a certain extent this was a limiting factor in the development of the methodology. This concerns specifically the monitored flow and SSC data.

4.1 Spatial data

Digital Terrain Model (DTM)

A digital terrain model is essential for this study. A DTM can be used to define drainage areas for any point on a river network, thus allowing river basins to be viewed. Many variables which are required for calculation of sediment delivery ratios can be determined only from a DTM. Typically these are relief-length ratio, or mean slope in the catchment. For these purposes a DTM at 250 metre resolution was obtained from the National Soil Resources Institute (NSRI) at Cranfield University, Silsoe, UK. Elevation data were obtained during an 11-day shuttle radar topography mission (SRTM) which took place in February of 2000.

Soils

Soil layers are highly important for soil erosion estimation because soil properties strongly affect rates of soil erosion. However in this case soil erosion information was obtained from the PESERA map. Nevertheless, soil layers are also required for determination of certain parameters in sediment delivery equations. The European soil database with GIS layers is readily downloadable, without charge, from http://eusoils.jrc.it.

Runoff data

Some authors use runoff information for sediment delivery ratio determination. Therefore runoff data for the European continent were sought. Also, runoff data will be required when converting sediment yields to sediment concentration. Mean annual runoff data can be easily downloaded, without charge, from: http://www.grdc.sr.unh.edu/html/Runoff/index.html. Unfortunately it is not very good quality data in terms of spatial resolution (0.5 degree) hence the layer was not used as a source for SY calculation.

Land cover

Some of the sediment delivery equations also require information about land cover. The only available source was CORINE land cover obtained from the Institute of Water and Environment (IWE) at Cranfield University. This is also at 250 metre resolution and it is for the year 2000. Unfortunately this data source is not suitable due to accuracy levels such as, for example, for estimating the parameter CN in Williams's (1977) equation.

River network, catchment boundaries

These layers were fundamental for this study, catchment boundaries in particular. The river network layer was obtained with the PESERA administrative layers. The catchment boundaries layer is an output of a project called "Deriving drainage networks and catchment boundaries at the European scale" (Colombo *et al.*, 2001).

Soil erosion

There are a number of soil erosion approaches for the European continent, but their use is limited mainly due to their spatial resolution and GIS layers are not always available. For this study the latest approach – PESERA (see section 2.1.1.3) was used. Data are also available, free of charge, upon request. All necessary detail can be found at http://eusoils.jrc.it/ESDB_Archive/pesera/pesera_data.html.

4.2 Revision of study area

The extent of the work is limited by available data sources. Data are not available for Scandinavia. In terms of the PESERA soil erosion map the continent is not entirely covered with soil erosion information either (Fig. 2.7). Overall there is a lack of information for Switzerland, Scandinavia and the former Yugoslavian area.

Unfortunately soil erosion information missing for one country often means missing information in more than one basin. These areas have been excluded from this study.

4.3 Temporal data

Temporal data in this study were used in both the stage of testing calculated sediment yields against those obtained from measured data and in the stage of predicting sediment concentration.

For sediment yield determination from measured data, information about sediment concentration and discharge were required. Obtaining such data proved to be one of the most time-consuming parts of the study. Moreover data of high quality, such as daily long-term sampling, must normally be paid for (CHMI, 2005). Nevertheless, sufficient data for testing were obtained from various sources with different temporal resolution and formats.

Sediment concentration data (Fig. 4.1) were obtained either from the internet or other sources. Contacting relevant people and hydrological institutions constituted major activities during this stage.

Flow data (Fig. 4.2) which were used for predicting sediment concentration were obtained from two sources. There are very good discharge data sources at: http://grdc.bafg.de/servlet/is/987/ or http://www.rivdis.sr.unh.edu/ (Vörösmarty *et al.*, 1996, 1998). Upon request, either daily or monthly data are free of charge.

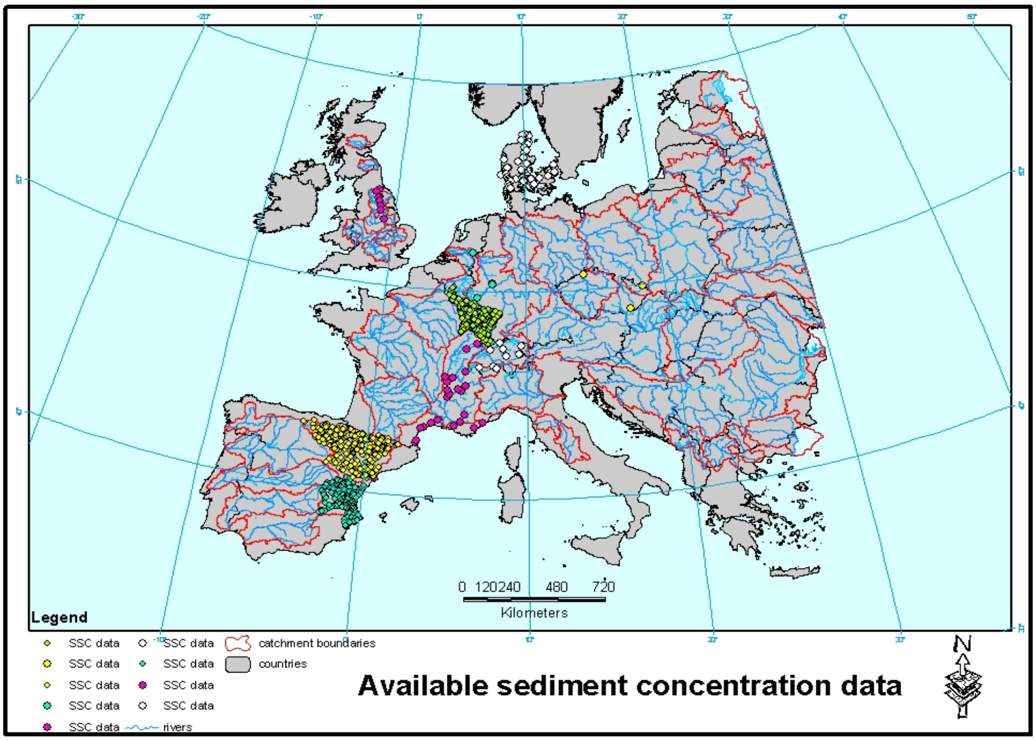


Figure 4.1 – Available sediment concentration data for Europe relevant to this study

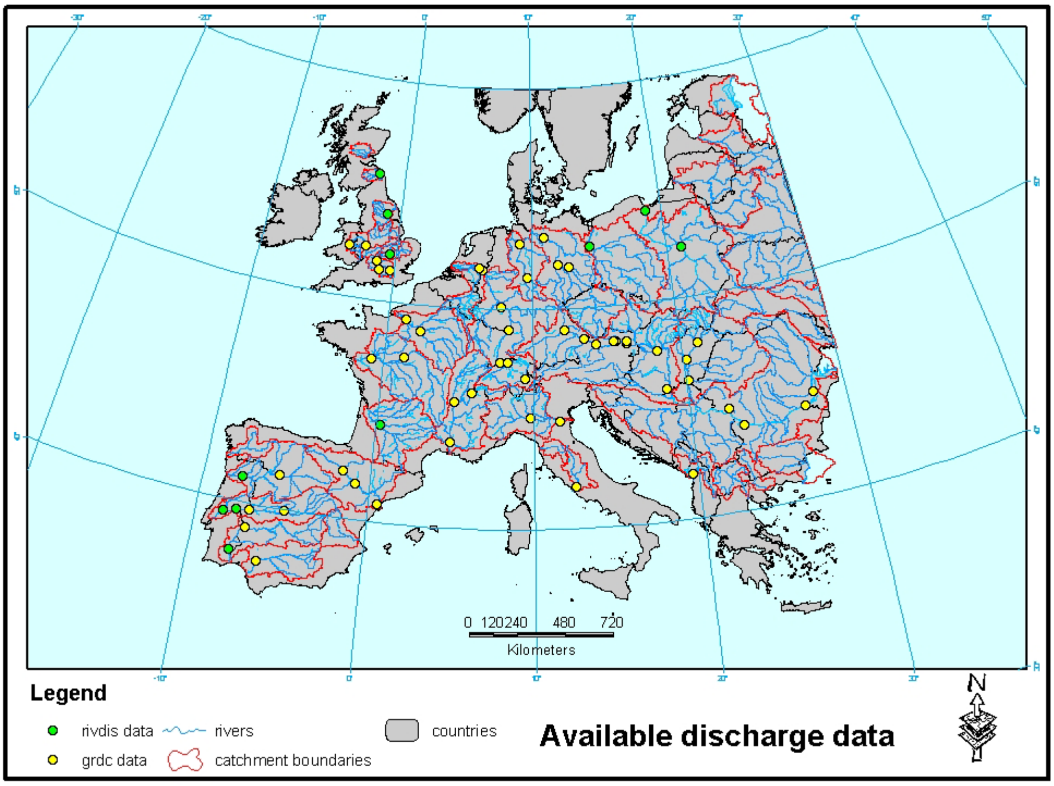


Figure 4.2 – Available discharge data for Europe relevant to this study

4.4 Sediment yield data

Published sediment yield data may be found for almost all of the catchments identified in Chapter 3. Often however, published sediment yield information may be for a location that is not at a defined basin outlet. The date of the estimation may also be a reason for rejecting published sediment yield. The reason for rejecting such data could be that the landscape is changing: land cover and land use patterns were changed particularly in former communist countries in eastern Europe (Van Rompaey *et al.*, 2002). However, published sediment yield (SY) information gives at least some information about the order of magnitude the actual sediment yield may be and may provide some general knowledge. Figures 4.3 and 4.4 show typical patterns – the further south the river the higher the sediment yield.

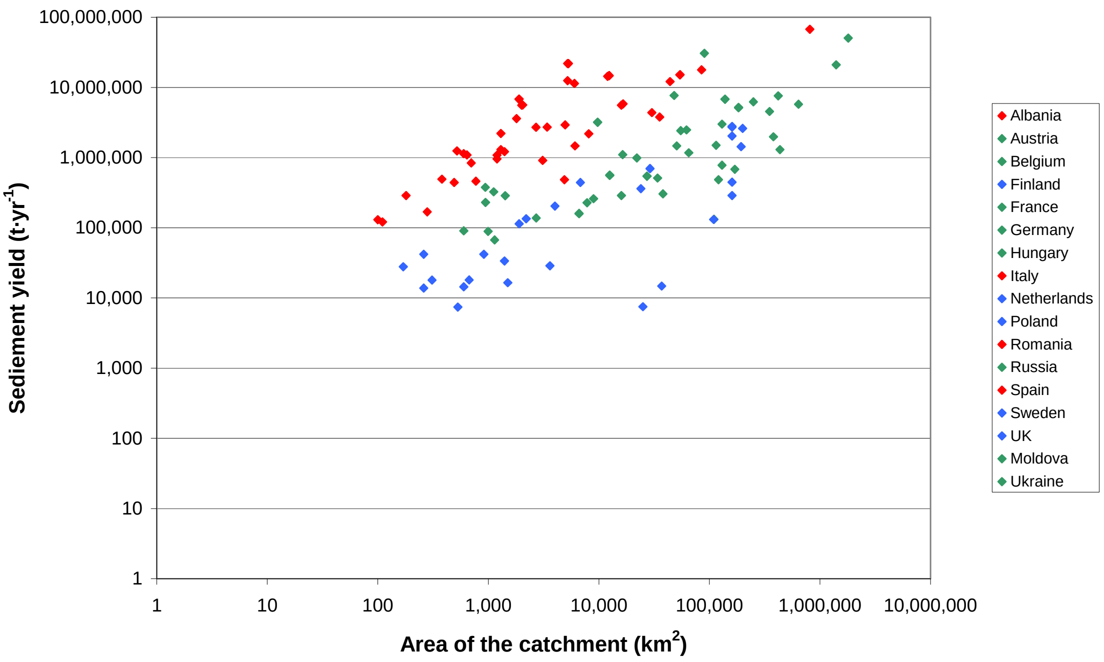


Figure 4.3 – Sediment yields – geographical distribution by country

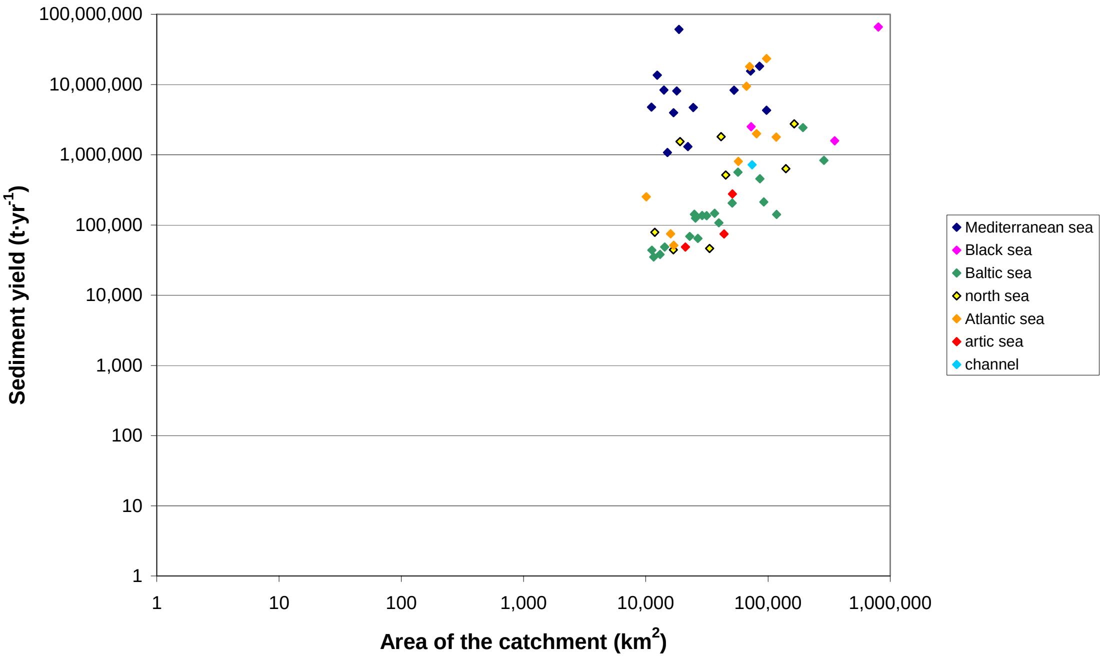


Figure 4.4 – Sediment yields – geographical distribution by ocean

The value of this information should not be underestimated in any case. Collected information from various sources regarding sediment yields in the area of interest can be found in Tables 4.1, 4.2, 4.3, 4.4 and Figures 4.5, 4.6. Data presented in this study come from four sources:

1) Laronne & Mosley have published SY for some European rivers in Erosion and Sediment Yield (Larone & Mosley, 1982) (Tab. 4.1).

Table 4.1 – Sediment yields for some European rivers (Laronne & Mosley, 1982)

River	Location	Area (mi^2)	Suspended load (t·yr^{-1})	Source
Volga	Dubovka	521,490	20,770,000	(Lopatin, 1952)
Danube	mouth	315,000	21,420,000	(Corbel, 1959)
Dnepr	Verkhnedneprovsk	167,520	1,210,000	(Lopatin, 1952)
Don	Razdorskaya	146,020	5,360,000	(Lopatin, 1952)
Ural	Topolinski	74,790	1,760,000	(Lopatin, 1952)
Vistula	Tczew	74,560	1,690,000	(Jarocki,

				1963)
Tisza	at the confluence	60,310	11,040,000	(Fournier, 1960)
Rhine	mouth	56,000	504,000	(Corbel, 1959)
Rhine	Lake Constance	4,600	9632000*****	(Corbel, 1959)
Loire	Nantes	46,740	467,000	(Corbel, 1959)
Order	Gozdowice	42,230	147,000	(IASH, 1967)
Po	Pontelaguscuro	20,960	16,770,000	(IASH, 1967)
Seine	Paris	17,140	1220000*****	(Corbel, 1959)
Tiber	Rome	6,390	6,420,000	(IASH, 1967)
Drin	Can Deje	4,770	16,220,000	(IASH, 1967)
Garonne	Tolouse	3,860	2,760,000	(Fournier, 1960)
Inn	Reisach	3,767	3,515,000	(IASH, 1967)
Arno	San Giovanni alla Vena	3,160	2,430,000	(IASH, 1967)
Semani	Urae Kucit	2,040	24,190,000	(IASH, 1967)
Simento	Giarretta	707	3,960,000	(IASH, 1967)
***** includes bed load				

2) One year later Walling (1983) has published SY for some European rivers in a paper entitled The Sediment Delivery Problem (Tab. 4.2).

Table 4.2 – Sediment yields for some European rivers (Walling, 1983)

River	Station	Area (km^2)	Tot. SS load (t·yr^{-1})	Source
Wisla	Zavichost	50,543	1,990,000	(Walling, 1983)
Wisla	Plock	168,857	1,180,000	(Walling, 1983)
Lech	Fussen	1,422	329,433	(Walling, 1983)
Lech	Feldheim	2,124	192,489	(Walling, 1983)
Po	Becca	30,170	4,374,650	(Walling, 1983)
Po	Piacenza	35,430	3,791,010	(Walling, 1983)
Atrak	Shirrin-Darrah	1,500	92,510	(Walling, 1983)
Atrak	Reza-Abad	5,430	31,406	(Walling, 1983)

3) Another source of SY information is the FAO (2005) internet sediment yield database (Tab. 4.3). The location where SY information exists is shown Figure 4.5. The FAO database does not provide geographical coordinates or names for all the locations therefore not all the records listed in Table 4.3 could be shown on the map (Figure 4.2).

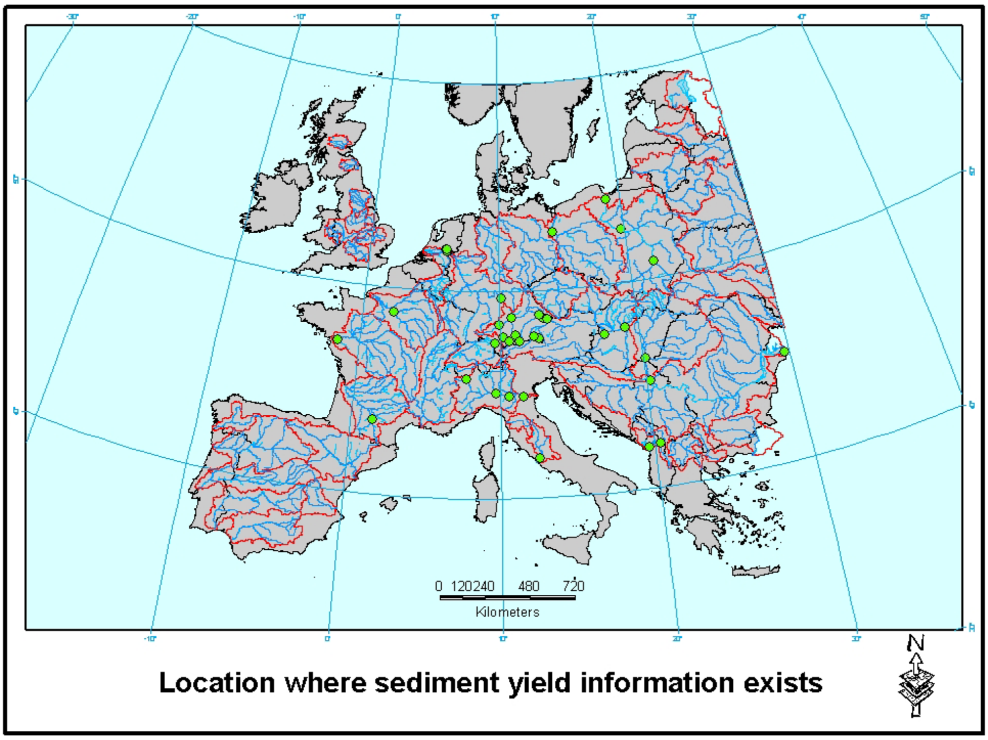


Figure 4.5 – Locations where sediment yield information exist in Europe

Table 4.3 – Sediment yields for some European rivers (FAO, 2005)

River	Location	Country	Area (km^2)	SY (t·yr^{-1})
Drini	Van Deje	Albania	12,368	14,717,920
Drini	Can Deje	Albania	12,368	14,717,920
Drini		Albania	12,000	14,400,000
Drini	Kukes	Albania	4,956	2,928,996
Osumi	Ura Vajgurore	Albania	2,042	5,635,920
Osumi		Albania	2,000	5,600,000
Semani	Urage Kucit	Albania	5,288	21,945,200
Semani		Albania	5,288	21,945,200
Semani		Albania	5,200	21,840,000
Shkumbini	Paper	Albania	1,890	6,785,100
Shkumbini		Albania	1,900	6,840,000
Burdekin		Austria	130,000	2,990,000
Scheldt		Belgium	22,000	990,000
Kalkkinen		Finland	25,000	7,500

River	Location	Country	Area (km^2)	SY (t·yr^{-1})
Kymi joki		Finland	37,000	14,800
Ardour		France	16,000	288,000
Garonne		France	55,000	2,420,000
Loire	Nantes	France	121,005	484,020
Loire		France	115,000	1,495,000
Rhone		France	90,000	30,600,000
Seine		France	65,000	1,170,000
Amner	Weilheim	Germany	600	90,600
Donau	Vilshofen	Germany	50,544	1,465,776
Elbe		Germany	130,000	780,000
Iller	Krugzell	Germany	1,118	326,456
Iller	Wiblingen	Germany	995	88,555
Inn	Passau	Germany	16,423	1,100,341
Inn	Reisach	Germany	9,760	3,191,520
Inn	Reisach	Germany	9,760	3,191,520
Isar	Platting	Germany	7,826	226,954
Isar	Platting	Germany	8,964	259,956
Isar	Sylvenstein	Germany	1,138	67,142
Lech	Feldheim	Germany	2,704	137,904
Lech	Fussen	Germany	1,422	287,244
Main	Marktbreit	Germany	27,225	544,500
Main	Marktbreit	Germany	27,225	544,500
Oder		Germany	110,000	132,000
Rhine		Germany	170,000	680,000
Saalach	Unterjettenberg	Germany	940	377,880
Tiroler Ache	Marquartstein	Germany	944	229,392
Weser		Germany	38,000	304,000
Danube	Nagymaros	Hungary	183,262	5,131,336
Danube	Nagymaros	Hungary	183,262	5,204,641
Raba	Arpas	Hungary	6,610	158,640
Raba	Arpas	Hungary	6,610	160,623
Tisza	Szeged	Hungary	138,408	6,781,992
Tisza	Szeged	Hungary	138,408	6,781,992
Tisza	Tivadar	Hungary	12,540	564,300
Tisza	Tivadar	Hungary	12,540	558,030
Arno		Italy	8,100	2,187,000
Arzilla		Italy	100	130,000
Aso		Italy	280	168,000
Biferno		Italy	1,300	2,210,000
Bradano		Italy	2,700	2,700,000
Chienti		Italy	1,300	1,300,000
Esino		Italy	1,200	960,000
Ete Vivo		Italy	180	288,000
Foglia		Italy	700	840,000
Lamone		Italy	5,200	12,480,000
Lamone		Italy	520	1,248,000
Metauro		Italy	1,400	1,218,000
Misa		Italy	380	494,000
Musone		Italy	640	1,088,000

River	Location	Country	Area (km^2)	SY (t·yr^{-1})
Pescara		Italy	3,100	914,500
Po	Pontelagoscuro	Italy	54,290	15,201,200
Po	Pontelagoscuro	Italy	54,290	15,201,200
Po		Italy	54,000	15,120,000
Po	Boretto	Italy	44,070	12,119,250
Po	Piacenza	Italy	35,430	3,791,010
Po	Becca	Italy	30,170	4,374,650
Po	Metrano	Italy	4,885	483,615
Puntenza		Italy	770	462,000
Reno		Italy	3,400	2,720,000
Savio		Italy	6,000	11,400,000
Savio		Italy	600	1,140,000
Simento		Italy	1,800	3,600,000
Tenna		Italy	490	441,000
Tesino		Italy	110	121,000
Tevere (Tiber)		Italy	16,545	5,823,840
Tevere (Tiber)		Italy	16,000	5,600,000
Tevere (Tiber)		Italy	6,075	1,470,150
Tronto		Italy	1,200	1,080,000
Hedel		Netherlands	29,000	696,000
Meuse		Netherlands	29,000	696,000
Rhine	Lobith	Netherlands	160,000	2,720,000
Rhine	Lobith	Netherlands	160,000	2,784,000
Rijn	Arnhem	Netherlands	160,000	448,000
Waal	Hulhuizen	Netherlands	160,000	2,032,000
Yssel	Westervoort	Netherlands	160,000	288,000
Oder (Odra)	Gozdowice	Poland	109,400	131,280
Vistula (Wisla)		Poland	200,000	2,600,000
Vistula (Wisla)	Tezew	Poland	193,900	1,434,860
Danube		Romania	810,000	67,230,000
Volga		Russia	1,400,000	21,000,000
Ebro		Spain	85,000	17,850,000
Muonio Alv		Sweden	24,000	360,000
Avon		UK	260	41,860
Bristol Avon		UK	670	18,090
Clyde		UK	1,900	114,000
Creedy		UK	260	13,780
Ely Ouse (Great Ouse)		UK	3,600	28,800
Esk		UK	310	17,980
Exe		UK	600	14,400
Nene		UK	1,500	16,500
Severn		UK	6,800	442,000
Swale		UK	1,400	33,600
Tyne		UK	2,200	134,200
Usk		UK	910	41,860
Welland		UK	530	7,420
Wye		UK	4,000	204,000
Ystwyth		UK	170	27,880

River	Location	Country	Area (km^2)	SY (t·yr^{-1})
Don		Russia	420,000	7,560,000
Amur		Russia	1,800,000	50,400,000
Dnester		Moldova	62,000	2,480,000
Dnieper		Ukraine	380,000	1,976,000
Dnieper	Verkhnedneprovsk	Ukraine	433,693	1,301,079
Kolyma		Russia	640,000	5,760,000
Kuban		Russia	48,000	7,680,000
Pechora		Russia	250,000	6,250,000
Rioni		Georgia	13,000	8,190,000
Severnay Dvina		Russia	350,000	4,550,000
Y. Bug		Ukraine	34,000	510,000

4) The latest information on SY was published in 2005 (Eurosion, 2005) as part of study about coastal erosion in Europe (Tab. 4.4, Fig. 4.6).

Table 4.4 – Sediment yields found for major European catchments (Eurosion, 2005)

River basin	Outlet sea	Area (km^2)	Annual SY in 2000 (t·km^{-2})
Danube	Black sea	799,169	82.8
Dneper	Black sea	351,585	4.5
Ladoga	Baltic sea	286,553	2.9
Wisla	Baltic sea	193,346	12.6
Rhine	North sea	163,896	16.8
Elbe	North sea	140,308	4.5
Oder	Baltic sea	117,843	1.2
Loire	Atlantic sea	116,724	15.3
Douro	Atlantic sea	97,473	240.1
Rhone	Mediterranean sea	97,310	44.2
Neman	Baltic sea	92,346	2.3
Zap. Dvina	Baltic sea	86,024	5.3
Ebro	Mediterranean sea	85,424	213.2
Garonne	Atlantic sea	80,528	24.8
Seine	Channel	74,268	9.7
Dnester	Black sea	72,904	34.5
Po	Mediterranean sea	72,158	216.0
Tejo	Atlantic sea	70,926	254.3
Guadiana	Atlantic sea	66,880	141.0
Guadalaqui	Atlantic sea	57,190	144.7

River basin	**Outlet sea**	**Area (km^2)**	**Annual SY in 2000 (t·km^{-2})**
Narva	Baltic sea	56,809	9.9
Evros	Mediterranean sea	52,770	157.4
Onega	Artic sea	51,219	5.4
Kemijoki	Baltic sea	51,047	4.0
Weser	North sea	45,130	11.4
Kem	Artic sea	43,736	1.7
Glomma	North sea	41,378	369.4
Tome alv	Baltic sea	39,706	2.7
Kymijoki	Baltic sea	36,615	4.0
Maas	North sea	33,308	11.6
Angerman	Baltic sea	31,497	4.3
Dalalven	Baltic sea	28,931	4.7
Kokemaenjo	Baltic sea	26,728	2.4
Indalsalve	Baltic sea	25,513	4.9
Lule alv	Baltic sea	24,989	5.7
Axios	Mediterranean sea	24,496	191.9
Oulujoki	Baltic sea	22,877	3.0
Jucar	Mediterranean sea	22,084	59.2
Pasvikely	Artic sea	21,126	2.3
Schelde	North sea	19,123	17.5
Bojana	Mediterranean sea	18,673	3,259.8
Tevere	Mediterranean sea	17,942	452.2
Adour	Atlantic sea	16,978	47.4
Strimonas	Mediterranean sea	16,885	235.4
Begna	North sea	16,829	107.1
Shannon	Atlantic sea	15,979	3.2
Segura	Mediterranean sea	15,057	71.6
Iijoki	Baltic sea	14,297	3.4
Adige	Mediterranean sea	14,070	594.5
Ljungan	Baltic sea	13,086	2.9
Neretva	Mediterranean sea	12,429	1,092.8
Ems	North sea	11,864	3.9
Skelleftea	Baltic sea	11,607	3.0
Pitealven	Baltic sea	11,235	3.9
Aliakmonas	Mediterranean sea	11160	426.2

River basin	Outlet sea	Area (km^2)	Annual SY in 2000 (t·km^{-2})
Tinne	North sea	10,720	143.9
Thames	North sea	10,527	4.2
Trent	North sea	10,311	7.6
Vilaine	Atlantic sea	10,098	7.4
Charente	Atlantic sea	9,873	25.5

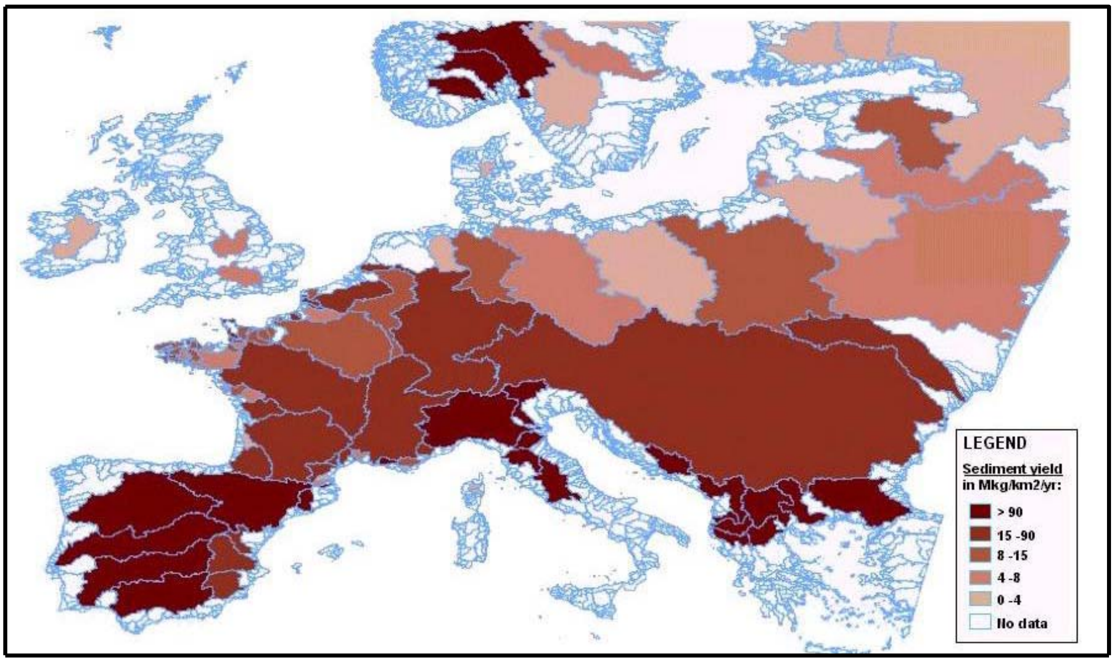


Figure 4.6 – Sediment yields for major European catchments (Eurosion, 2005)

This extent covered by this information certainly provides an opportunity to observe the difference between past and recent SY estimates, nevertheless SY in this study are calculated again in section 6 using a number of methods.

5 Methodology

The methodology followed in this study can be divided into two parts. The first part dealt with available traditional SY estimation methods which were tested against observed SY. Analyses were carried out to find new SY yield estimators. The second part used this knowledge for SY prediction and consequently the SSC prediction method was developed within this part.

I. Finding the best SY estimation method

It was decided that for this study the standard approach with SDR would be the most appropriate. As there are a number of SDR equations available the task in this part was to test them against monitored data and find those which, if any, performed well.

1) Firstly, soil erosion and SY were calculated for each of the 44 catchments from the study area. General behaviour of SDR formulae and some knowledge about the range of yields at catchment outlets were gained. This is covered in section 6.1.

2) Calculating erosion and SY using SDR again, this time at the locations where monitored data exist. This is covered in section 6.2.

3) Calculating SY using monitored flow and sediment concentration data. This is covered in section 6.2.

4) A comparison of the two. Comparisons were carried out in order to verify SDR equations and ascertain those with the best performance. During this stage three new methods for sediment yield estimation were established. This is covered in section 6.3.

II. Sediment concentration prediction

The methodology to predict sediment concentration was kept simple but consistent. It assumes that there is only one sediment source which is soil erosion. There were either no assessment tools suitable for this study to evaluate other sources of sediment or data needed to do so were lacking. The method can be described in three simple steps.

1) Estimation of total amount of detached particles above the point of interest. Since the only sediment source considered here is soil erosion, total soil erosion in catchment delineated above the point of interest was estimated using the PESERA map again. This step in detail is covered in section 7.

2) Estimation of total amount of particles which reach the stream at the point of interest – sediment yield (calculated here using the new SY estimation methods and one SDR with the best performance). This is covered in section 7.

3) Developing a procedure to translate those yields into sediment concentration using flow characteristics. The basic idea is redistribution of an annual amount of transported particles (sediment yield) into annual water volume at the point of interest. This is covered in sections 7.1 and 7.2.

6 Soil erosion and sediment yield calculation

6.1 Using sediment delivery ratio

Sediment yield calculation is one of the key issues of this work. It is basic information which is required for further sediment concentration studies. Notwithstanding that published sediment yield information were available at several locations (Fig. 4.5) it was decided that their calculation would be carried out again. One reason was that some of the published information was quite dated; another reason was that the recently published PESERA map represents the latest approach in terms of soil erosion rate estimation for the European continent. Thus this study provides an opportunity to carry out new sediment yield calculations and put them into context with previously published ones.

The methodology to calculate sediment yields is almost the same as that which has been used in several recent studies (Fig. 6.1) (Dostal *et al*., 2002; Dostal *et al*., 2003; Becvar, 2004a). In fact, for such large areas as investigated here, there are not many methods to calculate sediment yields apart from this empirical approach. A soil erosion map is usually the initial step in sediment yield calculation. In this case the PESERA soil erosion map was used (Fig. 2.7).

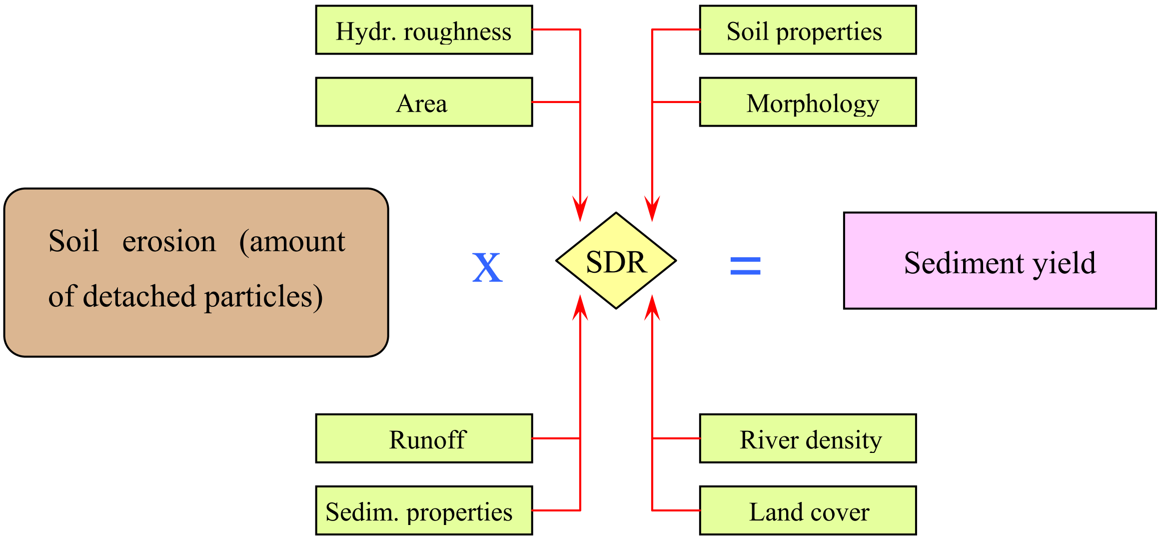


Figure 6.1 – Scheme of the traditional approach to sediment yield estimation using SDR

The key difference here is that for sediment delivery ratio determination various equations were used.

In this section sediment yields were calculated for the 44 selected river basins (see study area Fig. 3.2) using the PESERA map to calculate soil erosion and the following SDR formulae:

McPherson's equation (1975):

$\log TSE = 0.8797 \log \Phi - 0.690 \log D + 0.6462 \log L + 1.1035$ (equation 3)

Renfro's equation (1975): $\log(DR) = 1.87680 - 0.14191 \log(10A)$ (equation 5)

Renfro's equation (1975): $\log(DR) = 2.94259 - 0.82362 co \log(R/L)$ (equation 6)

Williams and Berndt's equation (1972): $SDR = 0.627(SLP)^{0.403}$ (equation 7)

Vanoni's equation (1975): $SDR = 0.42(A)^{-0.125}$ (equation 9)

USDA SCS's equation (1971): $SDR = 0.51(A)^{-0.11}$ (equation 10)

Maner's equation (1958):

$\log(DR) = 2.962 + 0.869 \log(R) - 0.854 \log(L)$ (equation 12)

ArcGIS tools were used in order to perform the GIS procedures. The relief of the catchment, required in equations 3, 6 and 12, is defined as a difference between the lowest point of the catchment (an outlet) and a mean altitude of the catchment divide. The length of a catchment (required for equations 3, 6 and 12) is defined as a longest water course from the outlet to the catchment boundary, measured approximately alongside the main channel. The relief-length ratio is a ratio of the two. The slope of the main channel (required for equation 7) is defined as the difference in altitude between headwaters and the outlet divided by the orthogonal projection of the length of the channel. To obtain a percentage this number has to be multiplied by 100. All these values were extracted from the DTM. Total (sum) of all pixel values found within a catchment were extracted from the PESERA map for each particular catchment to give an overall basin erosion rate. However, in order to get the best estimate of erosion, a correction was required. The PESERA pixel size is 1 km, however it has a value of $t \cdot ha^{-1} \cdot yr^{-1}$ unit. Therefore one pixel in the PESERA map having a value of ***x*** has actually a soil loss value of ***100·x*** $t \cdot yr^{-1}$ (100 hectares in 1 square km). After the correction had been made the best estimate rates were obtained. These rates were then used as an input to the equation:

$$SY = EROSION \cdot SDR$$

SDR parameters such as area and relief-length ratio were extracted from catchment polygons and DTM using ArcGIS tools.

It has to be noted again at this point that the PESERA map (Fig. 2.7) does not entirely cover the whole continent. As a consequence in some catchments the total erosion may be slightly underestimated. The intention was to use all SDR equations reviewed in section 2.2.3 in order to compare them. However, it was not possible to use them all purely because essential source data was either missing or were not accurate enough to determine the equation parameters (all the SDR equations are listed in section 2.2.3). Therefore variables in the equations which were used are mainly those which could be determined using the DTM. These are catchment relief, length of the catchment, their combination which is relief-length ratio, and slope of the main channel. Figure 6.2 shows sediment yields calculated at the outlets of the 44 focus catchments using seven SDR approaches.

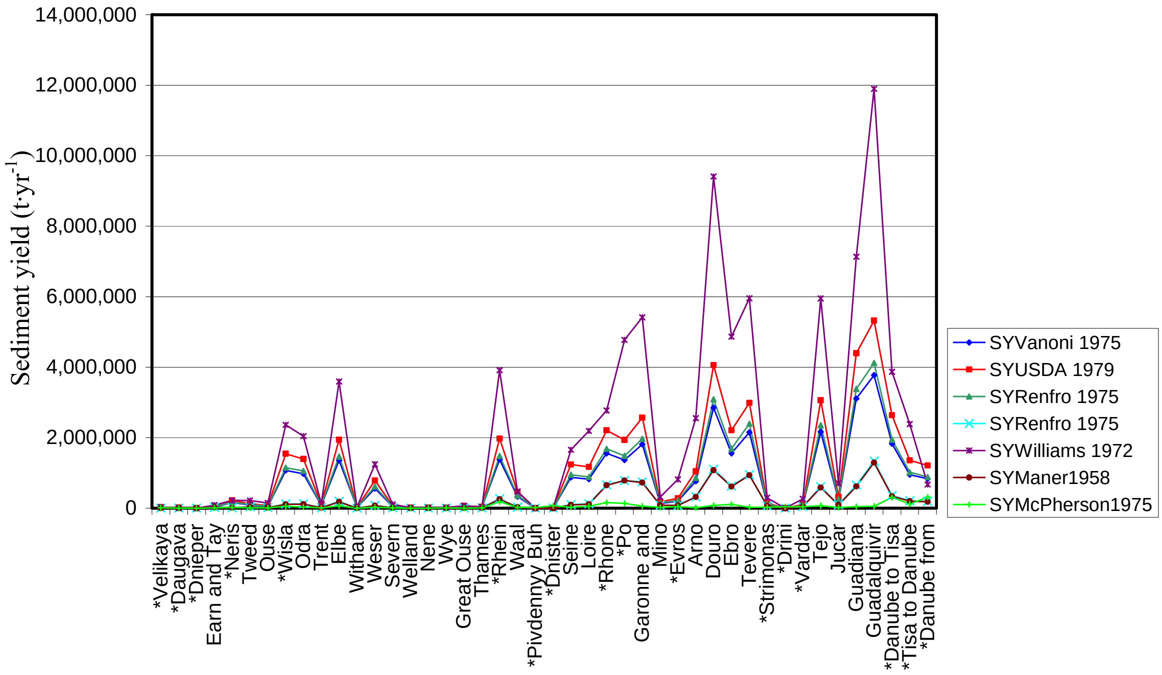


Figure 6.2 – Calculated sediment yields for study area using a range of SDR equations

Depending on the SDR formula used, sediment yield values vary quite significantly for each particular catchment. This is mainly due to the different variables and parameters used in the equations and the different environments for which they were derived. Nonetheless, it was still possible to observe the general behaviour of the equations and to gain some knowledge about the range of sediment yields which may be expected.

These calculations were affected by a lack of data which means that some of the variables required in the equations might have been slightly affected or even not calculated at all; therefore calculated sediment yields might also have been affected. Sediment yields which where significantly affected were excluded and thus are not further presented in this study. In Table 6.1 catchments marked with a * symbol were generally affected by the lack of data. The values in bold italics are those sediment yields where the lack of data affected their estimation. Catchment polygons were delineated using the DTM, therefore also catchment areas, representing an important variable in SDR equations, may be slightly different from the real ones. All values are listed in Table 6.1.

Table 6.1 – Calculated sediment yields (t·yr^{-1}) for major European catchments

Author River	Area (km^2)	Vanoni (1975)	USDA (1971)	Renfro (1975)	Renfro (1975)	Williams (1972)	Maner (1958)	McPherson (1975)
*Velikaya	56,809	***18,977***	***26,771***	***20,725***	***1,351***	***25,966***	***1,196***	8,989
*Daugava	86,024	***16,966***	***24,083***	***18,400***	*	*	*	*
*Dnieper	351,585	*	*	*	*	*	*	*
Earn and Tay	6,195	34,063	46,482	38,621	19,746	88,215	19,508	6,619
*Neris	92,347	***154,604***	***219,698***	***167,470***	***9,247***	***219,612***	***8,154***	22,044
Tweed	4,934	91,200	124,027	103,804	34,912	213,648	33,820	4,441
Ouse	10,943	49,425	68,024	55,504	13,473	142,928	12,768	4,909
*Wisla	193,347	***1,074,284***	***1,543,613***	***1,149,245***	***116,389***	***2,361,409***	***105,568***	55,624
Odra	117,843	976,317	1,392,465	1,053,217	125,316	2,042,712	114,717	31,004
Trent	10,312	81,944	112,679	92,114	11,925	123,813	10,981	3,886
Elbe	140,309	1,357,926	1,941,810	1,460,572	190,673	3,591,432	175,729	64,122
Witham	2,609	21,025	28,321	24,190	1,771	29,788	1,583	482
Weser	45,131	555,228	780,571	608,756	74,016	1,245,901	68,087	27,103
Severn	10,518	46,998	64,644	52,813	8,263	109,807	7,699	6,177
Welland	1,746	10,919	14,619	12,648	1,381	17,604	1,261	464
Nene	2,998	13,171	17,778	15,118	1,059	18,557	946	736
Wye	4,051	8,483	11,502	9,687	1,961	19,874	1,863	4,706

Author River	Area (km^2)	Vanoni (1975)	USDA (1971)	Renfro (1975)	Renfro (1975)	Williams (1972)	Maner (1958)	McPherson (1975)
Great Ouse	7,590	48,652	66,593	54,974	4,052	63,386	3,626	1,775
Thames	10,527	26,986	37,118	30,324	3,601	32,991	3,302	3,678
*Rhein	163,896	***1,376,539***	***1,973,019***	***1,476,708***	***266,956***	***3,911,495***	***251,009***	183,522
Waal	33,308	324,928	454,726	358,087	27,748	469,542	25,050	21,621
*Pivdennyy Buh	52,603	*	*	*	*	*	*	17,302
*Dnister	72,904	***2,150***	***3,044***	***2,338***	***202***	***3,530***	***184***	65,990
Seine	74,269	873,774	1,237,614	949,980	101,042	1,655,027	92,069	29,283
Loire	116,725	819,901	1,169,211	884,624	121,639	2,191,761	112,584	55,804
*Rhone	97,310	***1,553,282***	***2,209,005***	***1,681,058***	***661,910***	***2,769,398***	***647,938***	153,935
*Po	72,159	***1,366,113***	***1,934,127***	***1,485,983***	***784,440***	***4,774,532***	***780,285***	132,185
Garonne and Dordogne	80,528	1,809,846	2,566,580	1,965,003	744,738	5,412,215	724,787	60,734
Mino	17,043	129,558	179,498	144,405	84,098	317,221	83,888	22,497
*Evros	52,771	***199,648***	***281,336***	***218,318***	***77,136***	***816,865***	***74,887***	42,269
Arno	8,909	760,393	1,043,299	856,878	321,911	2,553,070	314,332	10,350
Douro	97,473	2,852,084	4,056,204	3,086,615	1,104,597	9,412,512	1,076,559	75,652
Ebro	85,425	1,555,474	2,207,804	1,687,141	626,071	4,864,595	611,860	108,219
Tevere	17,942	2,151,704	2,983,422	2,396,207	948,980	5,955,210	931,679	28,313
*Strimonas	16,885	***110,261***	***152,742***	***122,917***	***65,846***	***293,387***	***65,650***	26,961
*Drini	18,673	*	*	*	*	*	*	36,246
*Vardar	24,497	***75,490***	***105,160***	***83,627***	***42,880***	***261,924***	***42,591***	37,712
Tejo	70,927	2,163,046	3,061,626	2,353,529	608,259	5,949,153	584,262	70,085
Jucar	22,084	230,181	320,151	255,439	95,416	707,245	93,401	17,272
Guadiana	66,880	3,107,650	4,394,766	3,384,675	652,705	7,135,146	616,698	41,171
Guadalquivir	57,191	3,772,468	5,322,425	4,119,639	1,336,362	11,898,077	1,294,301	51,803
*Danube to Tisa	256,990	***1,827,895***	***2,637,692***	***1,946,059***	***361,181***	***3,868,667***	***339,730***	305,112
*Tisa to Danube	153,621	***946,043***	***1,354,665***	***1,015,997***	***207,990***	***2,386,778***	***196,110***	119,758
*Danube from Tisa	388,560	***835,114***	***1,212,584***	***882,909***	***192,743***	***669,448***	***181,853***	308,908

6.2 Using monitored data

In the previous section SY were calculated using the traditional approach (Fig. 6.1) – a soil erosion map with SDR. However, it was not possible to select a particular equation with the best performance in this way. An essential comparison against real data was missing at this stage and there was a great deal of variability between the approaches. Therefore calculation of sediment yields using monitored data was carried out in order to have the possibility to compare them. Existing relationships could be thus verified or new relationships could be found by relating observed sediment yields against catchment characteristics.

For this stage there was a high demand for sediment and flow data. It was impossible to collect data for all of the catchments. In some cases data must either be paid for or does not fulfil the requirements in terms of temporal resolution or other factors. Nevertheless sufficient data were collected to carry out testing on eight catchments.

Not all of the collected temporal data were used for the testing. Where possible, only the data for the main streams were used. This was sufficient to find a link between sediment yields obtained from measured data and available data sources. Fundamentally, the testing process lies in:

- delineating a catchment from the DTM at the sampling location

- calculating soil erosion and sediment yield (using both monitored data and the classical approach with SDR (Tab. A 1)); the McPherson (1975) equation was already excluded here as it does not perform well

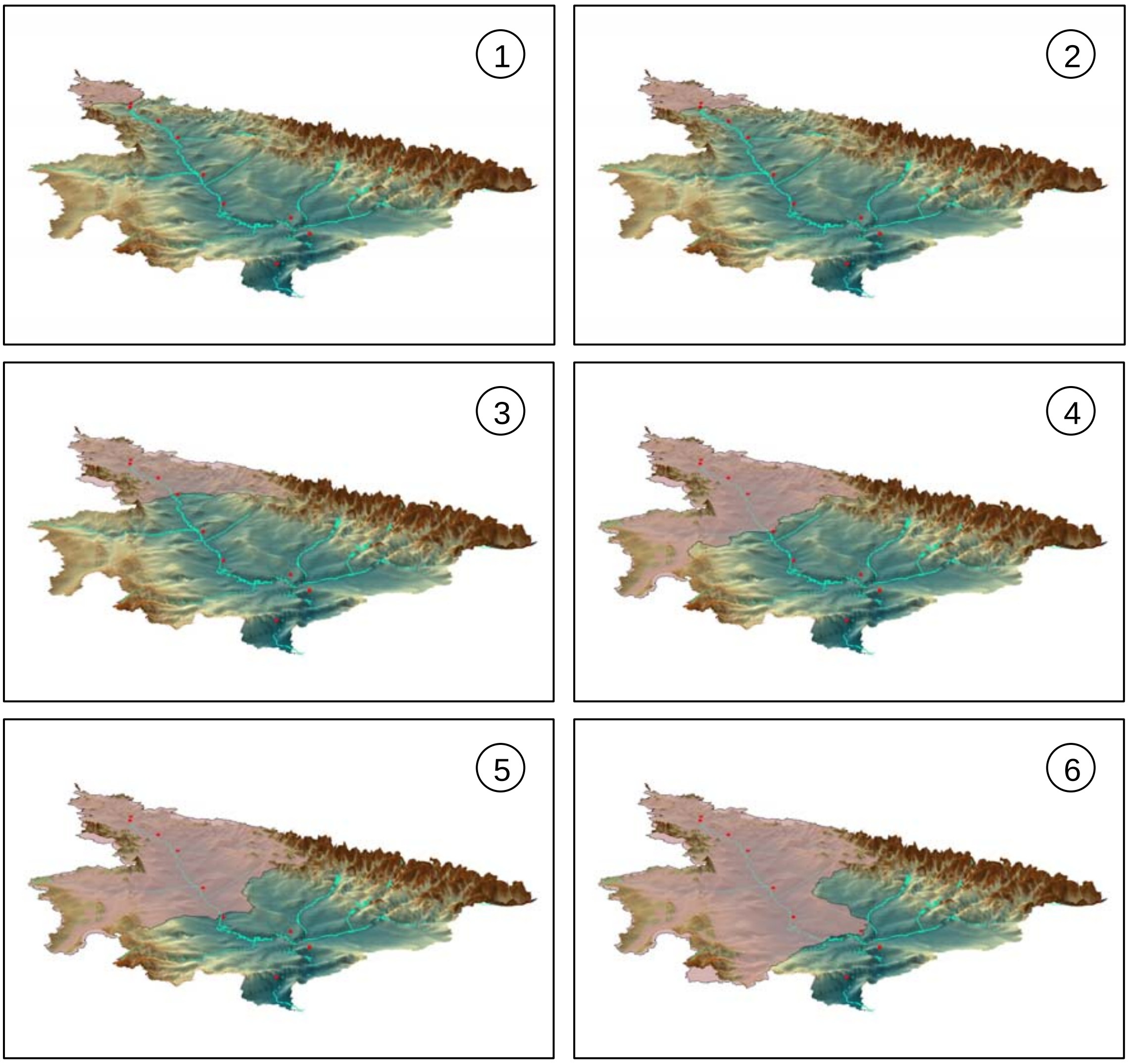
For soil erosion estimation, the PESERA approach was used again. Although in some respects the use of PESERA was probably not appropriate (particularly in small catchments as PESERA is typically designated for general estimations) it was used for all the estimations. No other soil erosion data source with better spatial resolution was available.

Delineating catchments is a classical task to be carried out in a DTM. This procedure demands a powerful computer otherwise it may become a time-consuming part of the procedure. Perhaps the biggest problem here is that most of the DTMs are not suitable for producing river network and, consequently, the catchment. The reason for this is the presence of pits which disturb the pixel connectivity when the algorithm creates the river network. Therefore, ‘pit removal’ or ‘fill’ function has to be used. However this means that the DTM may be changed using these procedures. Furthermore, even after the pit removal function had been used the algorithm sometimes failed, particularly where the difference in altitude is insignificant such as in flat areas. For this procedure ArcGIS and Idirisi GIS were used. ArcGIS uses the flow direction raster prior to the catchment delineation, whereas Idrisi does not require this. ArcGIS was not able to produce reasonable results for catchment boundaries. However, Idrisi was successful in defining catchment boundaries at the point of interest used in the testing stage.

Testing was successfully carried out using data from the eight following catchments: Rhine, Mosel, Rhone, Jucar, Ebro, Elbe, Morava (Danube tributary in the Czech Republic) and Oder.

However, the number of available locations with suspended sediment data (Fig. 4.1) within a catchment was limited. In some catchments there was only one point available. Furthermore the data were not of the same temporal resolution (from monthly sampling to daily sampling) and came from different sampling periods. Therefore obtained sediment yields were not calculated with the same accuracy. In cases where sampling has been carried out only once or twice per month, the value had to be considered as a representative sediment concentration for the gap between two samples. Of course this does not contribute to the accuracy of sediment yield determination but even under these circumstances it was possible to gain new knowledge about the relationship between observed sediment concentration, routed sediment yields from them and available data. Figure 6.3 shows a typical procedure carried out during this stage. The points represent locations where sediment concentrations have been monitored (gauging stations). At each point a catchment was delineated, SY was calculated from monitored flow and sediment concentration data and also using the PESERA map and SDR equations. Sediment yield from monitored sediment and flow data was calculated as annually transported amount of sediment at the location. An example for weekly sampling of flow and sediment concentration, the estimation of annual SY can be given as follows: SC (given in $mg.l^{-1}$) multiplied by 10^3·discharge (given in $m^3.s^{-1}$) determines transported amount of material (in mg) per second. This value was then multiplied by $6.048 \cdot 10^5$ (a week in seconds) which gives transported amount of sediment (in mg) between the two measurements. This procedure was then performed over the whole sampling period. The weekly transported amounts of sediment were toted up. Reduced by 10^{-9} the total sediment load per sampling period was obtained. For an annual value this figure was divided by number of years of observation). From the given description of the observed SY calculation using SSC and flow data it is clear that the sampling period strongly influences the accuracy of the estimation. The bigger the gaps between two samples, the bigger the error involved. Sediment concentrations and discharge have to be treated as if they do not change between sampling.

When SYs were calculated (observed ones and also using the existing methods) it was then possible to compare the performance of SDR equations against observed yields at several locations within a catchment. Such comparisons, and subsequent testing, resulted in recommendation of an SDR equation and new methods to estimate SY.



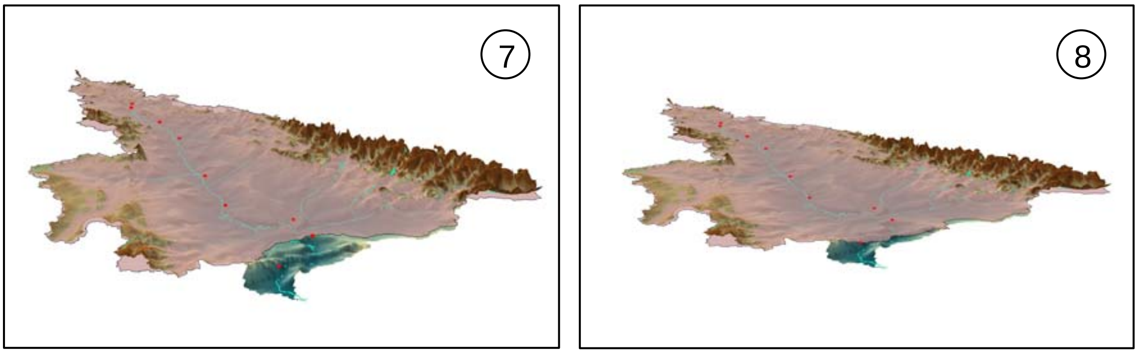


Figure 6.3 – Testing the SDR approach in the Ebro catchment – maps show the defined catchments for gauging stations down the main river channel

6.3 Comparison of the two methods

Here sediment yields calculated using PESERA and SDR were compared with those from monitored data to test which of the SDR approaches may be performing well. Comparing calculated yields against observed (an example from the Ebro catchment is shown at Fig. 6.4, others in appendices Fig. A 3) was a very important part of this study.

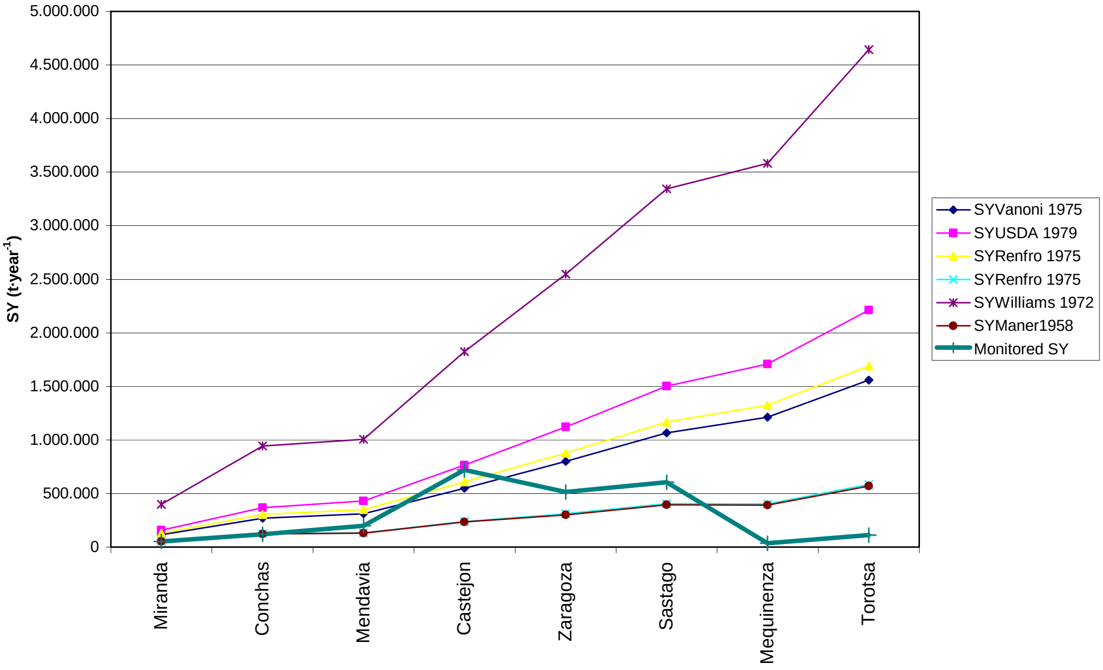


Figure 6.4 – Comparison of sediment yields for the Ebro river using a range of SDR approaches and monitored data

Figure 6.4 shows calculated sediment yields compared to the observed one in the Ebro catchment. The x-axis shows the gauging stations. Going from left to the right on the chart represents moving from headwater to the estuary in the catchment. These analyses were used to build new SY estimation methods which later became fundamental for sediment concentration prediction. It was also a moment where the main weakness of this methodology fully showed itself. In the case of the Ebro, sediment yields estimated using monitored data are affected by a variety of processes and mainly by trap efficiency of water reservoirs, whereas yields using SDR equations might not be. The intention here however was to use only non-infrastructure affected yields in order to get a good comparison. Taking this into account the data had to be treated carefully. This means that where it was demonstrably clear that sediment yield is affected by the trapping efficiency of water reservoir, indicated by a sudden decrease of sediment concentration or a dam identified on the map for example, it was not used. However, all the sediment yields are generally affected by any artificial structure built in the river. In other words even if sediment yield obtained from SSC data has an increasing trend in a particular catchment there still could have been an impact on sediment concentration (and thus sediment yield calculated using these data). Nonetheless this study is looking at general principles and investigations and thus all the details cannot be taken into account.

These calculations were carried out for each of the eight tested catchments. Applying the measurement of goodness of fit it was discovered that Vanoni's (1975) equation and the USDA approach were performing better than others. The best relationship was $SDR = 0.51(A)^{-0.11}$ developed by the USDA (1971) which, together with the soil erosion map, was the first relationship to be accepted for future sediment concentration prediction. The results of goodness-of-fit measurements are shown in Table 6.2 (where marked with a * symbol not all the data were used due to the identified dam impact). For selecting the best approach a simple ranking method was used shown in Table 6.2.

Table 6.2 – Goodness-of-fit for existing SDR approaches in each study catchment

Location	**Observed SY ($t \cdot yr^{-1}$)**	**SY_{Vanoni} 1975 ($t \cdot yr^{-1}$)**	**SY_{USDA} 1979 ($t \cdot yr^{-1}$)**	**SY_{Renfro} 1975 ($t \cdot yr^{-1}$)**	**SY_{Renfro} 1975 ($t \cdot yr^{-1}$)**	**$SY_{Williams}$ 1972 ($t \cdot yr^{-1}$)**	**SY_{Maner} 1958 ($t \cdot yr^{-1}$)**
Auxonne	136 345	211 354	289 914	238 243	50 630	374 417	47 827

Charrey	146 116	233 751	321 954	262 274	57 357	407 723	54 261
Ouroux	219 624	275 280	382 698	305 648	83 430	464 406	79 838
Chasse	1 562 437	750 828	1 057 549	821 466	419 939	1 243 704	415 630
Saint Vallier	1 337 146	1 018 706	1 435 994	1 113 552	526 426	1 686 578	519 554
Charmes	2 559 189	1 227 097	1 735 440	1 336 391	719 548	2 102 245	7149 44
Correl. R^2		0.95699	0.96144	0.956487	0.977227	0.957439	0.977925
MAD (t·yr^{-1})		446 740	319 994	415 240	683 921	311 595	688 134

Location	**Observed SY (t·yr^{-1})**	**SY_{Vanoni} 1975 (t·yr^{-1})**	**SY_{USDA} 1979 (t·yr^{-1})**	**SY_{Renfro} 1975 (t·yr^{-1})**	**SY_{Renfro} 1975 (t·yr^{-1})**	**$SY_{Williams}$ 1972 (t·yr^{-1})**	**SY_{Maner} 1958 (t·yr^{-1})**
Rekingen	110 401	141 969	196 267	158 626	105 027	494 607	105 815
Weil	443 650	144 744	202 783	159 322	101 105	523 046	101 267
Rhinau	1 065 784	173 454	243 335	190 632	98 773	591 062	98 105
Strasbourg	676 938	215 451	302 766	236 334	116 829	726 998	115 759
Lauterbourg	956 534	241 959	340 580	264 918	119 686	802 093	118 064
Koblenz	1 495 448	716 739	1 021 181	774 101	225 845	2 274 827	217 351
Lobith	3 197 913	1 381 739	1 979 697	1 482 941	323 878	4 132 046	307 222
Correl. R^2		0.95734	0.95762	0.95701	0.93286	0.95476	0.93000
MAD (t·yr^{-1})		713 392	547 399	682 321	979 361	408 048	983 298

Location	**Observed SY (t·yr^{-1})**	**SY_{Vanoni} 1975 (t·yr^{-1})**	**SY_{USDA} 1979 (t·yr^{-1})**	**SY_{Renfro} 1975 (t·yr^{-1})**	**SY_{Renfro} 1975 (t·yr^{-1})**	**$SY_{Williams}$ 1972 (t·yr^{-1})**	**SY_{Maner} 1958 (t·yr^{-1})**
Chavelot	9 485	1 171	1 561	1 363	764	3 854	761
Liverdun	115 022	85 864	116 316	98 161	24 577	240 396	23 537
Arry	166 650	159 812	218 871	180 461	42 839	444 071	40 844
Koblenz	493 367	642 595	897 013	710 197	136 333	1 632 431	128 590
Correl. R^2		0.99444	0.99552	0.99495	0.99905	0.99679	0.99915
MAD (t·yr^{-1})		48 384	116 271	63 906	145 003	386 873	147 698

***Location**	**Observed SY (t·yr^{-1})**	**Observed SY (t·yr^{-1})**	**SY_{Vanoni} 1975 (t·yr^{-1})**	**SY_{USDA} 1979 (t·yr^{-1})**	**SY_{Renfro} 1975 (t·yr^{-1})**	**SY_{Renfro} 1975 (t·yr^{-1})**	**$SY_{Williams}$ 1972 (t·yr^{-1})**
Jucar alto	527	43	55	51	67	139	70
Villalba	364	2 719	3 583	3 207	2 668	8 487	2 720
Cuenca	5 753	4 672	6 204	5 463	3 573	13 983	3 600
El Castellar	33 945	45 513	61 013	52 648	24 782	129 133	24 562
Correl. R^2		0.99494	0.99494	0.99493	0.99318	0.99488	0.99297
MAD (t·yr^{-1})		3 872	7 802	5 578	3 527	27 982	3 587

***Location**	**Observed SY (t·yr^{-1})**	**Observed SY (t·yr^{-1})**	**SY_{Vanoni} 1975 (t·yr^{-1})**	**SY_{USDA} 1979 (t·yr^{-1})**	**SY_{Renfro} 1975 (t·yr^{-1})**	**SY_{Renfro} 1975 (t·yr^{-1})**	**$SY_{Williams}$ 1972 (t·yr^{-1})**
Miranda	52 079	115 317	157 068	131 024	52 287	397 395	51 358
Conchas	119 901	268 248	367 838	302 484	125 532	943 085	123 330

Mendavia	198 065	311 426	429 207	349 179	133 096	1 005 817	130 567
Castejon	718 863	548 386	764 231	607 216	238 291	1 825 331	233 455
Correl. R^2		0.95235	0.95457	0.94973	0.94525	0.94980	0.94474
MAD (t·yr^{-1})		123 856	157 359	131 072	137 845	770 680	139 264

Location	**Observed SY (t·yr^{-1})**	**Observed SY (t·yr^{-1})**	**SY_{Vanoni} 1975 (t·yr^{-1})**	**SY_{USDA} 1979 (t·yr^{-1})**	**SY_{Renfro} 1975 (t·yr^{-1})**	**SY_{Renfro} 1975 (t·yr^{-1})**	**$SY_{Williams}$ 1972 (t·yr^{-1})**
Bohumin	228 244	83 299	113 182	94 905	49 568	233 054	48 940
MAD (t·yr^{-1})		144 945	115 062	133 339	178 676	4 810	179 304
Straznice	229 307	228 657	313 799	257 608	97 222	721 486	94 696
MAD (t·yr^{-1})		650	84 492	28 301	132 085	492 179	134 611
Decin	373 419	679 557	956 769	743 834	273 120	2 349 293	264 346
MAD (t·yr^{-1})		306 138	583 350	370 415	100 299	1 975 874	109 073

Table 6.3 – Selecting the best SDR approach using the ranking method

	Rhone		**Rhine**		**Moselle**		**Jucar**		**Ebro**		**Decin**		**Bohumin**		**Straznice**		
	Correl. R^2	MAD	Correl. R^2	MAD	Correl. R^2	MAD	Correl. R^2	MAD	Correl. R^2	MAD	Correl. R^2	MAD	Correl. R^2	MAD	Correl. R^2	MAD	Total
SYVanoni 1975	5	4	2	4	6	1	2	3	2	1	-	3	-	4	-	1	**38**
SYUSDA 1979	3	2	1	2	4	3	1	5	1	5	-	5	-	2	-	3	**37**
SYRenfro 1975	6	3	3	3	5	2	3	4	4	2	-	4	-	3	-	2	44
SYRenfro 1975	2	5	5	5	2	4	5	1	5	3	-	1	-	5	-	4	47
SYWilliams 1972	4	1	4	1	3	6	4	6	3	6	-	6	-	1	-	6	51
SYManer1958	1	6	6	6	1	5	6	2	6	4	-	2	-	6	-	5	56

Each approach was labelled with a rank concerning goodness of correlation and distance from the observed values (for example Manner's approach in the Ebro catchment had the worst correlation with observed data and the fourth best MAD amongst all the approaches). The ranks were summarised and the approach with the lowest value was thus selected as the best one. In all cases the empirical SDR estimation methods have quite good positive correlation with observed data. The amplitude between observed data and the SDR approaches (determined using mean absolute deviation) is quite wide. Therefore relationships between the sediment yields calculated from monitored data and inputs to the SDR formulae were further investigated here in order to see if any better relationships for sediment yield could be found. Two new yield estimators were discovered. A simple linear correlation between observed yields and inputs to the SDR formulae was performed. Figures 6.5 and 6.6 show these relationships.

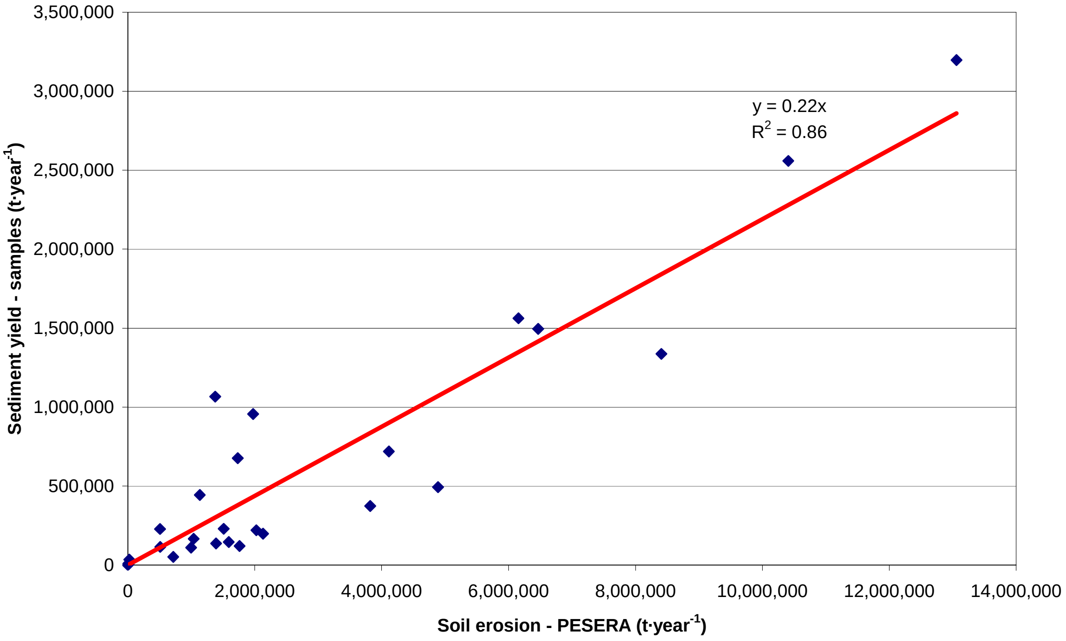


Figure 6.5 – Relationship between PESERA soil erosion and observed sediment yield

Figure 6.5 shows the relationship between observed sediment yield (calculated from flow and sediment concentration data) and estimated soil erosion rates using the PESERA map. The variation of sediment yield values which can be observed for lower soil erosion rates may have several causes. One might be that two catchments with the same erosion rates (according to the PESERA map) may have different sediment delivery and transport patterns and thus more or less material is supplied for the same erosion rates. There can be a plenty of other reasons for that because no two rivers are the same and neither are sediment patterns found for them. Despite of that, it is still possible and useful to find an empirical relationship that performs well also outside its place of origin. Figure 6.5 suggests that SY is approximately equal to one fifth of annual soil erosion.

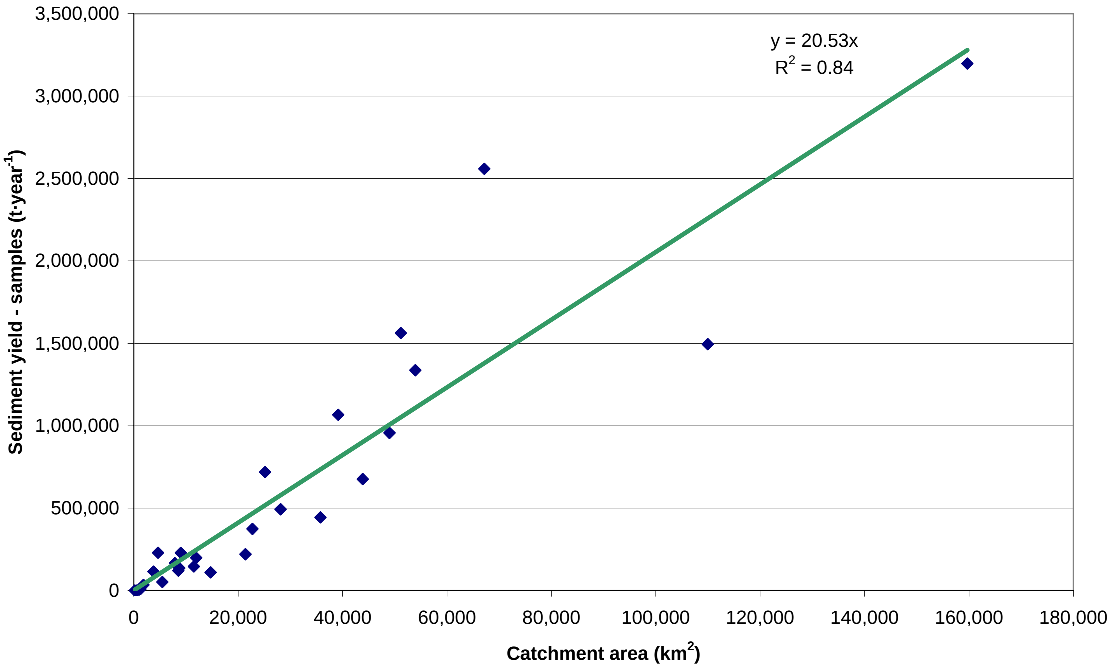


Figure 6.6 – Relationship between catchment area and observed sediment yield

Figure 6.6 shows the relationship between observed sediment yield (calculated from flow and sediment concentration data) and the catchment area (showing approx 20 t of sediment from each km^2). This relationship and its strength are strongly influenced by the isolated point in the upper right part of the chart. Unfortunately there are no other points with a similar catchment area available. All the available measurements have been taken relatively close to headwaters. Therefore more measurements in lower parts of catchments should be carried out to increase the relevance and reliability of this relationship. Both of the discovered relationships are linear even though slightly better correlation can be found using second degree polygon function. However such function has credibility only within the points and thus its behaviour might be very different outside these points. Therefore this function is not suitable for use in sediment yield estimation, whereas linear function has the same behaviour wherever outside the points.

Nonetheless, these relationships represent links (valid for this study area) discovered between observed yields and the latest soil erosion approach PESERA and the catchment area. Thus they can be used for SY and SSC prediction. These two found equations were also used to predict sediment yields which were used for the estimation of sediment concentrations. The reason for also using the USDA (1971) method (the recommended SDR equation) was to allow the possibility to compare between the standard approach (Fig. 6.1) and the new ones (Fig. 6.5, 6.6).

7 Suspended SC prediction

Predicting sediment concentration is the ultimate objective of this study. Steps introduced in section 5 were followed here. The fundamental idea of sediment concentration prediction is:

"Redistribution of an annual sediment yield into annual water volume using the flow variability at the point of interest"

So far two new methods to predict SY were introduced. In addition one traditional method (using SDR) with the best performance as a result of data analyses was recommended. All three were used to estimate SY for SSC prediction. SY was then predicted:

1) using the relationship between observed sediment yields and soil erosion rates (Fig. 6.5). Sediment yield was estimated directly from the rate of soil erosion in the catchment above the point of interest
2) using the relationship between observed sediment yields and catchment area (Fig. 6.6). Sediment yield was estimated directly from catchment area above the point of interest
3) using the established SDR approach (Fig. 6.1). The PESERA map was used for soil erosion estimation and the annual value of soil loss was reduced by SDR in order to get annual sediment yield

Flow data collected for various locations were also available. Thus annual water volume at the point of interest, as required for SSC predictions, could be estimated. By dividing annual sediment yield (mg) by annual water volume (l) the mean annual sediment concentration (mg.l^{-1}) at the point of interest could have been obtained. However this study aims to go a little further. The intention was to describe the sediment concentration variability in different flows.

7.1 Sediment concentration prediction method

Since the idea of SSC prediction is redistribution of an annual sediment yield into annual water volume using the flow variability at the point of interest, the first step was to describe sediment concentration behaviour in different parts of the flow. This was essential knowledge, required for sediment concentration predictions. White (pers. comm. 2005) suggested to plot available sediment concentration data using the flow exceedance curve (Fig. 7.1). The only difference is that instead of plotting percentage of exceedance against discharges, percentage of exceedance against sediment concentrations were plotted. Data from all the locations were plotted using the flow exceedance. By looking at the charts it become clear the behaviour of SSC can be divided into two groups according to flow exceedance.

The first area is where sediment concentrations remain relatively constant – in flows that are not higher than those exceeded for 30 % of time – Q_{30}. Therefore the predicted SSC will have constant progression in this part of flow. The second group can be identified for flows greater than Q_{30}. A relationship can be established here: the higher the flow the higher is the concentration. Predicted SSC will not have a constant progression but logarithmical progression corresponding with the observed behaviour.

The pattern described above could be identified all over the study area and thus was considered as a representative behaviour of suspended sediment concentrations that is a characteristic common for all the rivers. However there were locations where the pattern was different – no trend in Q_{30}-Q_0 or irregular scattering across the entire flows for example. Also quite common were differences between two neighbouring gauging stations. This approach is general so the general pattern of SSC behaviour observed all over the study area was chosen as a base for SSC predictions.

In order to generalize the behaviour of SSC, the data where the pattern was observed were gathered (Trent at North Miskham, Moselle at Liverdun, Rhein at Strasburg, Rhein at Lauterbourg, Moselle at Koblenz, Rhein at Koblenz, Rhein at Lobith, Rhone at Chasse sur Rhone, Rhone at Saint Vallier, Saone at Oroux, Saone at Auxonne, Ebro at Miranda, Elbe at Decin, Oder at Bohumin and Morava at Straznice). Figure 22 shows the result.

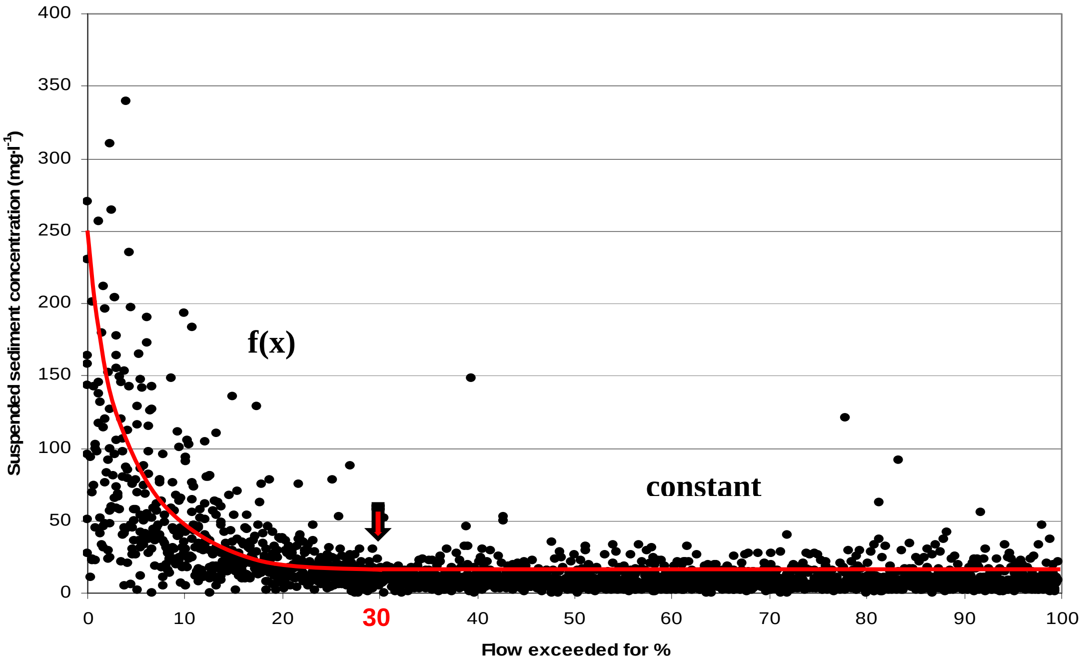


Figure 7.1 – Sediment concentrations using the flow exceedance curve

The line on the figure does not represent a fit to the data. It was manually added in order to demonstrate the behaviour of SSC that will be used for the prediction of sediment concentrations. The position of the line will differ in the y-axis direction according to the exposure of the location to the sediment.

The progression of predicted SSC will be constant in Q_{100}-Q_{30} and in Q_{30}-Q_0 will be replaced by a logarithmic function f(x) that was obtained from all the gathered data:

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

where x is a percentage of flow exceedance

So if the methodology to estimate sediment concentration was to redistribute annual sediment yield into annual water volume, the water volume now also has to be divided into two parts. Total annual water volume for Q_0 to Q_{30} and Q_{30} to Q_{100}. The principle of total water volume estimation is shown in Figure 7.2.

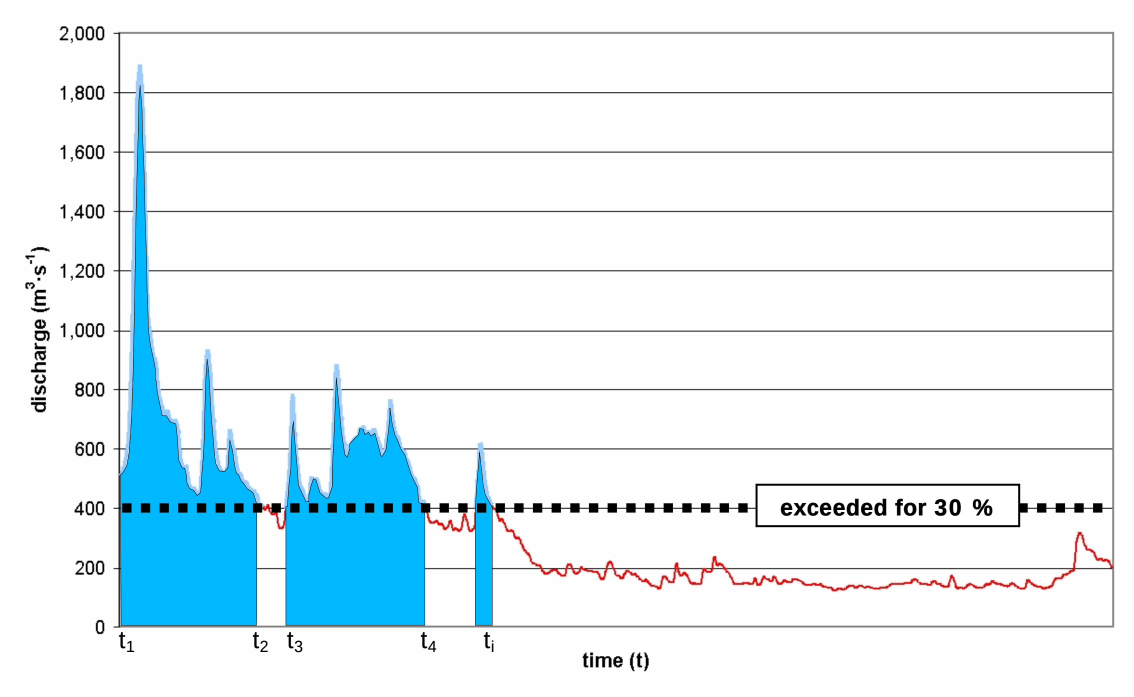


Figure 7.2 – Water volume estimation for various flow exceedance

For estimation of water volumes the flow data described in Section 4 were used. A time series of discharge observation was available for each of the locations where sediment concentration was predicted. Only flows Q_{30} – Q_0 were chosen – those which were reached or exceeded for 30 % of time or less. Daily discharges (or those with different sampling period) were given in $m^3 \cdot s^{-1}$. In order to get the water volume it had to be multiplied by a relevant time unit (depending on a sampling period). Adding all the relevant water volumes (those which occurred in Q_{30} – Q_0) across the whole time series, total water volume in Q_{30} – Q_0 was obtained. In order to get the mean annual water volume this value was then divided by a number of years. This procedure was used to calculate mean water volume which flows annually in the Q_{30} – Q_0 range. It can be also written as follows:

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

$$MEAN\ \ ANNUAL\ \ WATER\ \ VOLUME\ \ Q_{0-30} = TOTAL\ \ Q_{0-30}\,/\,no.\,YEARS$$

Exactly the same was done in order to get the annual water volume for $Q_{100} - Q_{30}$. So it can be given as follows:

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

$$MEAN\;\;ANNUAL\;WATER\;VOLUME\;Q_{30-100} = TOTAL\,Q_{30-100} \,/\, no.\,YEARS$$

However the function f(t), which would describe the progress of the flow in time, was not known so, instead of integrating this function, discrete water volume values were simply toted up. As the discharge was known, together with the time period for the discharge was representative, total amounts could be calculated.

The remaining question that had to be answered was how much material is actually transported in these two parts of flow. By analyzing existing river data it was found that flows greater than Q_{30} ($Q_{30} - Q_0$) transported 84.9 % of the annual transported material, and that 15.1 % of annually transported material is transported in flows Q_{30} to Q_{100}. These figures were calculated as a mean of values observed in catchments where SSC existed. Actual figures in particular catchments may thus vary around these values. Knowing that, it was then possible to estimate mean sediment concentration in both parts of the flows by simply dividing the corresponding values. Mean sediment concentration was a satisfactory result for the part Q_{30} to Q_{100} (according to the pattern shown on Figure 7.1 sediment concentration is constant) so there was no need to further deal with that. However sediment concentration being calculated as a constant also in flows greater than Q_{30} did not match the pattern (Fig. 7.1) of sediment concentration progression. In order to fix the problem, a simple mathematical correction was carried out (Fig. 7.3).

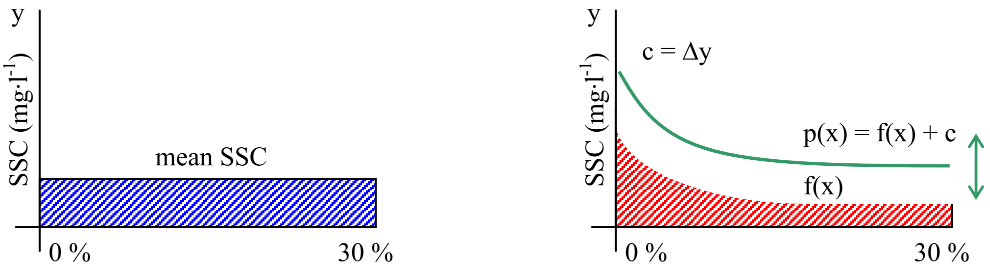


Figure 7.3 – Area matching procedure for estimation of sediment concentration

If the area below the calculated mean concentration (blue) and below the function f(x) (red) were the same then the same amounts of material would be transported. Since the red shape represents the progression of sediment concentration behaviour, the task to be performed was to reshape the blue area into the red one while the areas remain the same. This could be achieved by moving the function f(x) in the y-axis direction until the areas match. While moving the function, the mathematical expression remains the same except for a constant **c** which is determined by the movement in the y-axis direction.

The constant was obtained by following an expression:

$$MEAN\ SSC \cdot 30 = \int_0^{30} p(x)dx$$

$$MEAN\ SSC = \int_0^{30} (f(x)+c)dx$$

$$MEAN\ SSC = [F(x)]_0^{30} + [c \cdot x]_0^{30}$$

$$MEAN\ SSC = F(30) - F(0) + c \cdot 30$$

$$c = \frac{MEAN\ SSC - F(30) + F(0)}{30}$$

After the constant had been found Area$_1$ and Area$_2$ matched which means that transported amounts of material remain the same whilst the shape of the curve represents general behaviour of the sediment concentration in this particular part of flows. The intention was to apply this approach to SSC prediction – the progression of SSC behaviour in $Q_{30} - Q_0$ would be always described by the function f(x) varying only in the **c** constant. That would make the difference between locations whereas the SSC progression would fit the pattern shown on Figure 7.1.

The approach to estimate sediment concentration presented here seems to be methodologically clear and consistent and it fits the sediment concentration behaviour best. However some negative consequences were discovered by applying this approach (Fig. 7.4).

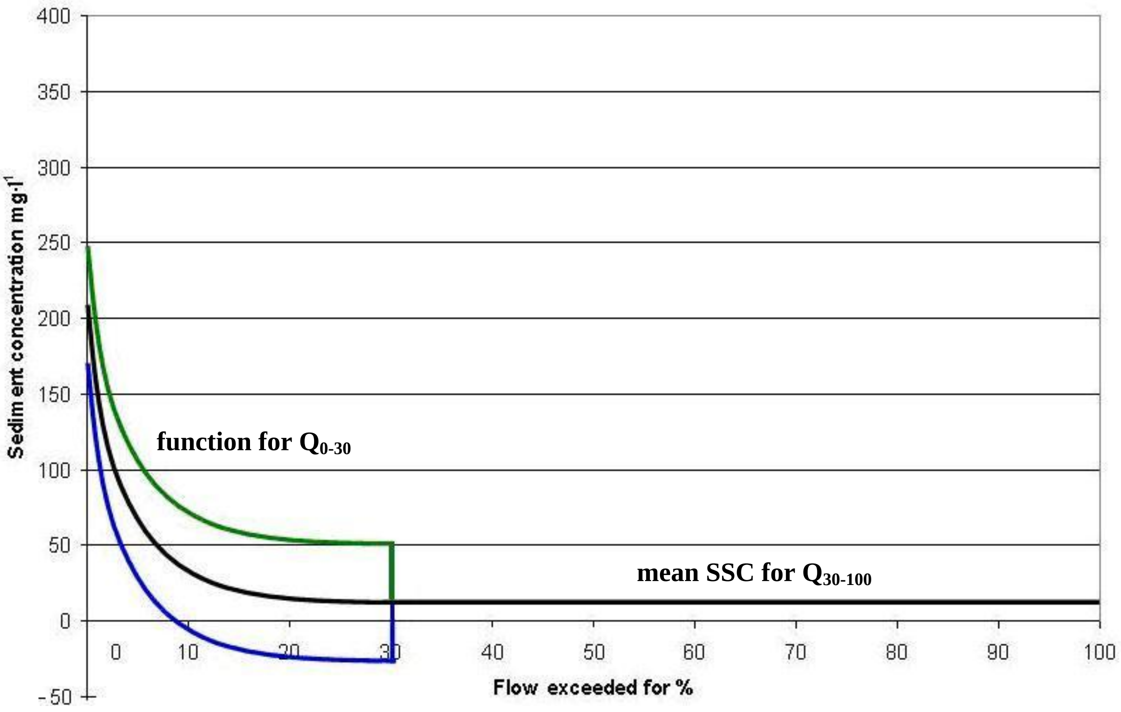


Figure 7.4 – Imperfections found in the methodology

The main problem was that the area required to get the appropriate transported amount of material in Q_{30} to Q_{100} was either to small or to big, depending on transported amounts. In some catchments the amount of transported material (sediment yield in Q_{30} – Q_0) was so small that after moving the curve in order to get the same area sediment concentrations were actually below zero. Conversely, in some catchments the yield was too high and thus a step appeared (Fig. 7.4) in the sediment concentration progression. This was considered as a critical shortcoming in the methodology causing a failure. Therefore an adjustment of the methodology was required.

7.2 An adjustment of the methodology

The solution to the problems reviewed in the previous section led to a slight change of the expected variability in sediment concentration. Instead of getting a coherent curve (constant for Q_{100} to Q_{30} and a function for Q_0 to Q_{30}), discrete values were used for determining the sediment concentration progression (Fig. 7.5).

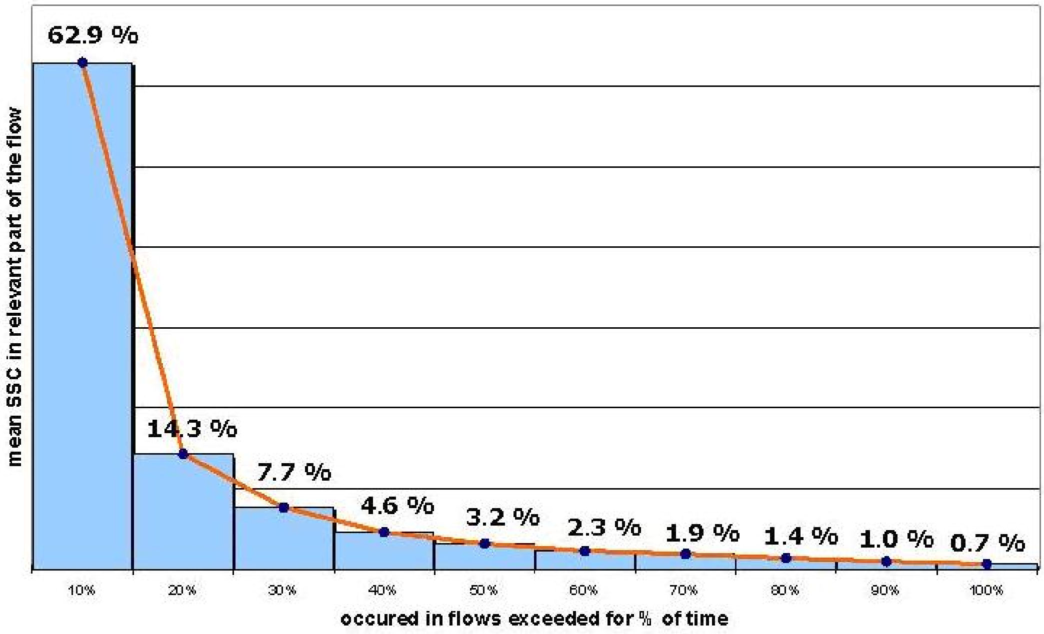


Figure 7.5 – Expected pattern of predicted sediment concentrations

In practical terms the flow was divided into ten parts which corresponded with each 10 % of the flow exceedance curve. Then, for each part of the flow, mean sediment concentration was estimated by dividing relevant annual amount of transported material (mg) by annual amount of water (l) occurring in relevant part of the flow. From this point on it was similar to previous actions. Instead of two parts of the flow there were ten of them. Obviously the percentage of transported material in relevant parts of the flow had to be reconsidered. New results were obtained by carrying out further analyses of available sediment data. In each river basin where SSC data existed, the amount of transported material was calculated for each ten percent of flow exceedance. These values were then averaged and a general ratio of transported material in each ten percent of flow exceedance was obtained. Table 7.1 shows new values used for the final predictions.

Table 7.1 – Percentage of annually transported material in various flow ranges

Part of the flow	$Q_0 - Q_{10}$	$Q_{10} - Q_{20}$	$Q_{20} - Q_{30}$	$Q_{30} - Q_{40}$	$Q_{40} - Q_{50}$	$Q_{50} - Q_{60}$	$Q_{60} - Q_{70}$	$Q_{70} - Q_{80}$	$Q_{80} - Q_{90}$	$Q_{90} - Q_{100}$
% of transported material	62.9	14.3	7.7	4.6	3.2	2.3	1.9	1.4	1.0	0.7

Using this approach, which was actually just a modification of the first method, it was then possible to achieve satisfactory results in terms of sediment concentration. The imperfections in the first method were eliminated. This approach was applied for the final sediment concentration predictions. All the predicted sediment concentrations can be found in Section 11 (Appendices).

7.3 Verifying the predicted sediment concentrations

An example of final predicted sediment concentrations is presented in this section (the values (Tab. A2, A3, A4, A5) and the rest of the figures (Fig. A2) can be found in appendices). Three approaches were used. The first two use the new SY estimators and the third one uses the traditional approach with a SDR equation. Also, figures upon which comparisons between predicted and observed sediment concentration are observed are presented here. The following figures are further discussed in Section 8.

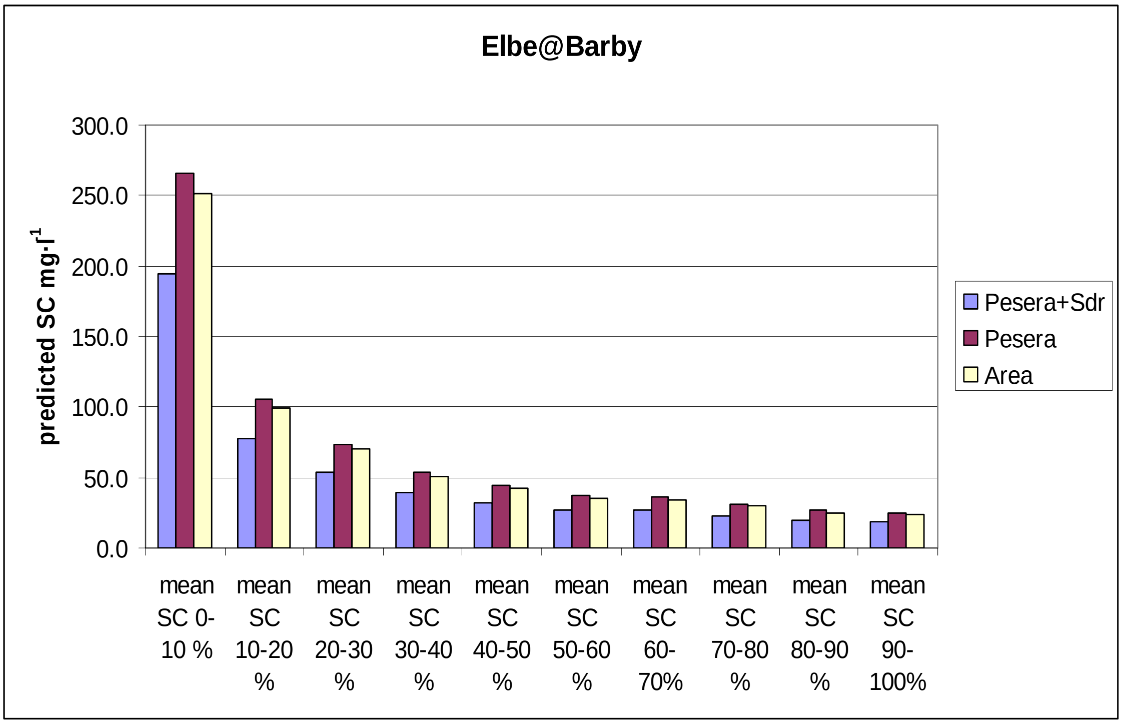


Figure 7.6 – An example of predicted SSC based on the three SY approaches for the River Elbe at Barby

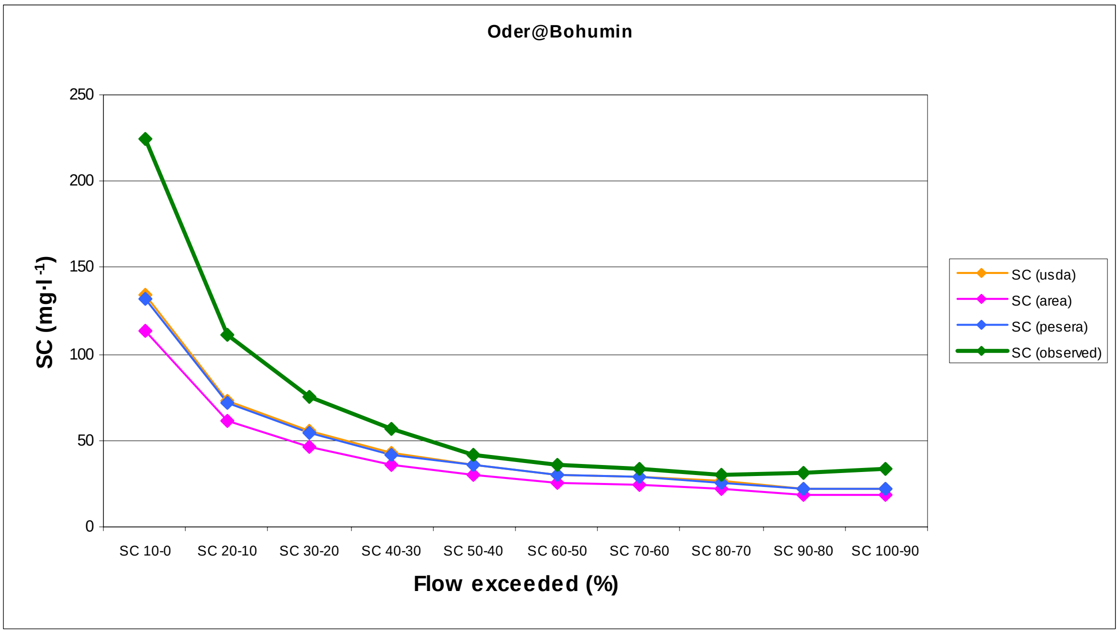


Figure 7.7 – Verification of the SSC estimation methodology for the River Oder at Bohumin

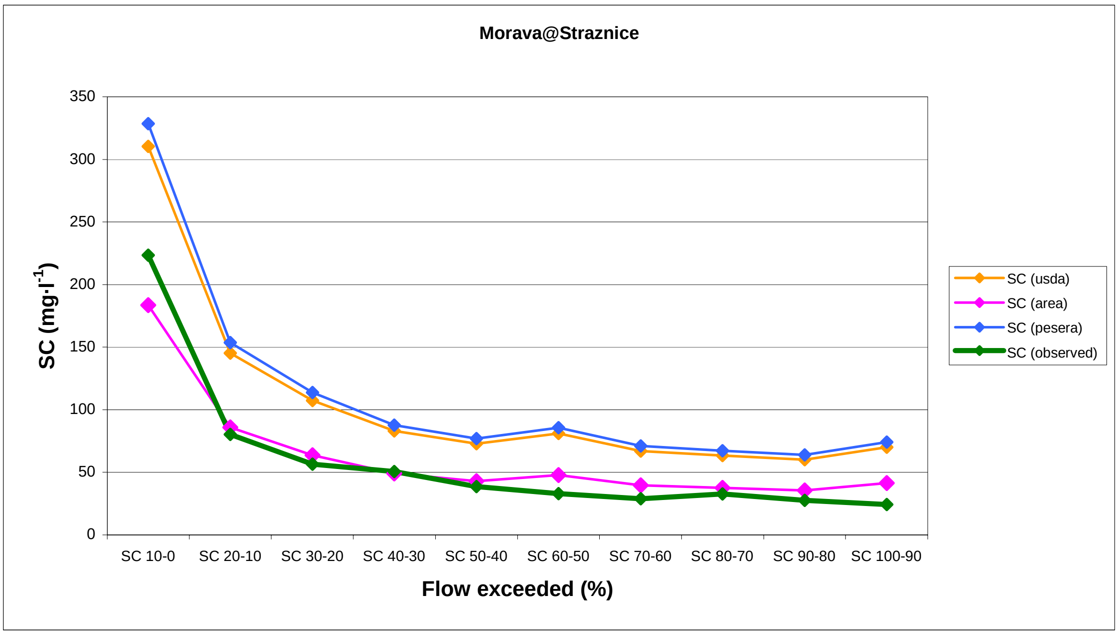


Figure 7.8 – Verification of the SSC estimation methodology for the River Morava at Straznice

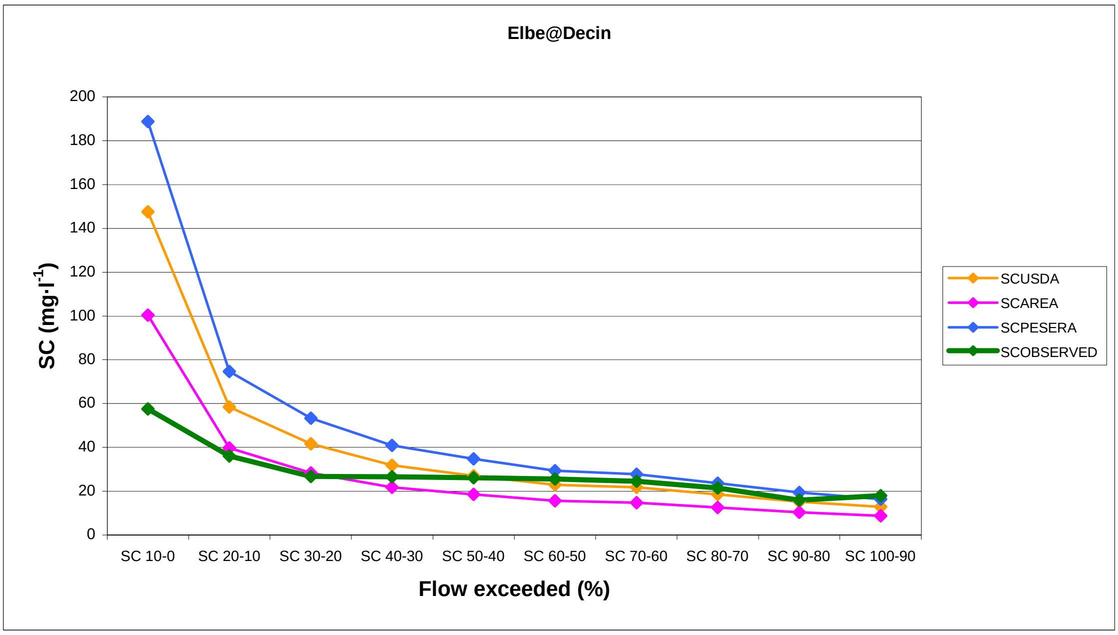


Figure 7.9 – Verification of the SSC estimation methodology for the River Elbe at Decin

Table 7.2 – Predicted sediment concentrations compared to observed concentrations

Method	**Oder@Bohumin**									
	SC_{10-0}	SC_{20-10}	SC_{30-20}	SC_{40-30}	SC_{50-40}	SC_{60-50}	SC_{70-60}	SC_{80-70}	SC_{90-80}	SC_{100-90}
SC_{USDA}	134.0	73.0	55.1	42.3	36.1	30.5	29.4	26.1	22.3	22.2
SC_{AREA}	113.1	61.6	46.5	35.7	30.4	25.7	24.8	22.0	18.8	18.7
SC_{PESERA}	131.8	71.9	54.2	41.6	35.5	30.0	28.9	25.7	21.9	21.8
$SC_{OBSERVED}$	224.5	110.8	75.8	56.3	42.1	35.7	33.2	30.4	30.8	33.1
	Morava@Straznice									
	SC_{10-0}	SC_{20-10}	SC_{30-20}	SC_{40-30}	SC_{50-40}	SC_{60-50}	SC_{70-60}	SC_{80-70}	SC_{90-80}	SC_{100-90}
SC_{USDA}	310.3	145.3	107.5	83.0	72.8	81.0	67.1	63.5	60.2	70.1
SC_{AREA}	183.5	85.9	63.6	49.0	43.0	47.9	39.6	37.5	35.6	41.5
SC_{PESERA}	328.4	153.7	113.8	87.8	77.0	85.7	71.0	67.2	63.8	74.2
$SC_{OBSERVED}$	223.4	80.3	56.5	50.7	38.5	33.0	28.9	32.8	27.6	24.2
	Elbe@Decin									
	SC_{10-0}	SC_{20-10}	SC_{30-20}	SC_{40-30}	SC_{50-40}	SC_{60-50}	SC_{70-60}	SC_{80-70}	SC_{90-80}	SC_{100-90}
SC_{USDA}	147.5	58.4	41.6	31.9	27.1	22.9	21.7	18.5	15.2	12.8
SC_{AREA}	100.4	39.7	28.3	21.7	18.5	15.6	14.7	12.6	10.3	8.7
SC_{PESERA}	188.7	74.7	53.3	40.9	34.7	29.3	27.7	23.7	19.4	16.3
$SC_{OBSERVED}$	57.5	36.1	26.7	26.6	26.2	25.5	24.5	21.5	15.9	17.9

In order to evaluate how well the predicted SSC fit to the observed ones, a basic measurement of goodness-of-fit was carried out. Two descriptive statistics were used. Linear regression coefficient r^2 was the first one used. It helps to evaluate the trend between predicted and observed data. This value indicates whether the model of SSC behaviour (Figure 7.5) and the ratio used for redistribution of the material (Table 7.1) is representative for SSC predictions. The second statistic used was the mean absolute deviation (MAD). It is conceptually comprehensive and relatively simple measure of goodness-of-fit that is easy to understand. It is represents how far from the observed data the prediction is (in actual units of prediction).

The measurements of goodness-of-fit are presented in the following table (Tab. 7.3). For further comparisons the essential monitored data are missing. However for some rivers SSC or SY data may be found in literature (e.g. for the UK rivers see Science of the Total Environment, vol. 251-252 (2000)). Nonetheless for the comparisons raw monitored data are required.

Table 7.3 – Measurement of goodness-of-fit of predicted SSC

Location	Approach	Correlation with observed data	MAD (mg.l^{-1})
Bohumin	SSC PESERA	0.996	20.90
	SSC Area	0.996	27.54
	SSC USDA	0.996	20.17
Straznice	SSC PESERA	0.994	52.67
	SSC Area	0.994	11.44
	SSC USDA	0.994	46.49
Decin	SSC PESERA	0.977	23.35
	SSC Area	0.977	10.41
	SSC USDA	0.977	14.76

7.4 Sediment yield prediction

The three approaches to calculate sediment yield used for sediment concentration prediction were also used to calculate sediment yield for all the river basins from the study area. These values may be considered as the most likely sediment yields estimated for the major European catchments. Values and maps can be found below (Tab. 7.4) and Fig. 7.10, 7.11 and 7.12).

Table 7.4 – Sediment yields (t·yr^{-1}) calculated for the study area using the new methods

ID	River	SYUSDA (1971)	SYPESERA	SYAREA
1	*Velikaya	26,770	34,520	1,156,234
2	*Daugava	24,083	32,505	1,750,847
3	*Dnieper to Kremenchutska dam	*	*	7,155,810
4	Earn and Tay	46,481	46,971	126,086
5	*Neris	219,698	298,850	1,879,518
6	Tweed	124,027	122,233	100,401
7	Ouse	68,023	73,180	222,703
8	*Wisla	1,543,613	2,277,544	3,935,171
9	Odra	1,392,465	1,945,625	2,398,459
10	Trent	112,678	120,430	209,860
11	Elbe	1,941,809	2,765,777	2,855,689
12	Witham	28,321	26,022	53,101
13	Weser	780,570	981,374	918,531
14	Severn	64,644	69,242	214,053
15	Welland	14,619	12,851	35,516
16	Nene	17,778	16,586	60,998
17	Wye	11,502	11,092	82,450
18	Great Ouse	66,592	68,814	154,459
19	Thames	37,118	39,762	214,256
20	*Rhein	1,973,019	2,858,679	3,335,775
21	Waal	454,726	552,919	677,918

22	*Pivdennyy Buh	*	*	1,070,609
23	*Dnister	3,043	4,034	1,483,815
24	Seine	1,237,613	1,643,633	1,511,577
25	Loire	1,169,210	1,631,969	2,375,684
26	*Rhone	2,209,005	3,022,216	1,980,550
27	*Po	1,934,126	2,560,518	1,468,632
28	Garonne and Dordogne	2,566,580	3,439,067	1,638,986
29	Mino	179,498	202,750	346,876
30	*Evros	281,336	359,848	1,074,028
31	Arno	1,043,299	1,097,277	181,305
32	Douro	4,056,203	5,550,455	1,983,868
33	Ebro	2,207,804	2,977,597	1,738,635
34	Tevere	2,983,422	3,389,004	365,174
35	*Strimonas	152,742	172,352	343,660
36	*Drini	*	*	380,052
37	*Vardar	105,159	123,617	498,567
38	Tejo	3,061,625	4,045,500	1,443,557
39	Jucar	320,150	372,078	449,477
40	Guadiana	4,394,766	5,769,656	1,361,209
41	Guadalquivir	5,322,425	6,868,254	1,163,988
42	*Danube to confluence with Tisa	2,637,692	4,015,561	5,230,497
43	*Tisa to confluence with Danube	1,354,664	1,948,823	3,126,628
44	*Danube from confluence with Tisa	1,212,583	1,931,895	7,908,362

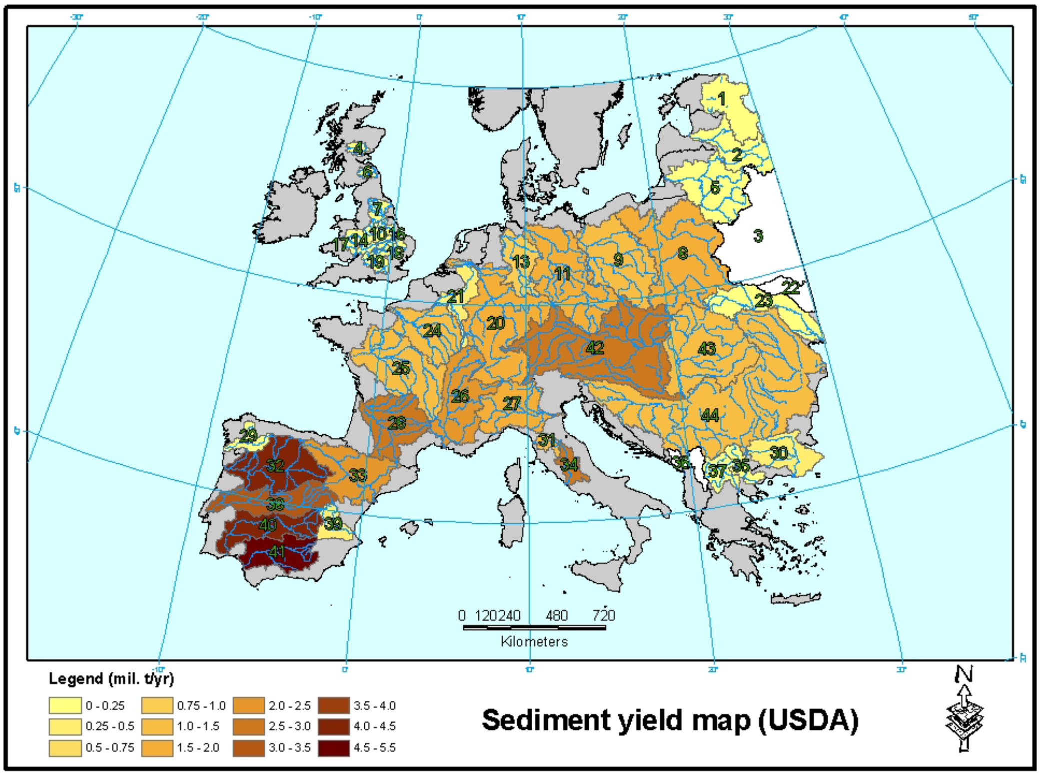


Figure 7.10 – Sediment yield map for Europe (USDA)

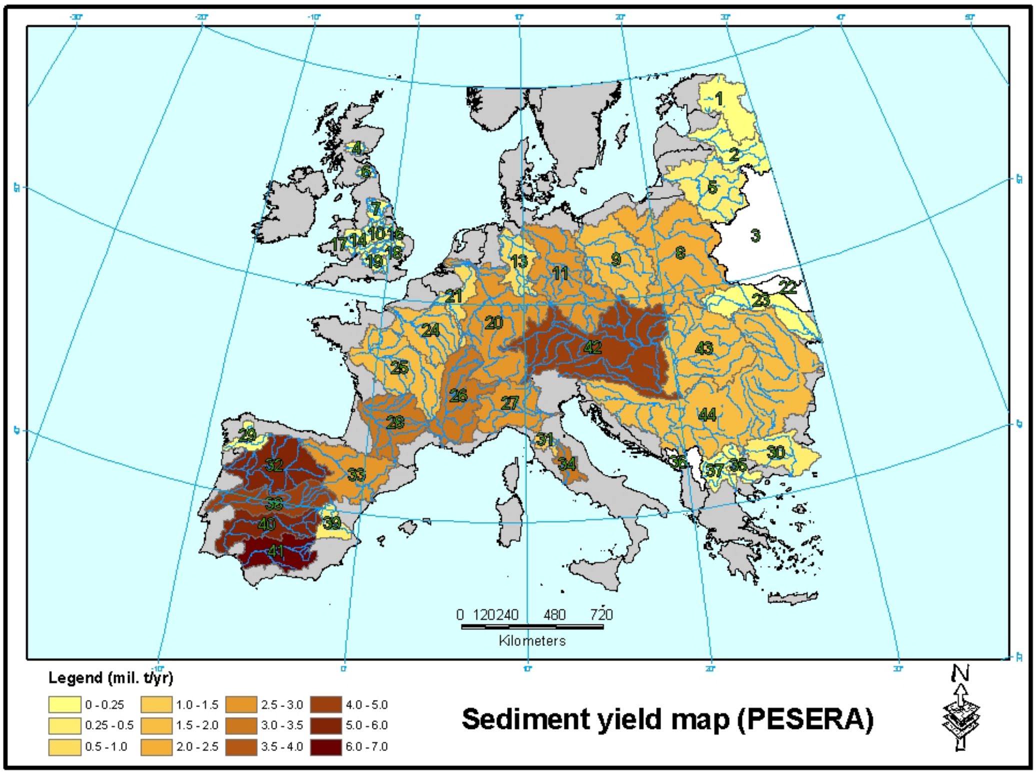


Figure 7.11 – Sediment yield map for Europe (PESERA)

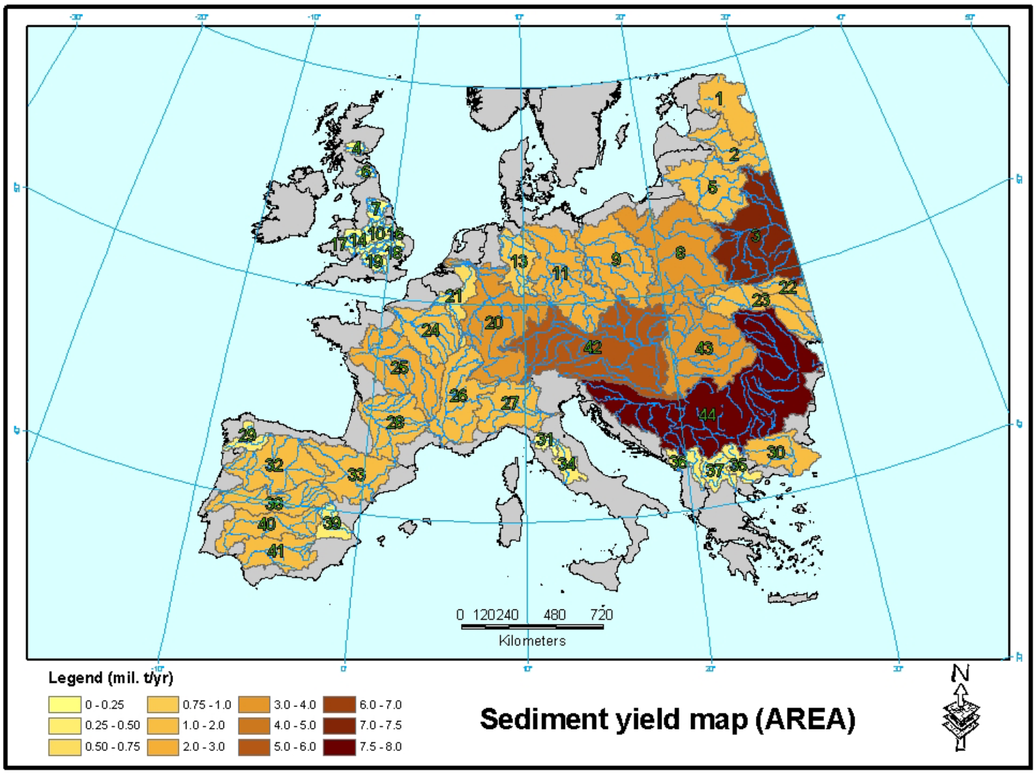


Figure 7.12 – Sediment yield map for Europe (AREA)

8 Discussion

The presented methodology to calculate sediment yields in large catchments and to predict sediment concentration is now quite consistent and seems to be providing sensible results at this level. However, due to the limited sources of SSC data very few comparisons were performed. In addition, only soil erosion was considered as a source of sediment. Other relevant sediment sources such as bank erosion could not be evaluated as there is a lack of assessment methods that could be applied in a study of this extent. It is certain that ignoring other sediment sources means introducing an error into the approach. Nevertheless at this stage the predicted SSC should be treated as provisional until the shortcomings can be eliminated. Apart from that, there are certain issues that deserve further discussion.

Sediment Yield

In terms of sediment yield estimation there are certainly plenty of points in the methodology that should be considered and subject of further investigations. Firstly, the sediment delivery process by itself is affected by a variety of uncertainties and random processes which could not be included in this study. Sediment yield estimation at the point of interest (where sediment concentration was predicted) is crucial as the basic idea to predict the concentrations is redistribution of an annual sediment yield into annual water volume using the flow variability. Sediment yield is estimated using three different methods which seem to be similar in some respects because the same kind of data is used. However they are not dependent on each other. The relationships used were developed from different data and under different circumstances and thus they produce different results and there is no reason to consider them as dependent. The relationships are only similar in terms of used variables. The difference is also quite obvious from the final sediment yield maps for the study area (Fig. 7.10, 7.11 and 7.12). Direct prediction of sediment yield from the area of the catchment seems to provide different results to the two other methods, particularly in the Mediterranean area where soil erosion is dominant and the prediction from the area is underestimated. Using only area to calculate sediment yield does not take into account, for example, the morphology in catchments. It may lead to a situation where two catchments of the same size will have the same predicted sediment yield even thought one of them may have much higher soil erosion rates and thus potentially higher sediment yields. Therefore using soil erosion information in a catchment as a variable for SY prediction is apparently more sensible.

The three methods used for SY estimation consist of two new methods developed within this work and an existing one. The selection of the existing SDR approach was based on goodness-of-fit measurements. A ranking method was used in order to select an approach which has the best combination of correlation with the observed data and mean absolute deviation from the observed data. Using this method the USDA SCS SDR approach (1971) was chosen as the third method for SSC predictions.

Another issue deserving of attention is that the PESERA approach used for sediment yield calculations is only another estimation of erosion. Of course, there are relatively exact methods to measure soil erosion; but, these could not be applied over such large areas as investigated here. This could be a reason why some of the sediment delivery equations provided non-sensible results. Possibly, they might have succeeded and provided excellent results if another soil erosion approach had been used. In terms of investigating and improving knowledge of sediment delivery process the methods used here to calculate sediment yields actually constitute a step backwards to the black box approach, because the process of sediment delivery is not investigated at all and sediment yields are predicted directly from the inputs. Only inputs and outputs are linked here, which is typical for black box models. However, in as generalised an approach as applied here, the methods are appropriate to get satisfactory results. Perhaps better results could have been obtained if a semi-distributed approach had been used such as to estimate sediment delivery ratio using different SDR equations in different environments. SDR equations vary in terms of applicability and variables used. In different environments there are different dominant controls on sediment delivery processes. Considering this, more appropriate equations could have been chosen for each environment. But again, the dominant parameter in various environments found across the continent would have to be known and, moreover, more data would have been needed to calculate the variables. However, some general spatial variability across the continent can be observed – rivers in southern Europe have typically higher sediment yields than those found further north (Fig. 4.3, 4.4). It is not only the matter of different environments that should be considered but also political boundaries may play an important role. Typically, large catchments as investigated here may cover more than one country. This means that the sediment delivery process may be very different than could have been expected even if the catchment characteristics are fairly similar. This can be due to different environmental policies – within a catchment there may be countries where the environmental policy includes careful sediment management and *vice versa*. Therefore environmental policy may also affect SDR and SY. Perhaps this would be even harder to consider and much more data and information would be required.

Suspended Sediment Concentration

In terms of suspended sediment concentration prediction the main idea of the methodology (redistribution of an annual sediment yield into annual water volume using the flow variability at the point of interest) is probably the only one that could be applied here. This approach assumes that sediment occurs in a river solely as a consequence of soil erosion. No other sources of sediment which would influence sediment concentration were taken into account. Of course there are other sources of sediment that can be dominant in some cases; however, soil erosion occurring in the catchments is recognised as a major source of sediment and pollutants.

Using the flow exceedance curve was useful for observing the behaviour of sediment concentration in certain parts of the flow. The key issue of the methodology was to determine sediment concentration as constant in flows that are smaller than those which are reached or exceeded for 30 % of time – Q_{30}. In flows higher than Q_{30} the concentrations were changing according to a logarithmic function. In order to derive the function, data from various locations were gathered, so a generally representative function could be obtained. The fact that data were from various locations was probably also the cause of later failure of this method. It is actually a general representation of sediment concentration behaviour and perhaps because of its generality it fails at particular places. Some critical imperfections appeared that could not be tolerated. The solution of this problem could potentially have been found by classifying rivers into several classes and to produce a function which would be representative for the class. In order to apply this approach, a river would have to be classified in the first place and then an appropriate function could have been selected. The classification would probably be based on the catchment characteristics. However this would require far more work and, moreover, data were not available from all the different environments so the classification would not be complete in any case.

The solution of the problem came with a modification of the method. Instead of getting a coherent curve (consisting of a logarithmic function for Q_{0-30} and constant for Q_{30-100}), discrete values were aimed for. Annual sediment yield was then redistributed into each 10 % of flow exceedance and mean sediment concentrations in each part were obtained. Redistribution of annually transported material was not linear. Instead, it was distributed with respect to the ratios observed in transported amounts of material taken from available sediment data. It was discovered that the majority (more than 80 %) of annually transported material is actually transported by flows which occur for 30 % of time in one year. It seems that the ratio is different for the Mediterranean area where even more material is transported in high flows. Thus, the final sediment concentration prediction was achieved using discrete values (annual mean) in relevant parts of the flow. Sediment concentration values are strongly dependent upon sediment yield values. Therefore if sediment yield values vary significantly among the three methods, sediment concentration will also vary significantly. The comparison of the predicted sediment concentration at various locations using the three SY approaches is shown at Figure 8.1. The methods perform fairly similarly apart from a few Mediterranean catchments, where the differences between the new SY estimation methods are significant. The methods use either soil erosion or catchment area as a variable. However, in this case soil erosion is dominant in relatively small catchments. Therefore the prediction of sediment yield using just the area is in this case underestimated. Hypothetically it could also be the other way around – a big flat catchment with low erosion rates would have higher prediction of SY using the area as a variable. As discussed above, using just the area for SY prediction may lead to inaccurate results. For most of the locations where sediment concentrations were predicted, satisfactory results were obtained by applying this approach. However in a few cases this approach seems to fail. It appeared predominantly in catchments in Spain and Portugal (Mediterranean area once again). Predicted sediment concentrations were higher for low flows than for high flows. The reason for that is that a unified ratio to redistribute sediment yield was used and it was gained from an analysis of samples from northern parts mostly. Only a few data were available from southern areas.

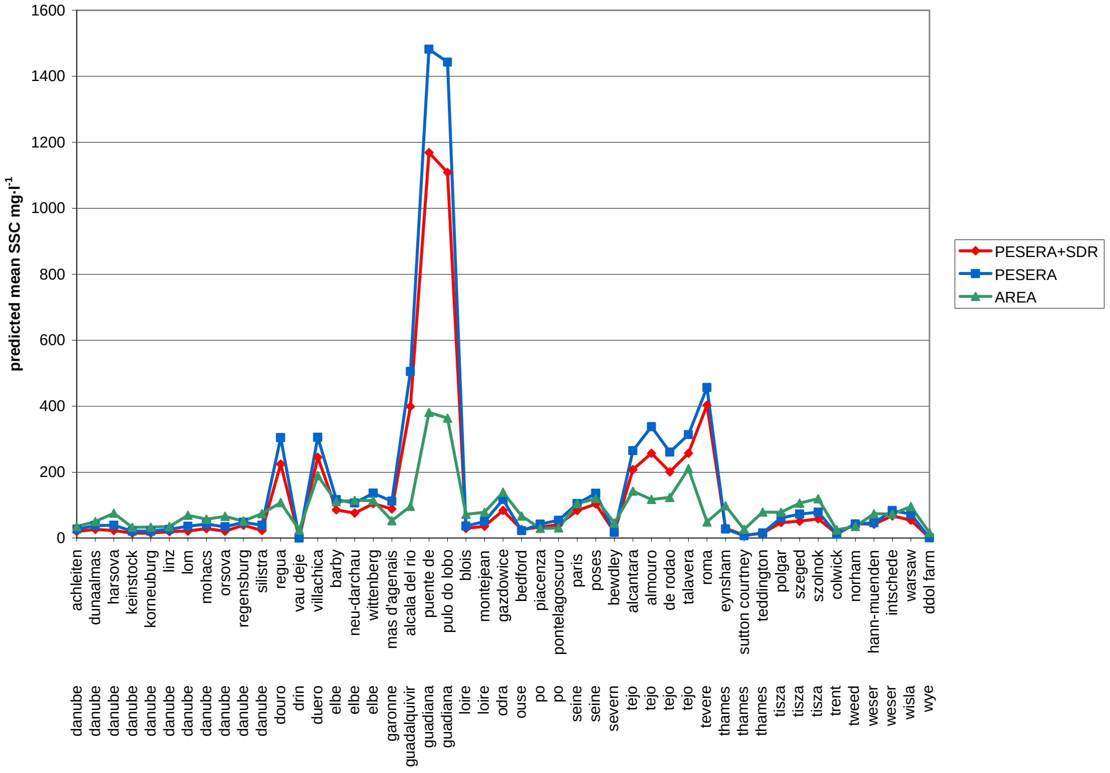


Figure 8.1 – Comparison of performance of different SSC prediction methods

Apparently, the ratio of transported material is different for those particular rivers in Spain and Portugal. More material is transported in higher flows in these catchments. However, by applying the current ratio, more material ought to be transported in lower flows. In order to transport this amount of material in such low flows the concentration is consequently estimated as very high. In order to solve this problem more data from southern Europe are required to be analysed. There were some data available from the Ebro and Jucar catchments but these rivers are either strongly affected by dams or do not have very good quality data. One of the problems was that the measurements have not been taken regularly and with sufficient frequency of sampling. Therefore one sediment concentration had to be considered as representative for a relatively long period of time and it does not make the estimation of transported material in certain part of the flow very accurate.

More accurate estimates of likely sediment concentration may be achieved by applying additional processing after using this methodology. Predicted concentration values can be modified by taking local conditions into account. This means that where the information about dams and other sources of sediment exist then the concentrations can be adjusted and thus become more relevant.

The methodology was also applied where SSC data were available. Sediment concentration and flow data with a daily sampling period were available for three basins in the Czech Republic. Predicted sediment concentrations were compared to observed ones (Fig. 7.7, 7.8, 7.9 and Table 7.2). It became obvious that the methodology suffers from its generality and insufficient quality of primary data. Basic measurements of goodness-of-fit were used here in order to evaluate the goodness-of-prediction. Predicted SSC at all three locations have strong positive correlation with observed data. This shows that the model of SSC behaviour (Figure 7.5) selected for SSC predictions represents the real data quite well. Additionally, the descriptive statistic (MAD – mean absolute deviation) was used in order to show the mean difference between predicted SSC and observed ones across the flow range. None of the methods seem to perform better than the others. Nevertheless, in a study of such scale, an actual fit of final predicted data cannot be used as a measurement of success. The criteria for success should be whether or not the methodology can be used for SSC predictions. Here, it was shown it can be used. Therefore this was an initial step which determined there is a potential in the methodology that can be further developed to attempt to obtain more accurate predictions of SSC.

Since this study aims to look at general long term estimations it can be concluded that it performs well. None of the local mechanisms influencing sediment concentration can be taken into account in this case. Therefore in one case the real SSC are higher (additional sediment sources may play a role) than observed ones and *vice versa* (sediment may be trapped). The biggest difference between predicted and observed sediment concentrations can be identified in high flows, which is expected. Additional mechanisms and sediment sources may be stronger and more relevant in extreme flows than in normal flows. Moreover every river is different and has different sediment patterns which is best demonstrated in their behaviour during high flows, whereas this approach is general. It only shows that the methodology needs to be further developed and cleared of imperfections caused by the lack of good quality data in terms of spatial and temporal resolution.

In terms of using the results in the GREAT-ER model the methodology should be further verified with real SSC data prior the use in the GREAT-ER model. As presented here, in its current state it would mean an improvement on the state of sediment modelling if used in the model. First of all, mean sediment concentrations from all available river data was 23.mg.l^{-1} (including some locations with strong impact of dams) and the mean from predicted concentrations was 50 mg.l^{-1} (any effect of reservoirs or additional sediment sources was not taken into account). This is reasonably higher than 15.mg.l^{-1} which GREAT-ER currently uses. Thus if a single number must be used it is recommended that it should be a value ranging between 23.mg.l^{-1} and 50.mg.l^{-1}. Moreover the GREAT-ER uses this concentration for all the rivers in Europe, whereas this methodology can provide spatial variability depending on flow data availability. In order to link the sediment concentration with the concentration of chemicals that are present, there are some crucial issues that may play an important role. For example the particle size distribution may be essential information - the same sediment concentration but consisting of fine particles will bind more chemicals as the specific surface area is considerably greater. Further investigation of similar issues does not fit within the scope of this work. The aim was to develop a methodology to predict sediment concentration in order to improve sediment modelling in the GREAT-ER model, which was achieved.

9 Conclusions and recommendations

The methodology presented in this work is suitable to predict sediment yields and sediment concentration for European rivers. Although the methodology uses crude estimation of soil erosion, empirical sediment delivery ratio equations and ‘black box’ relationships, it is still good enough to achieve sensible results.

However, all the predicted concentrations should be considered as long term values and it has to be noted that actual sediment concentration may differ by orders of magnitude at particular times. The methodology has its limitations. Generally the methodology is not suitable for application or may fail in three cases:

1) The first one is when sediments predicted at the point of interest are strongly influenced by a number of processes that could not be included in the methodology. Typically this can be the trapping of sediment in reservoirs or the presence of additional sediment sources (for example resulting from bank erosion, in-channel processes or temporary remobilisations of sediment) which would dramatically decrease or increase sediment concentration. Also to calculate the concentrations at estuaries would not be an appropriate case for applying this methodology because additional dilution and mixing processes, typically occurring there, strongly influence sediment concentration.

2) The second case is when the methodology was applied in very different environments to those in which it was developed. This means either very flat or very hilly areas. In these areas different principles may be dominant in terms of sediment delivery and sources of sediment other than soil erosion may be important (such as mass movement events).

3) The third case where the methodology may fail or be inappropriate is when applied in very small catchments as the PESERA soil erosion model is based on a 1 km grid and therefore estimation of soil erosion in very small areas may be biased.

Nonetheless the methodology developed here works and can be applied. Using the methodology and its results in the GREAT-ER river model may be appropriate and it would mean reasonable improvement of sediment modelling in the model as discussed in section 8.

This study presents a methodology to predict sediment concentration in large European river catchments and also suggests other avenues of investigation in order to improve the methodology. All of the processes investigated here involve high uncertainty. Therefore "what would have happened if…" was also discussed here in order to show all possible extents of this work. Perhaps the most important limitation in the potential continuation of this method would be the availability of data of sufficient quality. If such data could be obtained it would be worth verifying the methodology using these data. The methodology should be verified using non-infrastructure affected data (if possible) collected from somewhere outside the locations where the methodology was developed (where presumably it would succeed). Predicted sediment concentration using the presented methodology could be compared to observed ones as was done for the three locations in the Czech Republic. The lesson learnt emphasised even more the need to further develop the methodology with an emphasis on good quality data. Another issue is taking into account the other relevant sediment sources such as bank erosion. Assessing the magnitude of other sediment sources and their influence on suspended sediment concentrations would greatly improve the predictions of SSC and SY. Therefore, it is obvious that evaluating the other sources is also one of the actions clearly needed for future development of the methodology.

Another recommendation for improving the methodology would be to investigate the differences in sediment behaviour and occurrence in different environments and time periods of the year. Consequently the modification of the method would contribute to its accuracy and credibility. It would also be very interesting and useful to carry out similar work using different soil erosion approaches and observe how the results differ. By refining the extent of this study, further investigation of sediment delivery principles in catchments and primarily if sufficient data are available, it is very likely that this methodology will be able to produce even better results.

Stated objectives of this study were successfully achieved.

Take-home messages

Estimation of sediment yield in typically large catchments:

1) The most reliable method is to use time series of measured sediment concentration or to carry out a survey of sediment deposition in reservoirs.
2) Use soil erosion maps combined with sediment delivery ratio equation with a general validity.
3) Use the approaches presented in this thesis: the links discovered between observed sediment yields and the PESERA map and catchment area, or the PESERA map with SDR_{USDA} equation.

Prediction of suspended sediment concentrations:

1) Estimate annual sediment yield at the point of interest following point 2 or 3 from the above given methods for SY estimation; use flow data to construct flow exceedance curve, distribute the budget of sediment according to discovered ratio of transported material.
2) Where flow data are not available another method is suggested based on finding similarities in catchment characteristics between catchments where sediment concentration are known and where they are not, assuming that catchments similar in certain characteristics might have similar concentration it will be possible to predict SSC.

A bottom note:

Another study (a PhD thesis entitled “A study of erosion and sediment transport in the Elbe catchment in the Czech Republic”, expected to be published in 2007) with similar objectives and with emphasis on further development of this methodology is planned by the author of this work. Data collection and a review of specific issues regarding the work are currently underway.

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11 Appendices

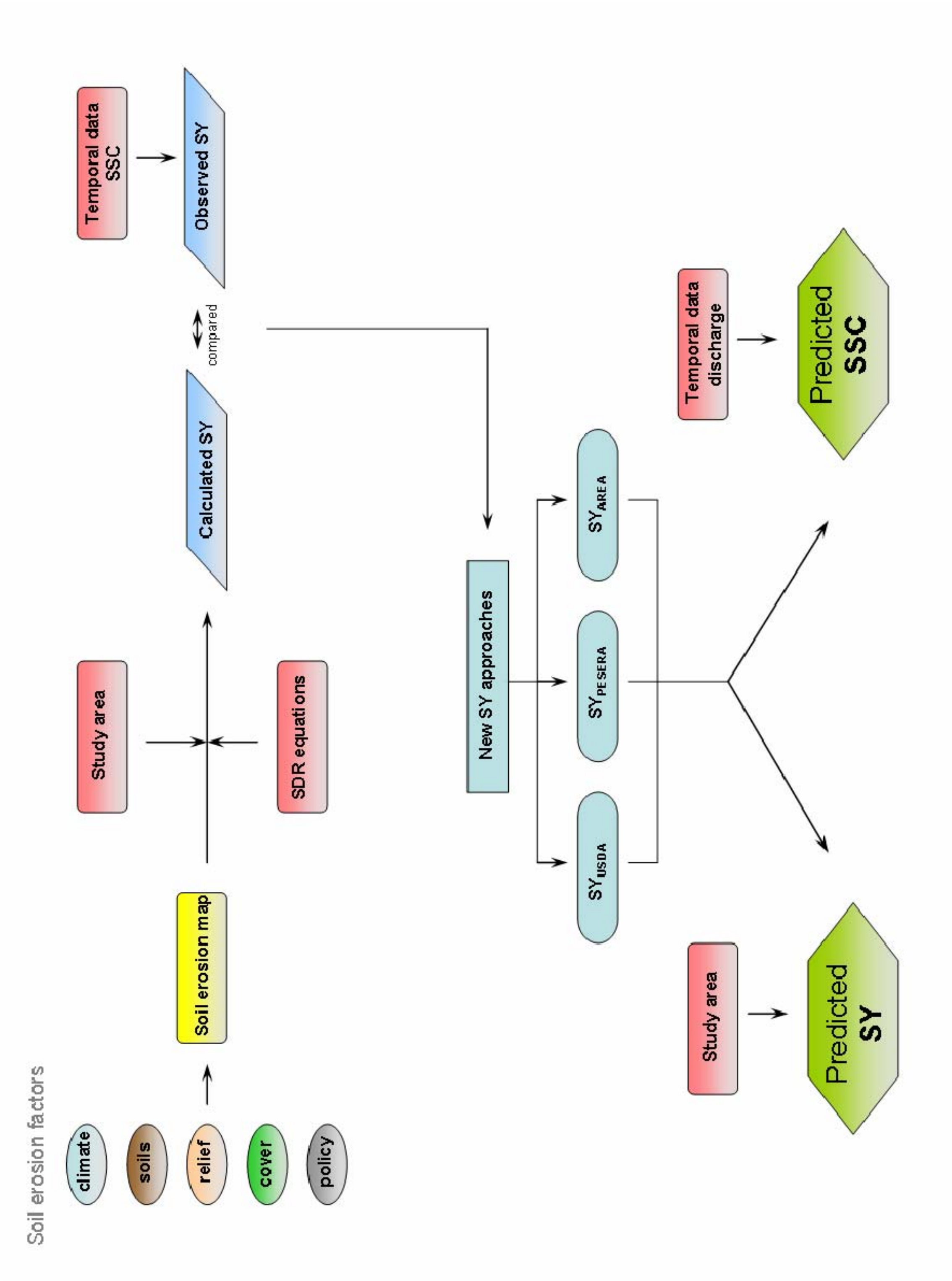
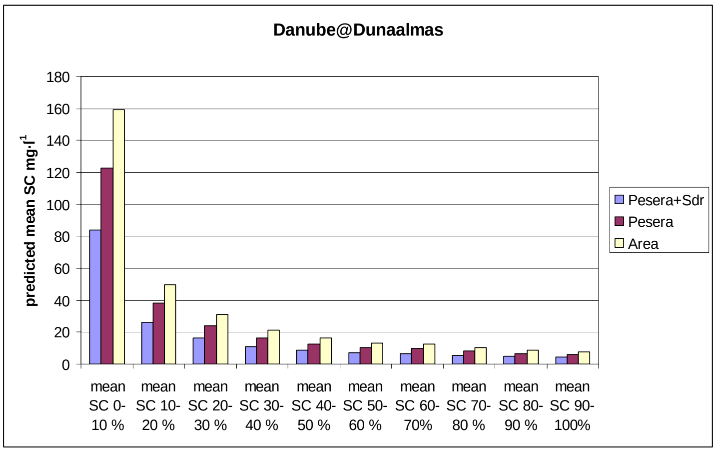
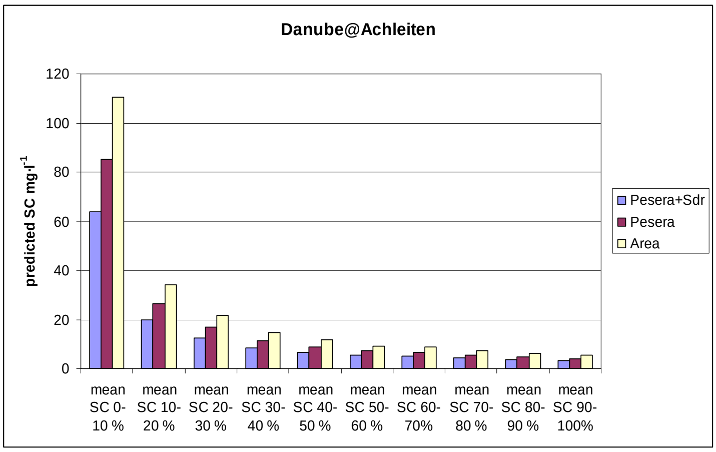
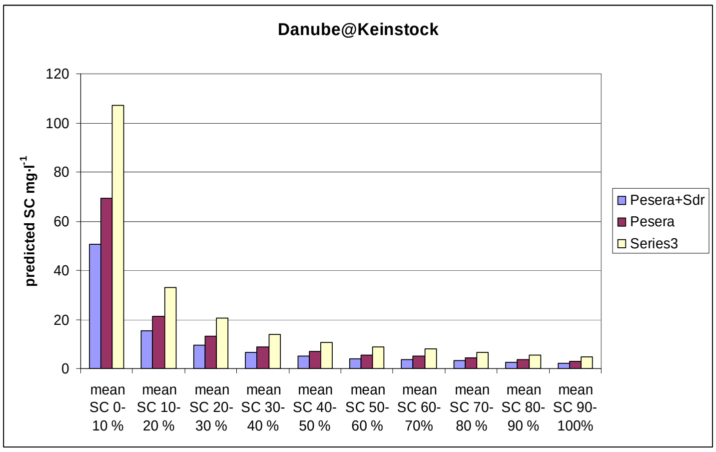


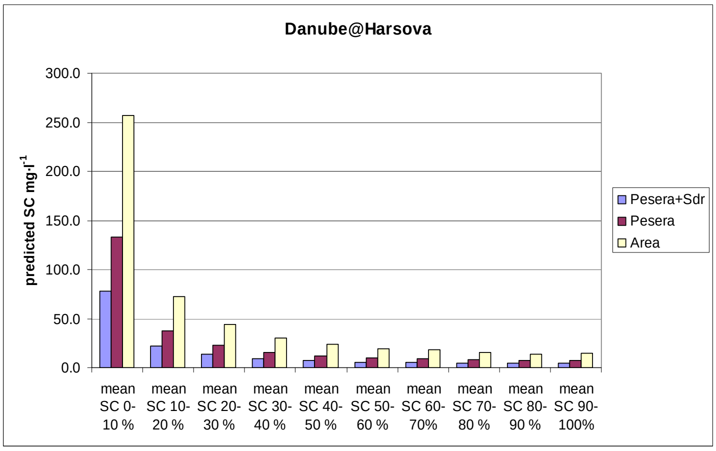
Figure A 1 – Scheme of the work

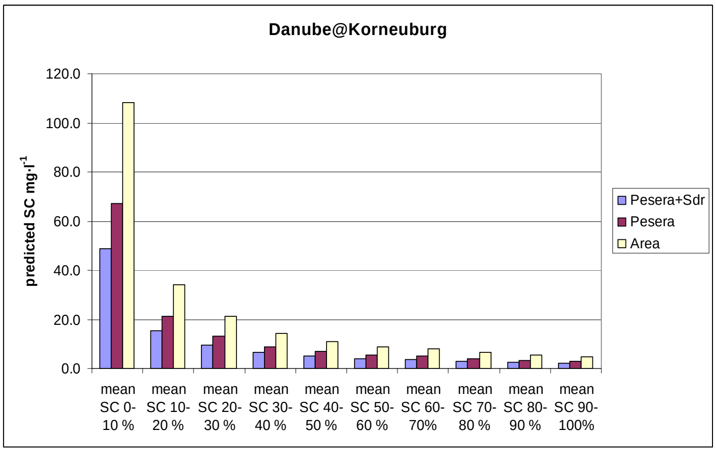
Final predicted sediment concentrations are presented in this section. Three approaches were used. The first two use the new SY estimators and the third the traditional one with SDR. The following figures are further commented upon and discussed in section 8.

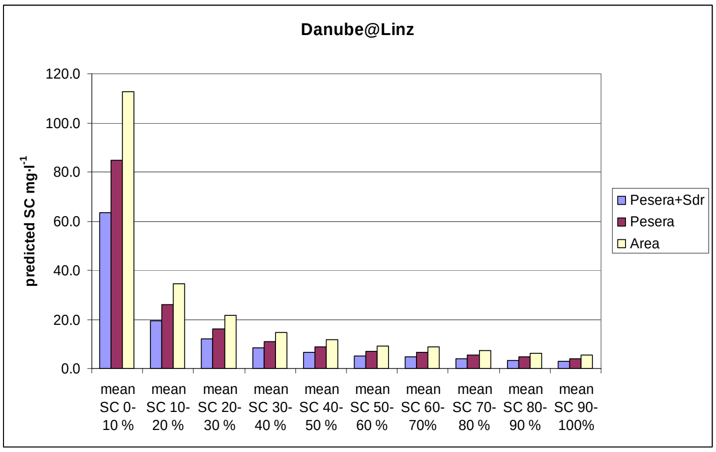


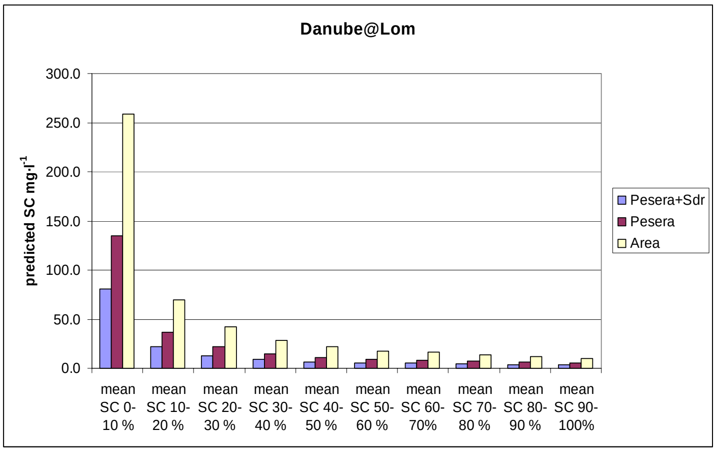








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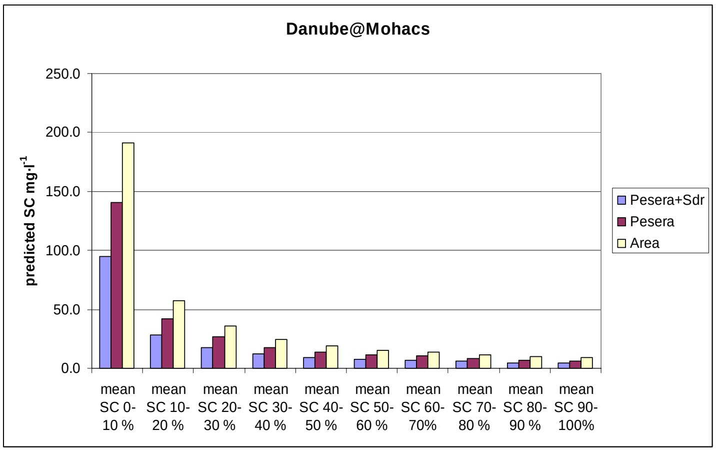
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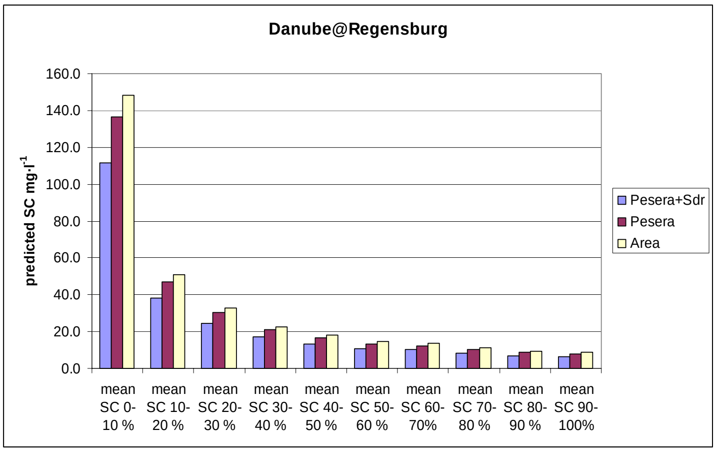
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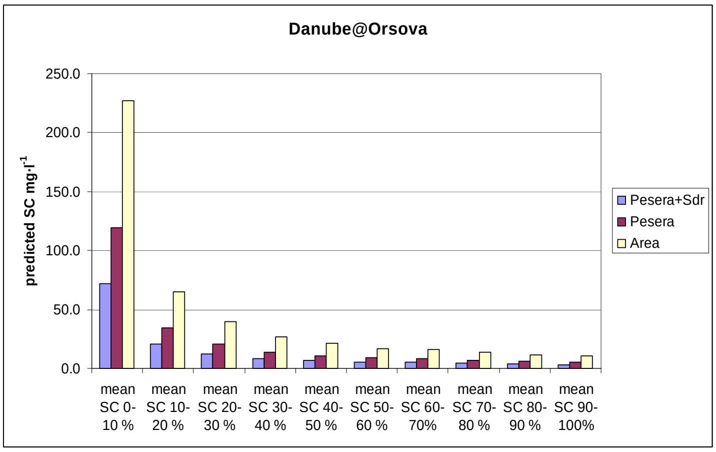
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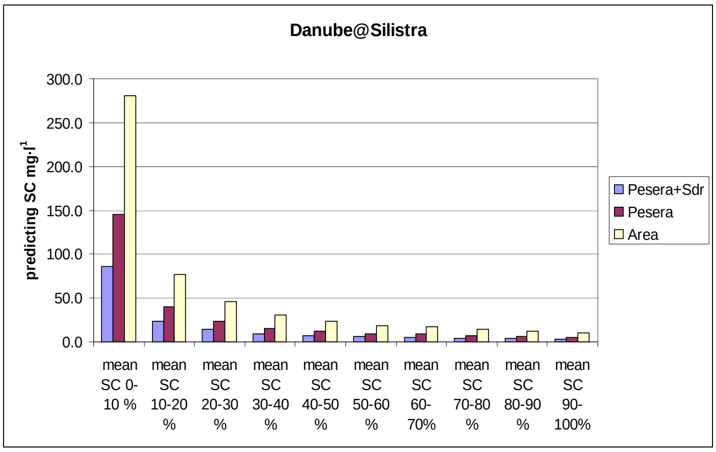
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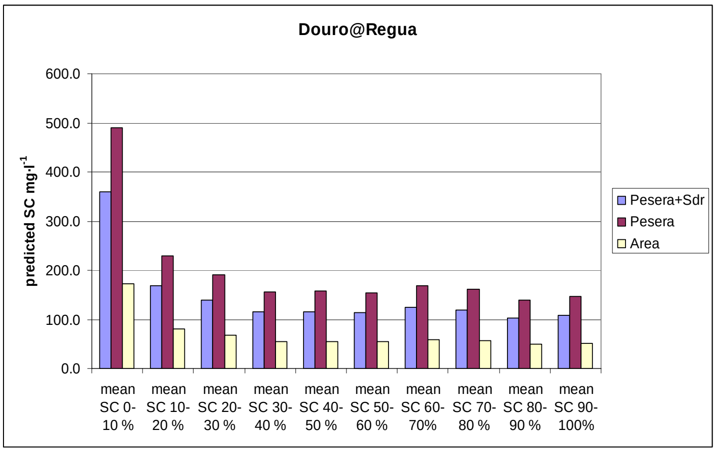
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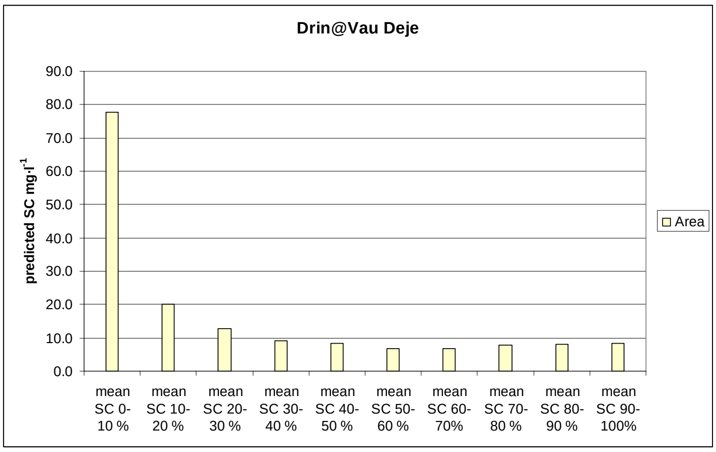
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mean SC 80-90 %
mean SC 90-100%
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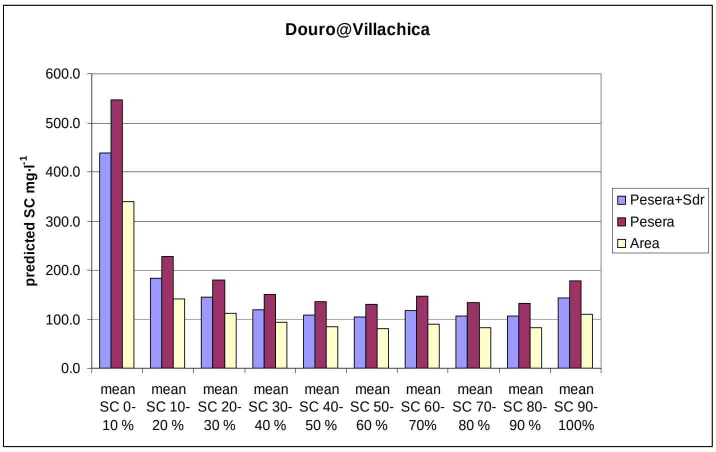
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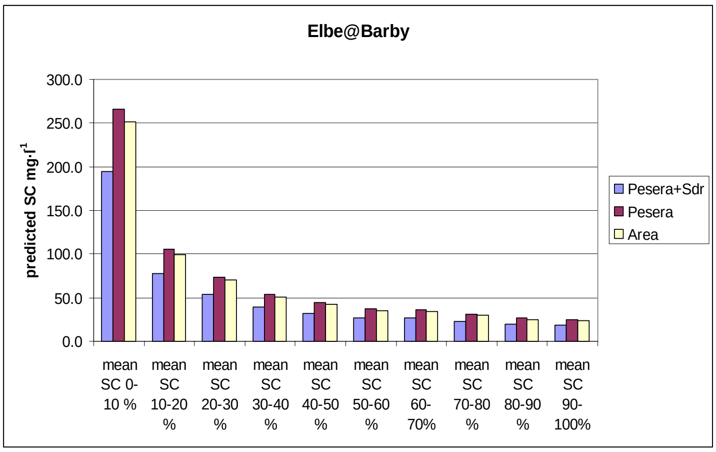
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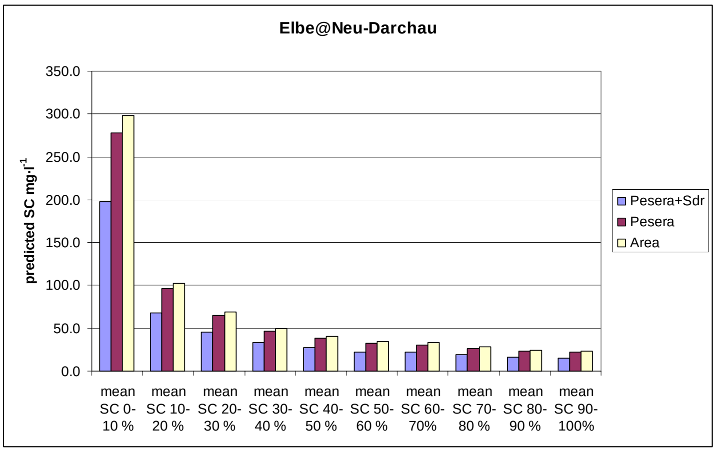
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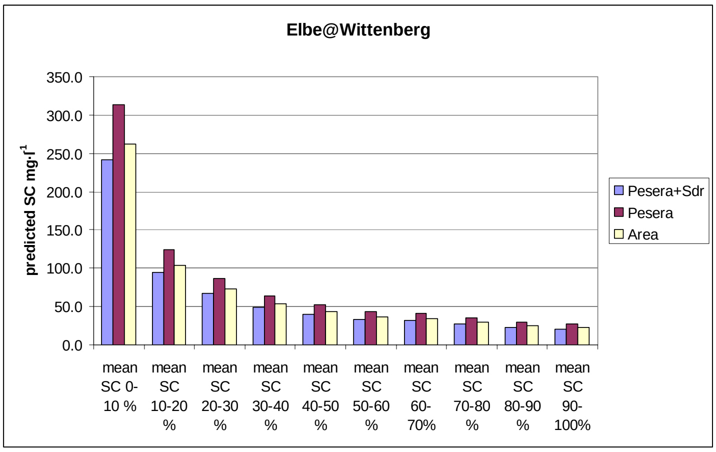
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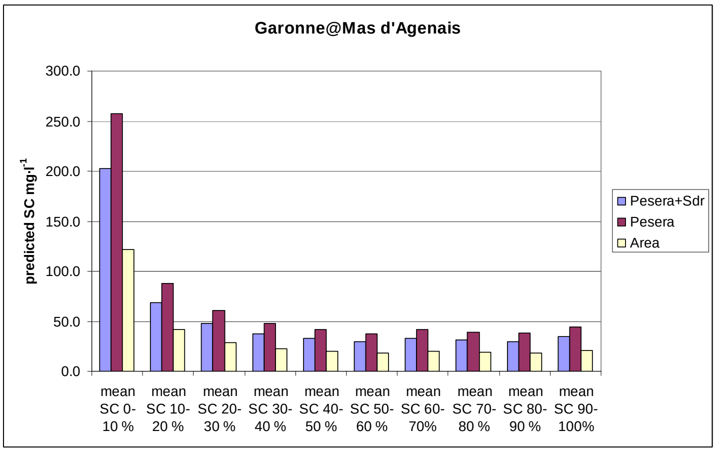
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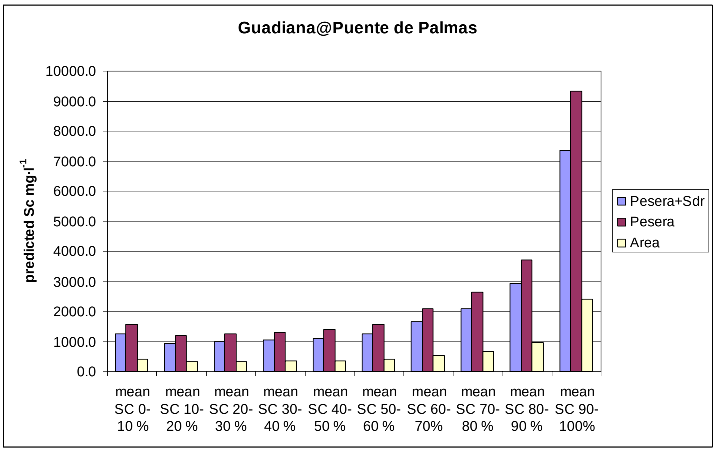
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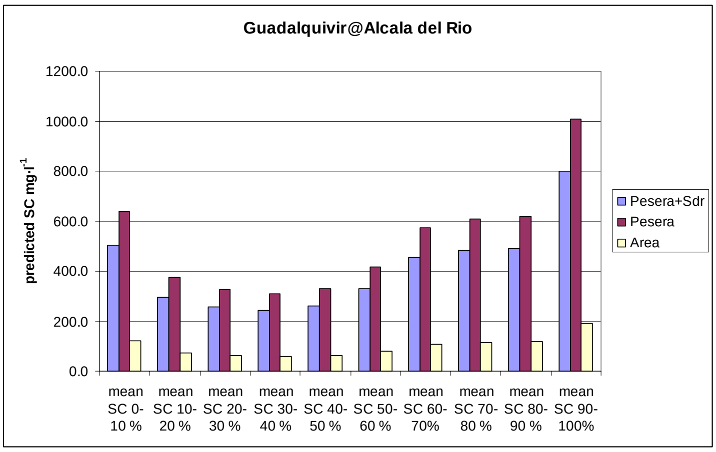
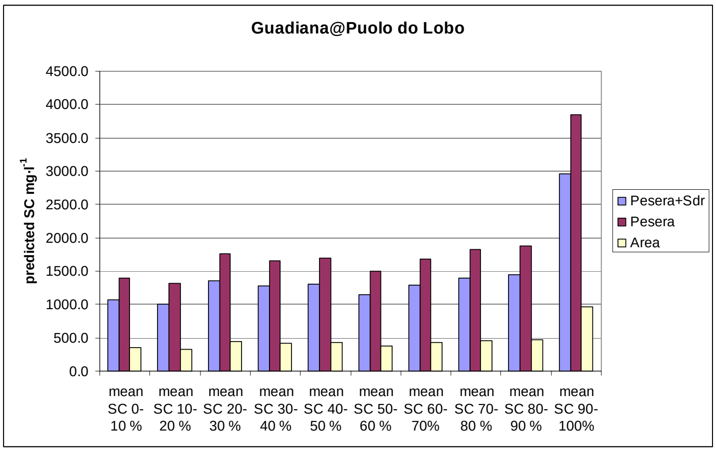
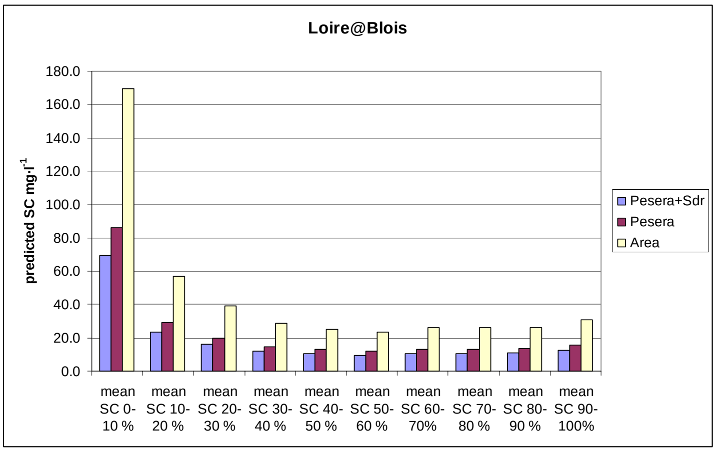
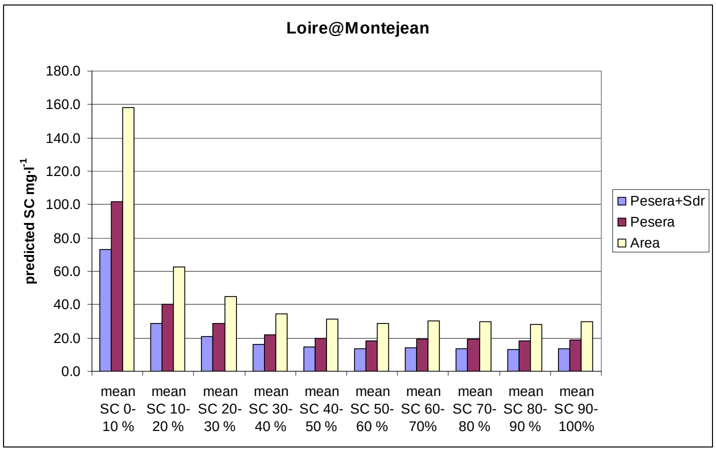
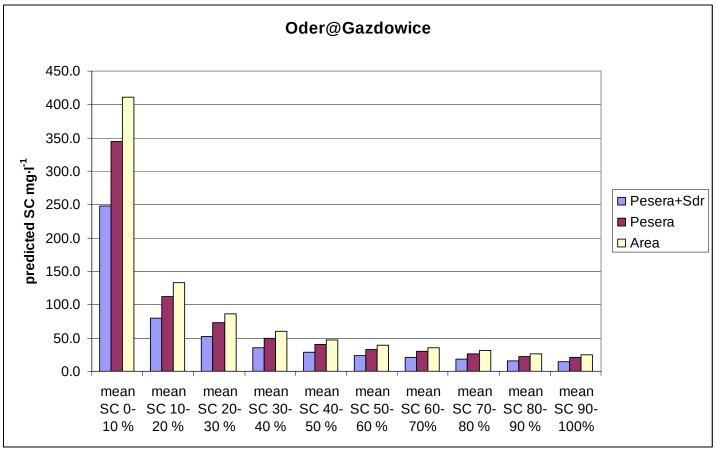
8000.0
7000.0
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

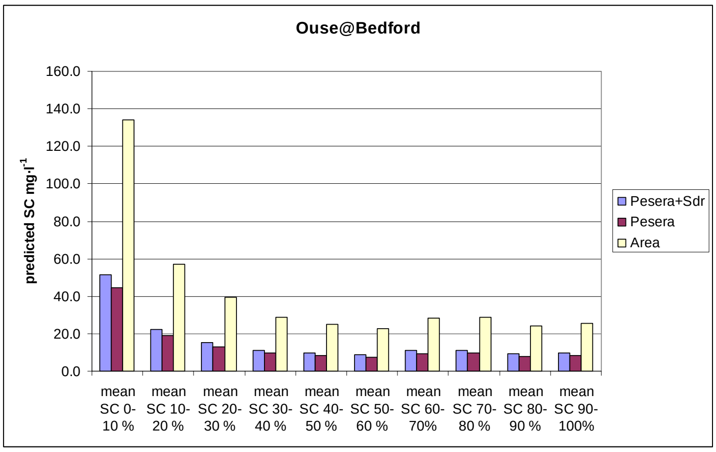

Guadalquivir@Alcala del Rio
predicted SC mg·l^{-1}
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

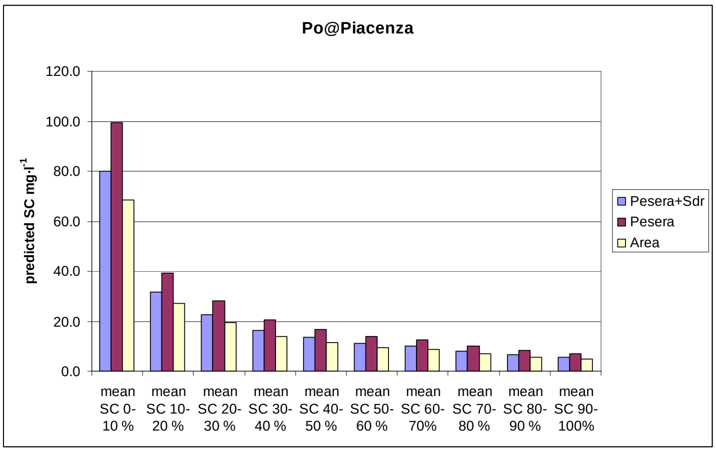

Guadiana@Puolo do Lobo
predicted SC mg·l^{-1}
4500.0
4000.0
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

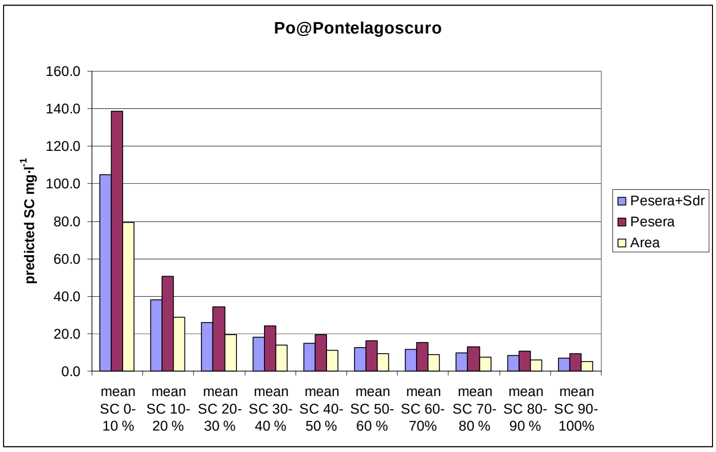

Loire@Blois
predicted SC mg·l^{-1}
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

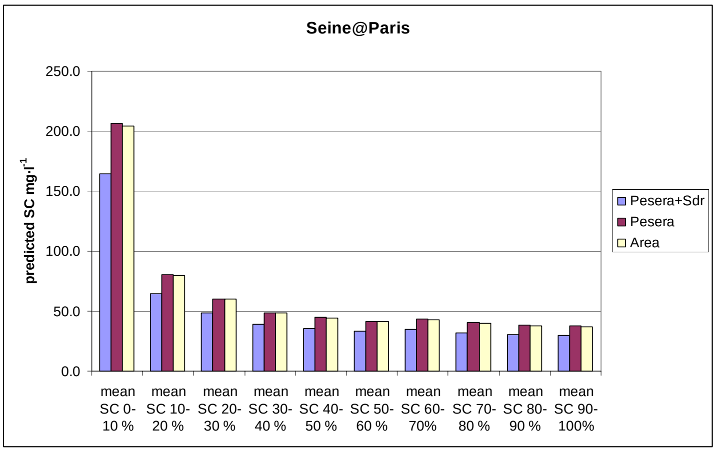

Loire@Montejean
predicted SC mg·l^{-1}
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

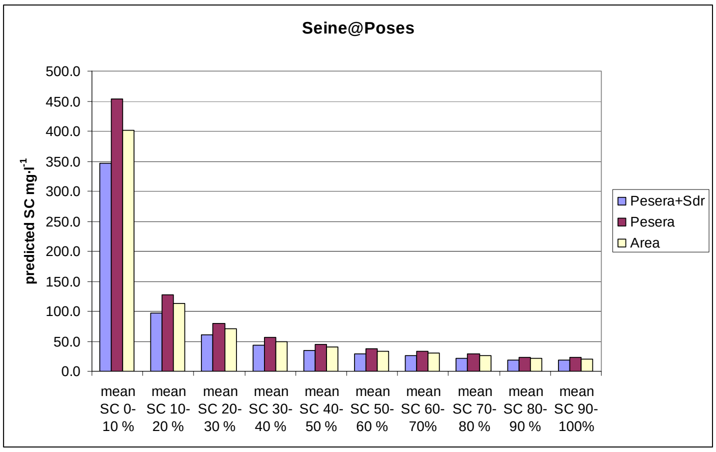

Oder@Gazdowice
predicted SC mg·l^{-1}
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

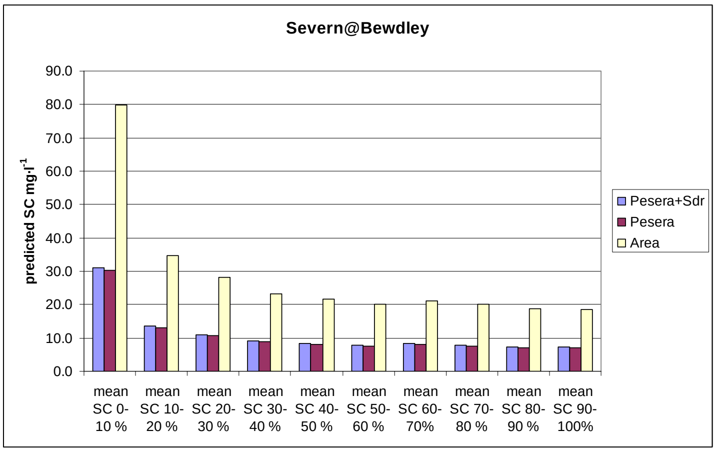

Ouse@Bedford
predicted SC mg·l-1
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

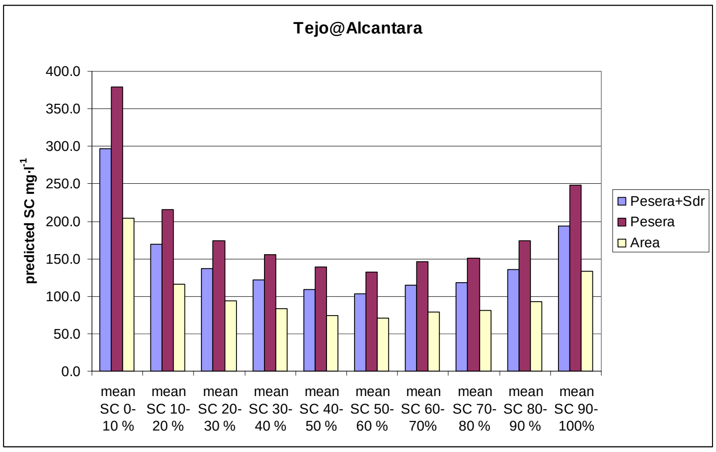

Po@Piacenza
predicted SC mg·l-1
0.0
20.0
40.0
60.0
80.0
100.0
120.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

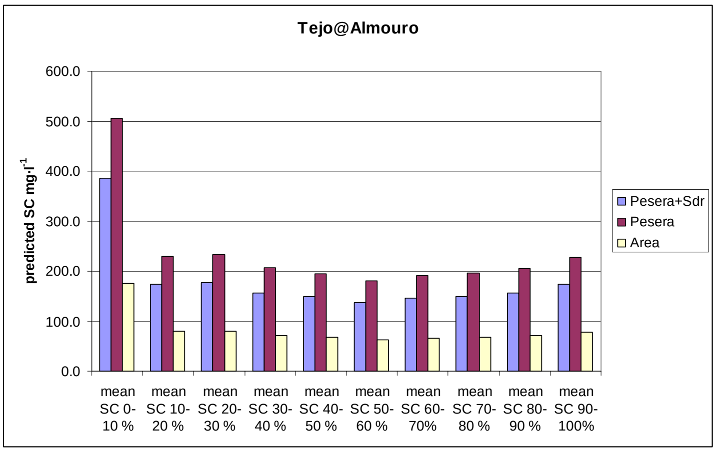

Po@Pontelagoscuro
predicted SC mg·l-1
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

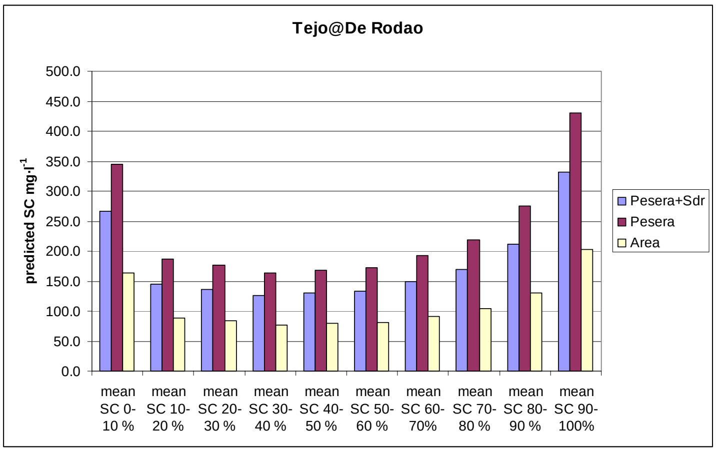

Seine@Paris
predicted SC mg·l-1
0.0
50.0
100.0
150.0
200.0
250.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

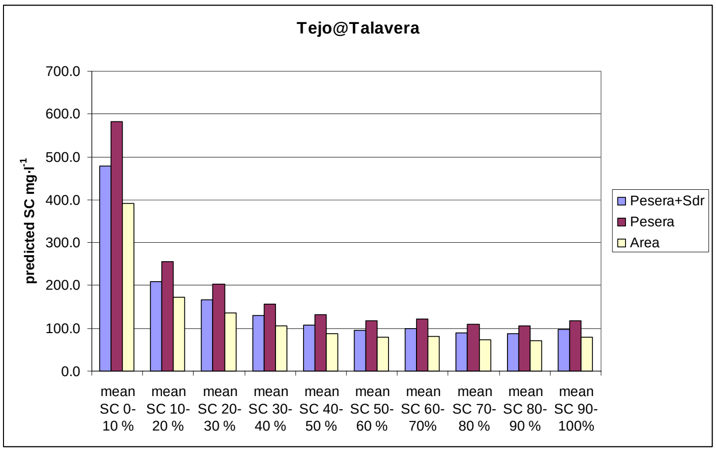

Seine@Poses
predicted SC mg·l-1
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

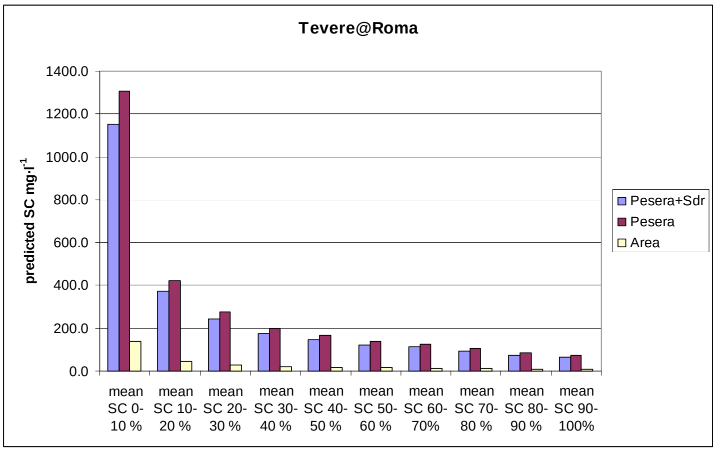

Severn@Bewdley
predicted SC mg·l-1
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

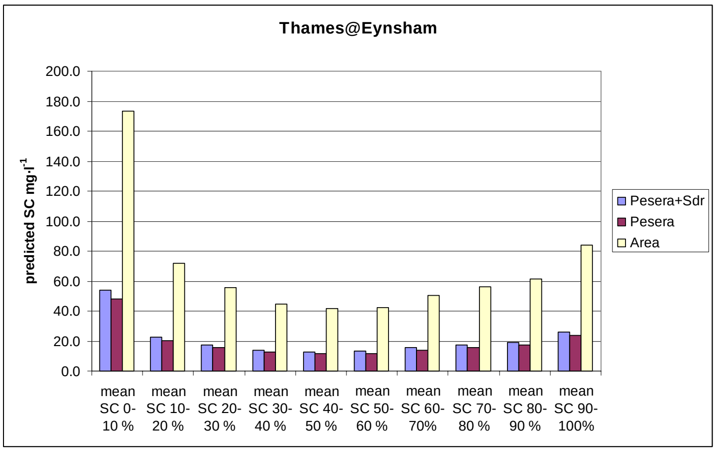

Tejo@Alcantara
predicted SC mg·l-1
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

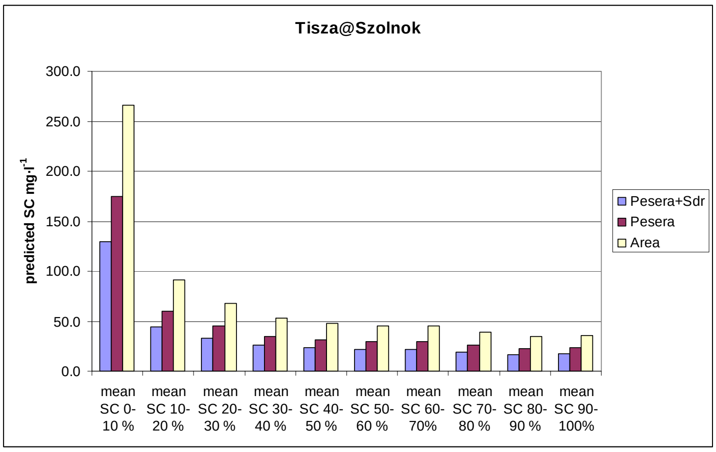

Tejo@Almouro
predicted SC mg·l-1
600.0
500.0
400.0
300.0
200.0
100.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

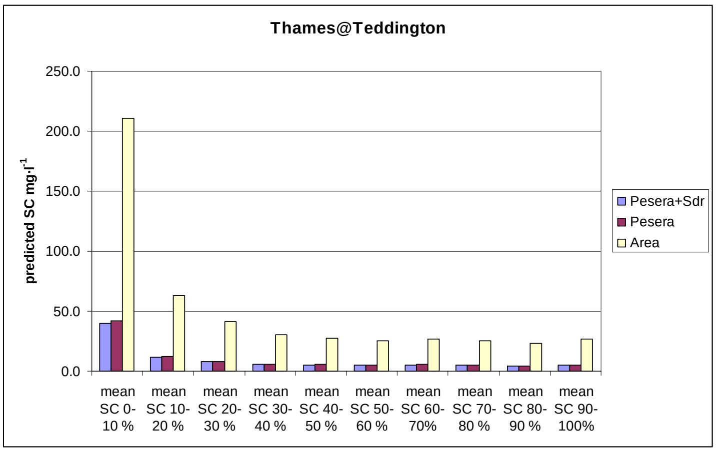

Tejo@De Rodao
predicted SC mg·l-1
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

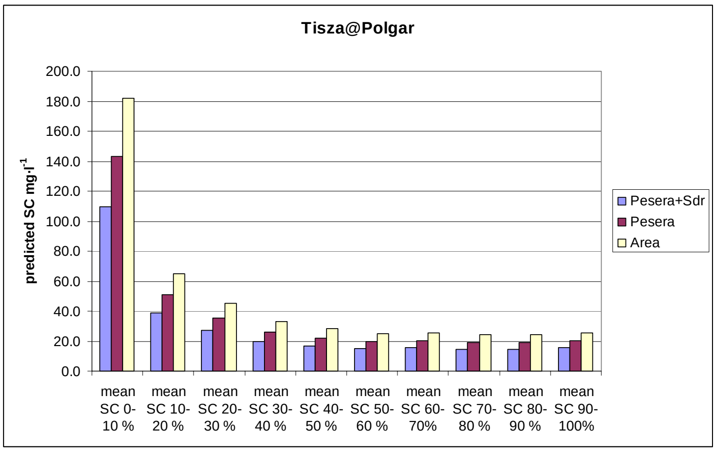

Tejo@Talavera
predicted SC mg·l-1
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

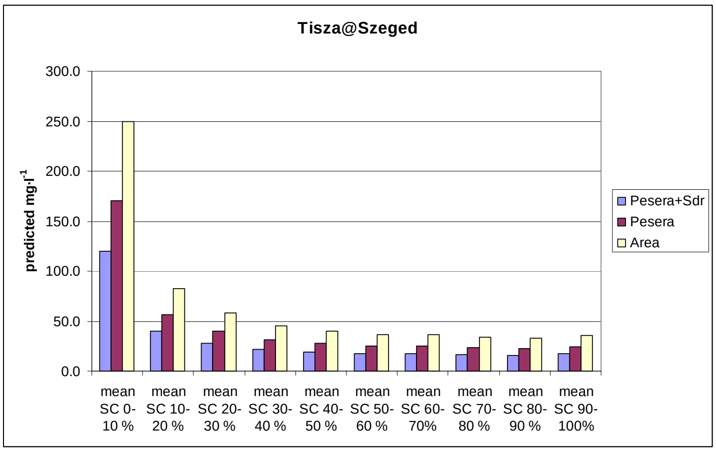

Tevere@Roma
predicted SC mg·l-1
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

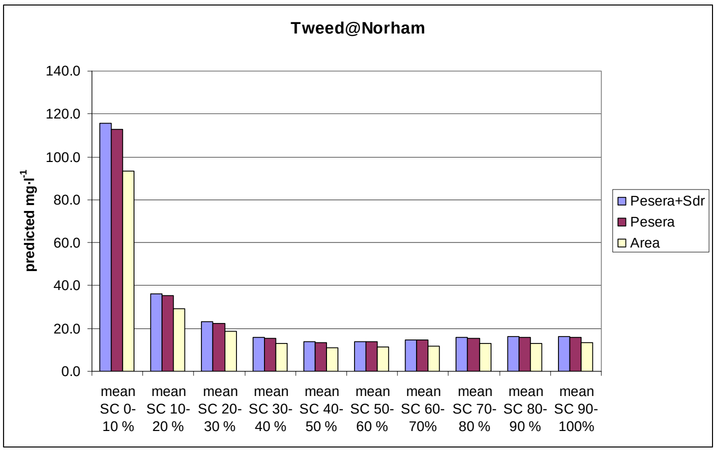

Thames@Eynsham
predicted SC mg·l-1
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

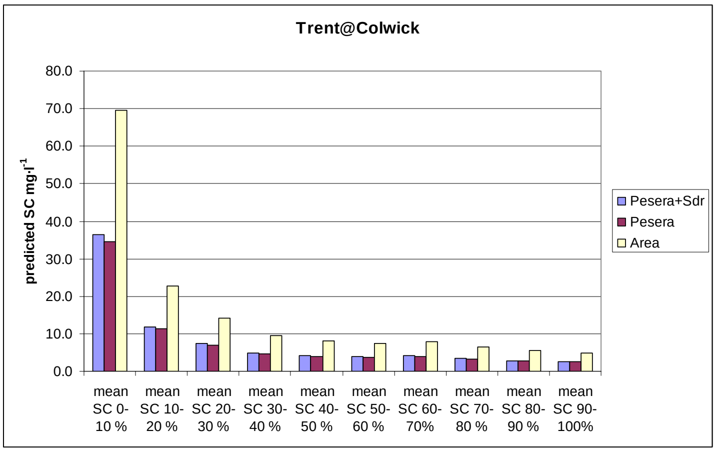

Tisza@Szolnok
predicted SC mg·l^{-1}
300.0
250.0
200.0
150.0
100.0
50.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area


Thames@Teddington
predicted SC mg·l^{-1}
250.0
200.0
150.0
100.0
50.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area


Tisza@Polgar
predicted SC mg·l^{-1}
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area


Tisza@Szeged
predicted mg·l^{-1}
300.0
250.0
200.0
150.0
100.0
50.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area


Tweed@Norham
predicted mg·l^{-1}
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area


Trent@Colwick
predicted SC mg·l^{-1}
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
mean SC 0-10 %
mean SC 10-20 %
mean SC 20-30 %
mean SC 30-40 %
mean SC 40-50 %
mean SC 50-60 %
mean SC 60-70%
mean SC 70-80 %
mean SC 80-90 %
mean SC 90-100%
Pesera+Sdr
Pesera
Area

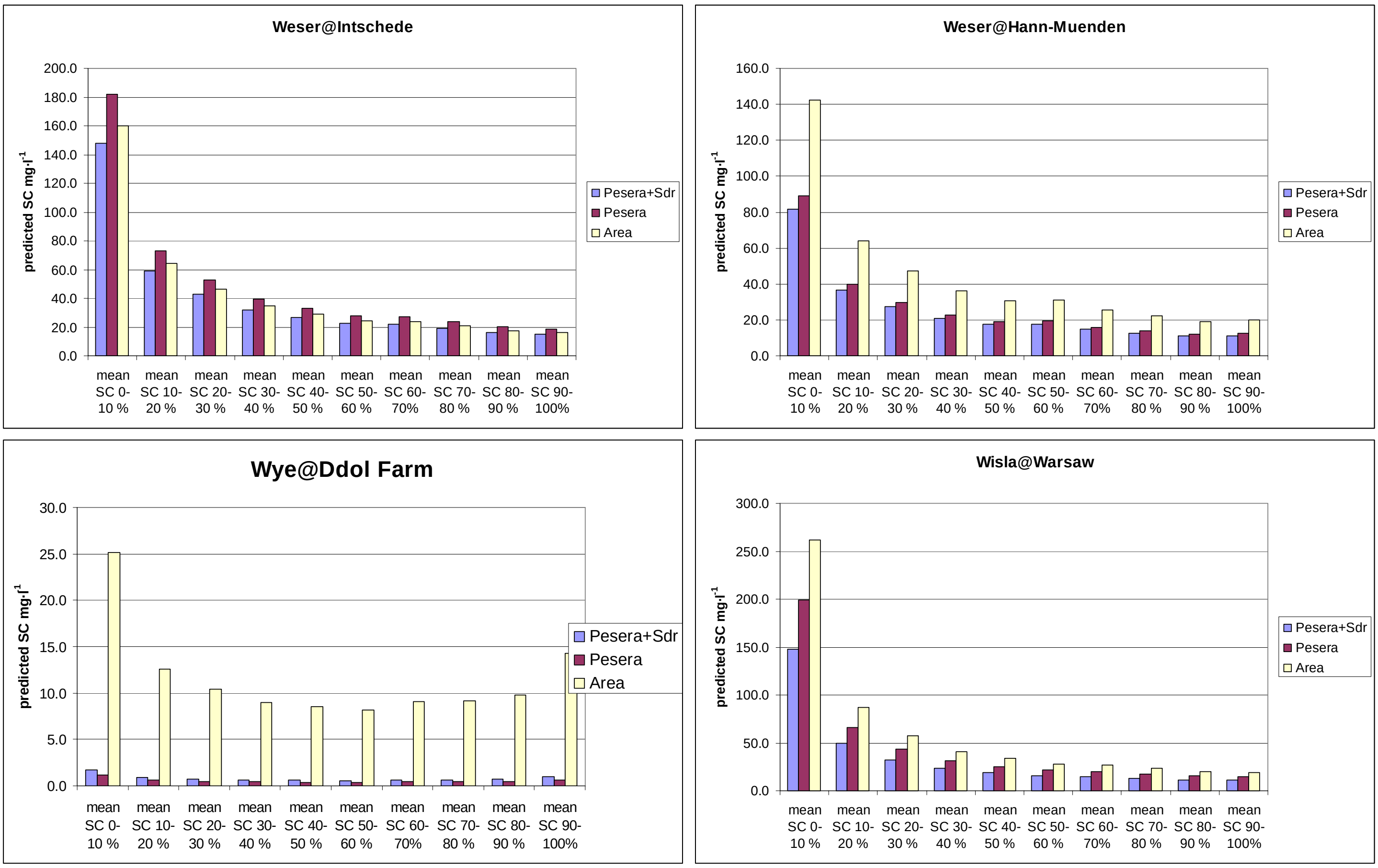
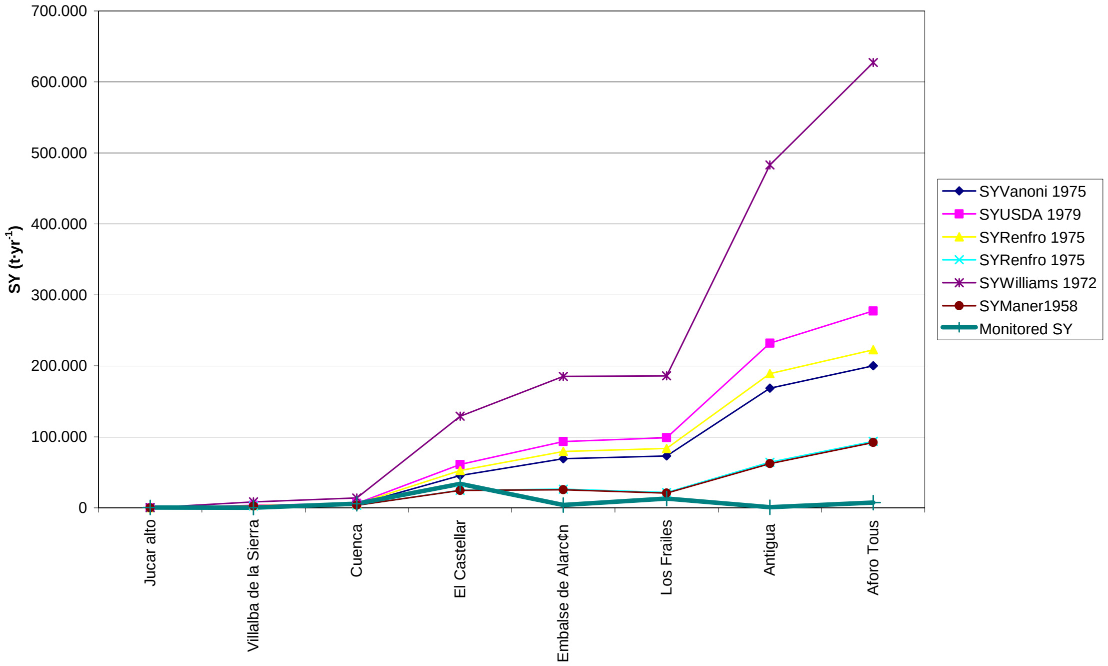


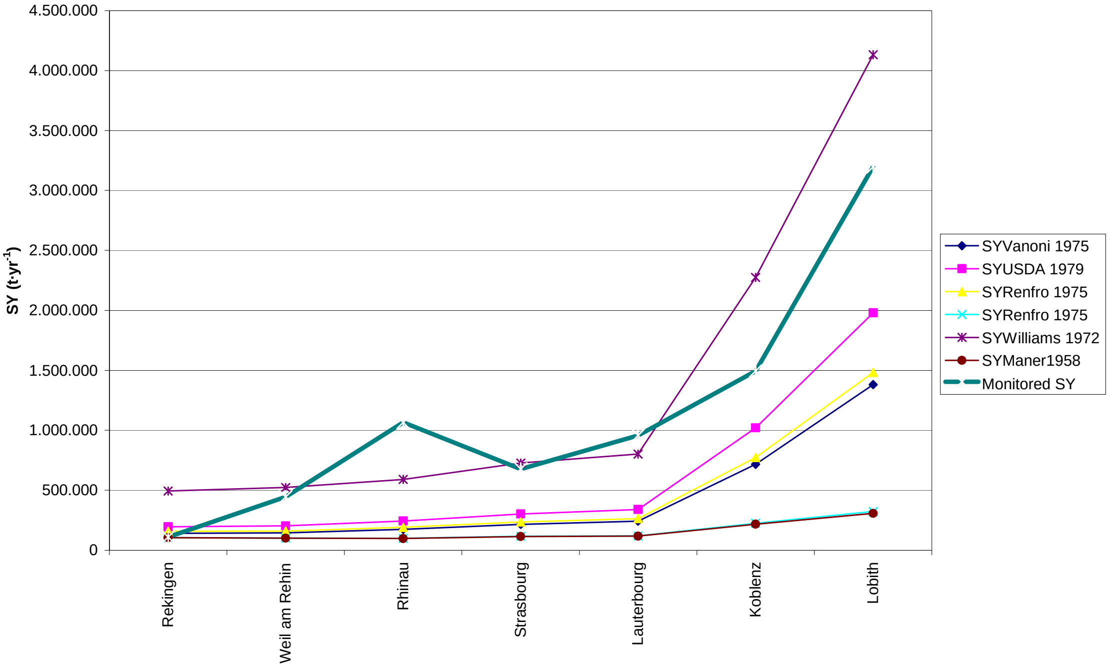
Figure A 2 – Final predicted sediment concentrations

The next section contains the comparisons between calculated sediment yields and monitored sediment yields determined using monitored sediment concentration and flow data.

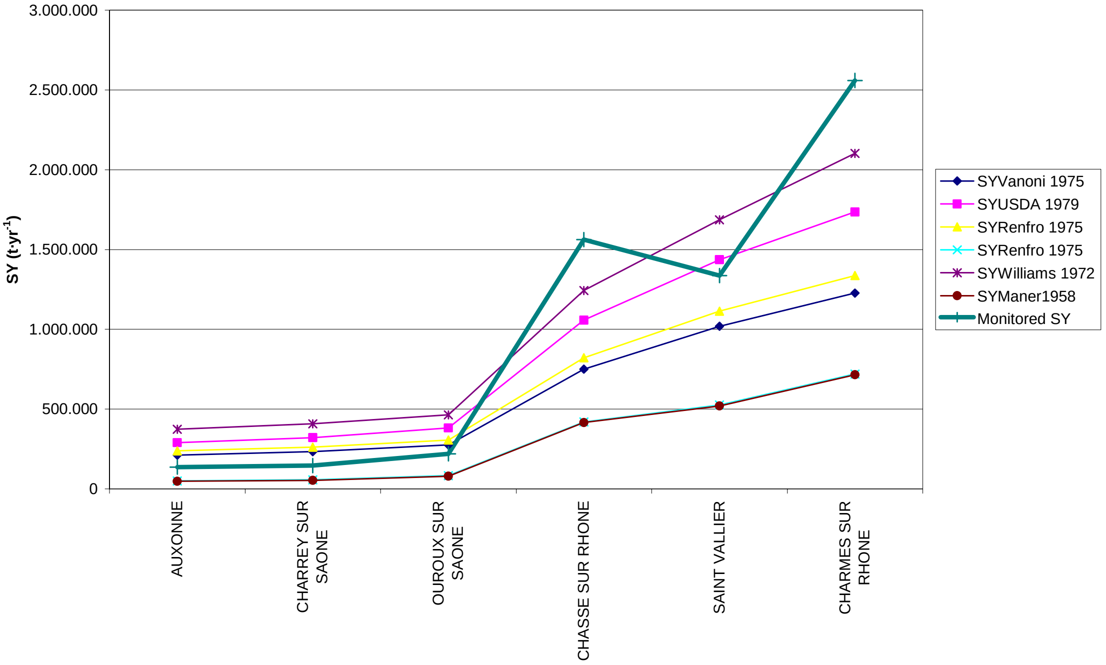
Jucar



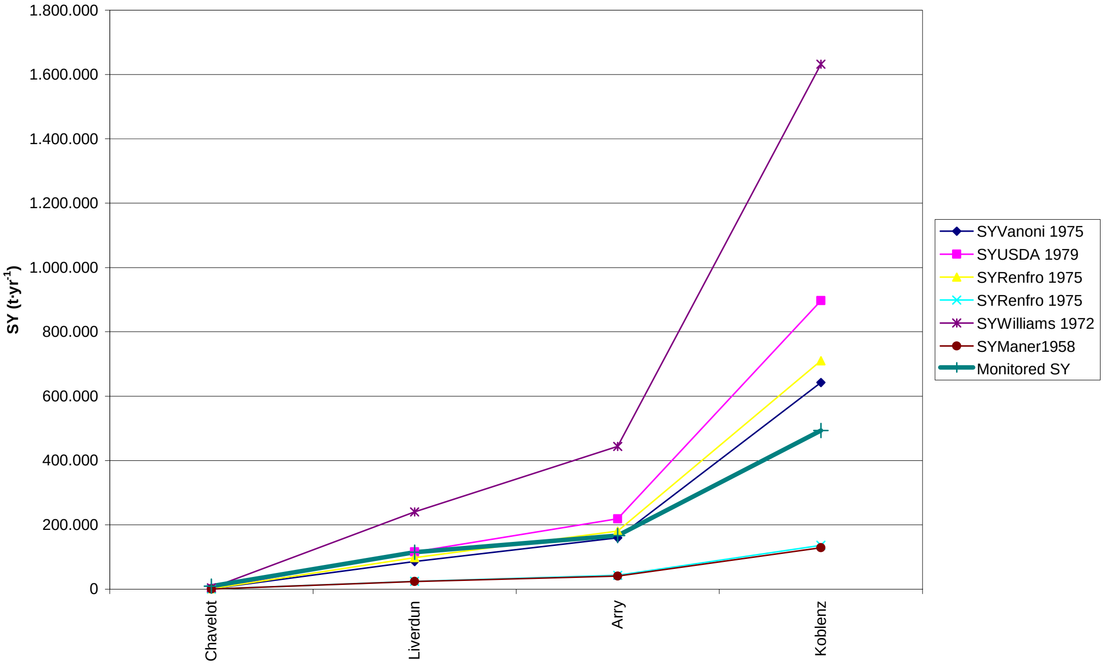
Rhine



Rhone


SY (t·yr⁻¹)
3.000.000
2.500.000
2.000.000
1.500.000
1.000.000
500.000
0
AUXONNE
CHARREY SUR SAONE
OUROUX SUR SAONE
CHASSE SUR RHONE
SAINT VALLIER
CHARMES SUR RHONE
SYVanoni 1975
SYUSDA 1979
SYRenfro 1975
SYRenfro 1975
SYWilliams 1972
SYManer1958
Monitored SY

Mosel


SY (t·yr⁻¹)
1.800.000
1.600.000
1.400.000
1.200.000
1.000.000
800.000
600.000
400.000
200.000
0
Chavelot
Liverdun
Arry
Koblenz
SYVanoni 1975
SYUSDA 1979
SYRenfro 1975
SYRenfro 1975
SYWilliams 1972
SYManer1958
Monitored SY

Oder, Morava, Elbe

(each of the points is in a different catchment, the trend line only helps to identify them)

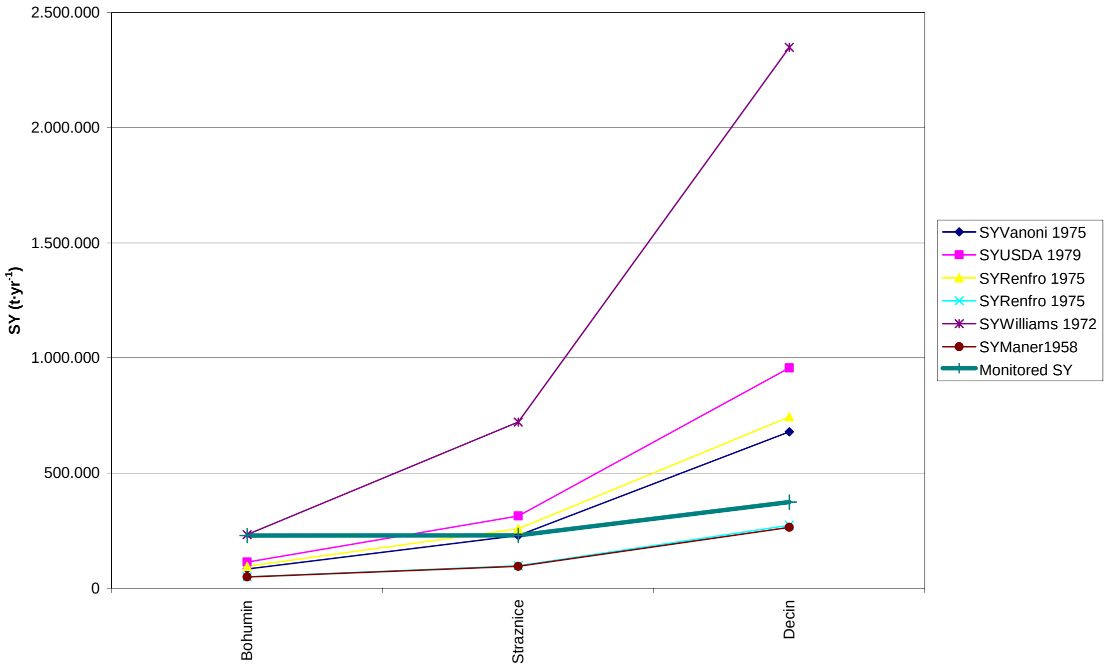


Figure A 3 – Comparisons of sediment yields

The next section contains final predicted sediment concentration values (using the new methods – overall mean values and also mean in relevant parts of the flow). Where marked with a * symbol or in bold italics, values may be slightly affected due to a lack of data.

Table A 1 – Estimated sediment yields for SSC predictions (the three methods used)

Location	River	$SY_{USDA\ 1971}$ ($t \cdot yr^{-1}$)	SY_{PESERA} ($t \cdot yr^{-1}$)	SY_{AREA} ($t \cdot yr^{-1}$)
Achleiten	Danube	***903,882***	***1,204,318***	1,556,844
Dunaalmas	Danube	***1,840,939***	***2,680,297***	3,486,376
Harsova	Danube	***4,334,967***	***7,367,839***	14,235,743
Keinstock	Danube	***919,844***	***1,256,184***	1,948,067
Korneuburg	Danube	***931,854***	***1,280,664***	2,063,432
Linz	Danube	***907,583***	***1,214,099***	1,614,532
Lom	Danube	***3,737,388***	***6,231,492***	11,957,723
Mohacs	Danube	***2,116,822***	***3,152,155***	4,278,384
Orsova	Danube	***3,671,816***	***6,105,370***	11,662,853
Regensburg	Danube	***540,043***	***660,771***	717,497
Silistra	Danube	***4,287,327***	***7,273,691***	14,003,404
Regua	Douro	3,860,906	5,242,050	1,847,699
Vau Deje	Drin	0	0	258,606
Villachica	Duero	1,106,439	1,380,212	855,355
Barby	Elbe	1,489,538	2,031,604	1,925,707
Neu-Darchau	Elbe	1,691,761	2,380,245	2,554,317
Wittenberg	Elbe	1,157,221	1,506,124	1,257,929
Mas d'Agenais	Garonne	1,697,788	2,160,036	1,023,186
Alcala del Rio	Guadalquivir	4,006,224	5,064,025	964,599
Puente de Palmas	Guadiana	3,045,520	3,862,087	993,285
Pulo do Lobo	Guadiana	3,834,019	4,989,149	1,256,021
Blois	Loire	338,607	420,861	827,594
Montejean	Loire	1,037,932	1,439,557	2,242,347
Gazdowice	Odra	1,422,423	1,984,650	2,367,539
Bedford	Ouse	11,329	9,754	29,376
Piacenza	Po	994,637	1,240,385	853,093
Pontelagoscuro	Po	1,969,527	2,612,670	1,495,925
Paris	Seine	720,552	903,261	894,340
Poses	Seine	1,142,764	1,495,295	1,320,681
Bewdley	Severn	34,683	33,737	89,135
Alcantara	Tejo	1,544,674	1,972,645	1,058,800
Almouro	Tejo	3,016,034	3,962,761	1,371,147
de Rodao	Tejo	1,966,830	2,547,474	1,203,787
Talavera	Tejo	843,317	1,027,498	690,490
Roma	Tevere	2,945,415	3,336,794	356,305
Eynsham	Thames	13,047	11,675	41,757
Sutton Courtney	Thames	6,811	5,641	20,630
Teddington	Thames	38,289	40,787	203,589
Polgar	Tisza	776,561	1,013,444	1,289,384
Szeged	Tisza	1,349,847	1,918,828	2,804,791
Szolnok	Tisza	835,859	1,125,515	1,713,816
Colwick	Trent	36,961	35,042	70,602
Norham	Tweed	113,908	111,180	91,950
Hann-Muenden	Weser	144,811	157,948	252,412

Location	**River**	**$SY_{USDA\ 1971}$ ($t \cdot yr^{-1}$)**	**SY_{PESERA} ($t \cdot yr^{-1}$)**	**SY_{AREA} ($t \cdot yr^{-1}$)**
Intschede	Weser	690,805	849,083	747,734
Warsaw	Wisla	968,719	1,304,625	1,716,297
Ddol Farm	Wye	241	164	3,483

Table A 2 – Mean annual predicted sediment concentrations

Location	**River**	**SSC$_{USDA\ 1971}$ (mg.l^{-1})**	**SSC$_{PESERA}$ (mg.l^{-1})**	**SY$_{AREA}$ (mg.l^{-1})**
Achleiten	Danube	***10***	***13***	17
Dunaalmas	Danube	***13***	***18***	24
Harsova	Danube	***11***	***19***	36
Keinstock	Danube	***7***	***10***	16
Korneuburg	Danube	***7***	***10***	16
Linz	Danube	***9***	***13***	17
Lom	Danube	***11***	***18***	34
Mohacs	Danube	***14***	***21***	28
Orsova	Danube	***10***	***17***	32
Regensburg	Danube	***18***	***22***	24
Silistra	Danube	***11***	***19***	37
Regua	Douro	***86***	***116***	41
Vau Deje	Drin	-	-	12
Villachica	Duero	96	120	75
Barby	Elbe	50	69	65
Neu-Darchau	Elbe	34	48	51
Wittenberg	Elbe	46	60	50
Mas d'Agenais	Garonne	37	47	22
Alcala del Rio	Guadalquivir	140	177	34
Puente de Palmas	Guadiana	392	497	128
Pulo do Lobo	Guadiana	364	473	119
Blois	Loire	13	16	31
Montejean	Loire	15	20	32
Gazdowice	Odra	40	55	66
Bedford	Ouse	11	9	27
Piacenza	Po	15	19	13
Pontelagoscuro	Po	18	24	14
Paris	Seine	34	43	43
Poses	Seine	51	67	59
Bewdley	Severn	7	6	17
Alcantara	Tejo	78	99	53
Almouro	Tejo	95	124	43
De Rodao	Tejo	72	93	44
Talavera	Tejo	105	128	86
Roma	Tevere	188	213	23
Eynsham	Thames	12	11	38
Sutton Courtney	Thames	3	3	10
Teddington	Thames	6	7	34
Polgar	Tisza	27	36	45
Szeged	Tisza	21	31	45
Szolnok	Tisza	24	33	50
Colwick	Trent	6	6	11
Norham	Tweed	19	18	15
Hann-Muenden	Weser	17	19	30
Intschede	Weser	29	36	31

Location	**River**	**$SSC_{USDA\ 1971}$ (mg.l^{-1})**	**SSC_{PESERA} (mg.l^{-1})**	**SY_{AREA} (mg.l^{-1})**
Warsaw	Wisla	25	33	44
Ddol Farm	Wye	0	0	6

Table A 3 – Mean predicted sediment concentrations estimated using SY_{USDA}

mean SSC_{USDA} ($mg.l^{-1}$)											
Location	**River**	**0-10**	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**70-80**	**80-90**	**90-100**
Achleiten	Danube	***64.0***	***19.9***	***12.6***	***8.6***	***6.7***	***5.4***	***5.1***	***4.3***	***3.6***	***3.2***
Dunaalmas	Danube	***84.2***	***26.3***	***16.4***	***11.1***	***8.6***	***7.0***	***6.6***	***5.6***	***4.7***	***4.2***
Harsova	Danube	***78.3***	***22.2***	***13.5***	***9.2***	***7.2***	***5.9***	***5.6***	***4.9***	***4.2***	***4.4***
Keinstock	Danube	***50.7***	***15.6***	***9.7***	***6.5***	***5.1***	***4.1***	***3.8***	***3.2***	***2.6***	***2.2***
Korneuburg	Danube	***48.9***	***15.4***	***9.6***	***6.4***	***5.0***	***4.0***	***3.7***	***3.0***	***2.5***	***2.1***
Linz	Danube	***63.4***	***19.4***	***12.2***	***8.3***	***6.5***	***5.3***	***4.9***	***4.1***	***3.5***	***3.1***
Lom	Danube	***80.9***	***21.7***	***13.1***	***8.7***	***6.8***	***5.4***	***5.1***	***4.3***	***3.6***	***3.3***
Mohacs	Danube	***94.5***	***28.3***	***17.8***	***12.0***	***9.4***	***7.5***	***7.0***	***5.9***	***4.8***	***4.4***
Orsova	Danube	***71.6***	***20.5***	***12.6***	***8.5***	***6.6***	***5.4***	***5.1***	***4.3***	***3.7***	***3.4***
Regensburg	Danube	***111.7***	***38.2***	***24.7***	***17.0***	***13.4***	***10.9***	***10.1***	***8.5***	***7.1***	***6.4***
Silistra	Danube	***85.8***	***23.5***	***14.0***	***9.3***	***7.1***	***5.7***	***5.3***	***4.5***	***3.7***	***3.3***
Regua	Douro	360.2	168.6	140.1	115.0	116.3	113.4	123.9	118.4	102.8	107.6
Vau deje	Drin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Villachica	Duero	437.9	182.8	144.8	119.9	108.3	104.6	117.0	107.3	106.4	143.0
Barby	Elbe	194.8	77.1	54.1	39.3	32.4	27.4	26.5	22.9	19.5	18.4
Neu-Darchau	Elbe	197.5	68.2	45.9	33.1	27.1	22.8	21.9	19.1	16.3	15.5
Wittenberg	Elbe	241.3	95.0	66.9	48.9	39.9	33.3	31.8	27.3	23.1	21.0
Mas d'Agenais	Garonne	202.5	68.7	47.9	37.4	32.6	29.6	32.7	31.1	29.8	34.7
Alcala del Rio	Guadalquivir	505.7	297.2	257.8	243.7	260.4	330.2	454.6	482.4	490.1	799.1
Puente de Palmas	Guadiana	1232.9	934.0	991.0	1032.2	1108.2	1245.4	1641.6	2085.3	2926.6	7364.6
Pulo do Lobo	Guadiana	1068.3	1010.1	1354.4	1273.8	1305.7	1148.2	1297.8	1402.0	1445.8	2956.4
Blois	Loire	69.4	23.4	16.0	11.8	10.4	9.6	10.7	10.6	10.7	12.5
Montejean	Loire	73.2	28.9	20.8	16.0	14.4	13.3	14.1	13.7	13.0	13.7
Gazdowice	Odra	247.2	80.0	52.0	35.8	28.5	23.4	21.4	18.4	15.9	14.6
Bedford	Ouse	51.6	22.0	15.3	11.0	9.7	8.7	11.0	11.1	9.3	9.8
Piacenza	Po	79.8	31.6	22.6	16.4	13.4	11.1	10.1	8.1	6.7	5.5
Pontelagoscuro	Po	104.7	38.0	25.8	18.2	14.7	12.3	11.6	9.8	8.2	7.0
Paris	Seine	164.8	64.3	48.2	39.0	35.7	33.2	34.6	32.2	30.4	29.9
Poses	Seine	346.8	97.5	61.2	43.2	34.7	28.4	26.0	22.0	18.2	18.1
Bewdley	Severn	31.1	13.5	10.9	9.0	8.4	7.8	8.2	7.8	7.3	7.2
Alcantara	Tejo	297.0	169.2	136.4	121.4	108.8	103.4	114.8	118.3	135.9	194.1
Almouro	Tejo	385.2	174.7	177.3	157.3	148.8	137.9	145.6	149.1	156.1	174.0
De Rodao	Tejo	266.7	144.6	137.0	126.1	130.0	132.9	148.6	169.4	212.3	332.5
Talavera	Tejo	478.5	209.8	166.0	129.0	107.4	95.9	99.9	89.9	87.0	96.8
Roma	Tevere	1152.1	372.0	245.2	174.8	147.4	120.7	112.1	93.2	74.3	62.9
Eynsham	Thames	54.1	22.5	17.3	14.0	13.0	13.3	15.8	17.5	19.3	26.3
Sutton Courtney	Thames	14.5	6.3	5.0	4.2	4.1	4.2	5.0	5.4	5.8	7.2
Teddington	Thames	39.7	11.9	7.7	5.7	5.2	4.7	5.1	4.7	4.4	5.0
Polgar	Tisza	109.8	39.0	27.1	19.8	17.1	15.1	15.5	14.7	14.7	15.4
Szeged	Tisza	120.0	39.8	28.2	21.9	19.4	17.4	17.7	16.3	15.8	17.2
Szolnok	Tisza	129.8	44.7	33.3	25.9	23.2	22.0	22.0	19.1	16.9	17.3

mean SSC$_{USDA}$ (mg.l^{-1})

Location	River	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
Colwick	Trent	36.4	11.9	7.4	5.0	4.2	3.9	4.1	3.4	2.9	2.6
Norham	Tweed	115.7	36.1	23.0	15.9	13.6	13.9	14.8	15.9	16.2	16.4
Hann-Muenden	Weser	81.6	36.6	27.2	20.7	17.5	17.7	14.7	12.7	11.0	11.3
Intschede	Weser	148.0	59.4	43.0	31.9	26.7	22.7	22.2	19.3	16.3	15.0
Warsaw	Wisla	147.8	49.3	32.5	23.2	18.9	15.8	15.2	13.2	11.4	11.0
Ddol Farm	Wye	1.7	0.9	0.7	0.6	0.6	0.6	0.6	0.6	0.7	1.0

Table A 4 – Mean predicted sediment concentrations estimated using SY_{PESERA}

		mean SSC_{PESERA} ($mg.l^{-1}$)									
Location	**River**	**0-10**	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**70-80**	**80-90**	**90-100**
Achleiten	Danube	***85.3***	***26.5***	***16.7***	***11.4***	***9.0***	***7.2***	***6.7***	***5.7***	***4.7***	***4.2***
Dunaalmas	Danube	***122.6***	***38.3***	***23.9***	***16.1***	***12.6***	***10.2***	***9.6***	***8.1***	***6.8***	***6.1***
Harsova	Danube	***133.1***	***37.7***	***23.0***	***15.6***	***12.3***	***10.1***	***9.6***	***8.3***	***7.2***	***7.5***
Keinstock	Danube	***69.2***	***21.3***	***13.2***	***8.9***	***6.9***	***5.6***	***5.2***	***4.3***	***3.6***	***3.1***
Korneuburg	Danube	***67.2***	***21.1***	***13.2***	***8.8***	***6.9***	***5.6***	***5.0***	***4.2***	***3.4***	***2.9***
Linz	Danube	***84.8***	***25.9***	***16.3***	***11.1***	***8.7***	***7.0***	***6.5***	***5.5***	***4.6***	***4.1***
Lom	Danube	***134.9***	***36.3***	***21.9***	***14.6***	***11.3***	***9.1***	***8.6***	***7.2***	***6.0***	***5.4***
Mohacs	Danube	***140.7***	***42.1***	***26.5***	***17.9***	***14.0***	***11.2***	***10.4***	***8.7***	***7.2***	***6.5***
Orsova	Danube	***119.0***	***34.1***	***20.9***	***14.1***	***11.0***	***8.9***	***8.4***	***7.2***	***6.2***	***5.7***
Regensburg	Danube	***136.6***	***46.8***	***30.2***	***20.8***	***16.5***	***13.3***	***12.4***	***10.4***	***8.7***	***7.9***
Silistra	Danube	***145.6***	***39.9***	***23.8***	***15.8***	***12.1***	***9.7***	***9.0***	***7.6***	***6.3***	***5.6***
Regua	Douro	489.1	228.9	190.2	156.1	157.9	154.0	168.2	160.8	139.5	146.1
Vau Deje	Drin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Villachica	Duero	546.3	228.0	180.7	149.6	135.1	130.5	146.0	133.8	132.7	178.3
Barby	Elbe	265.7	105.2	73.8	53.6	44.3	37.3	36.1	31.2	26.5	25.1
Neu-Darchau	Elbe	277.9	95.9	64.6	46.5	38.2	32.1	30.8	26.8	23.0	21.8
Wittenberg	Elbe	314.1	123.7	87.1	63.6	51.9	43.4	41.4	35.6	30.0	27.3
Mas d'Agenais	Garonne	257.6	87.4	61.0	47.5	41.5	37.6	41.6	39.5	37.9	44.1
Alcala del Rio	Guadalquivir	639.2	375.7	325.8	308.1	329.2	417.4	574.6	609.8	619.4	1010.1
Puente de Palmas	Guadiana	1563.5	1184.4	1256.7	1309.0	1405.3	1579.3	2081.7	2644.4	3711.2	9339.2
Pulo do Lobo	Guadiana	1390.2	1314.4	1762.5	1657.5	1699.1	1494.2	1688.8	1824.4	1881.4	3847.2
Blois	Loire	86.2	29.0	19.8	14.7	12.9	11.9	13.3	13.2	13.3	15.6
Montejean	Loire	101.6	40.1	28.8	22.1	20.0	18.5	19.5	19.1	18.1	19.0
Gazdowice	Odra	345.0	111.6	72.6	50.0	39.8	32.6	29.9	25.7	22.2	20.4
Bedford	Ouse	44.4	19.0	13.1	9.5	8.3	7.5	9.5	9.6	8.0	8.4
Piacenza	Po	99.6	39.4	28.2	20.4	16.7	13.8	12.7	10.1	8.3	6.9
Pontelagoscuro	Po	138.9	50.5	34.2	24.1	19.4	16.3	15.4	12.9	10.9	9.3
Paris	Seine	206.5	80.6	60.5	48.8	44.8	41.6	43.4	40.4	38.2	37.5
Poses	Seine	453.8	127.6	80.0	56.5	45.4	37.2	34.0	28.8	23.8	23.7
Bewdley	Severn	30.2	13.1	10.6	8.8	8.2	7.6	8.0	7.6	7.1	7.0
Alcantara	Tejo	379.3	216.1	174.2	155.1	138.9	132.0	146.6	151.0	173.5	247.8
Almouro	Tejo	506.1	229.5	232.9	206.7	195.5	181.2	191.3	195.8	205.1	228.6
De Rodao	Tejo	345.5	187.3	177.4	163.3	168.4	172.2	192.5	219.4	274.9	430.6
Talavera	Tejo	583.0	255.6	202.2	157.2	130.9	116.9	121.7	109.6	105.9	118.0
Roma	Tevere	1305.2	421.5	277.8	198.1	166.9	136.8	126.9	105.6	84.1	71.3
Eynsham	Thames	48.4	20.1	15.5	12.5	11.6	11.9	14.2	15.7	17.2	23.5
Sutton Courtney	Thames	12.0	5.2	4.1	3.4	3.4	3.4	4.1	4.4	4.8	5.9
Teddington	Thames	42.3	12.6	8.2	6.1	5.5	5.0	5.4	5.0	4.6	5.4
Polgar	Tisza	143.3	50.9	35.4	25.8	22.3	19.7	20.2	19.2	19.2	20.1
Szeged	Tisza	170.7	56.6	40.1	31.2	27.6	24.8	25.1	23.2	22.4	24.5
Szolnok	Tisza	174.8	60.2	44.8	34.8	31.2	29.7	29.7	25.8	22.7	23.3
Colwick	Trent	34.5	11.3	7.0	4.7	4.0	3.7	3.9	3.2	2.7	2.4
Norham	Tweed	112.9	35.3	22.4	15.5	13.3	13.6	14.4	15.5	15.8	16.0

mean SSC$_{PESERA}$ (mg.l^{-1})											
Location	**River**	**0-10**	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**70-80**	**80-90**	**90-100**
Hann-Muenden	Weser	89.0	40.0	29.7	22.6	19.1	19.3	16.0	13.8	12.0	12.3
Intschede	Weser	181.9	73.0	52.9	39.2	32.8	27.9	27.3	23.7	20.0	18.4
Warsaw	Wisla	199.0	66.3	43.8	31.3	25.5	21.3	20.4	17.8	15.4	14.8
Ddol Farm	Wye	1.2	0.6	0.5	0.4	0.4	0.4	0.4	0.4	0.5	0.7

Table A 5 – Mean predicted sediment concentrations estimated using SY_{AREA}

mean SSC_{AREA} ($mg.l^{-1}$)											
Location	**River**	**0-10**	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**70-80**	**80-90**	**90-100**
Achleiten	Danube	***110.3***	***34.3***	***21.6***	***14.8***	***11.6***	***9.3***	***8.7***	***7.4***	***6.1***	***5.5***
Dunaalmas	Danube	***159.5***	***49.9***	***31.0***	***21.0***	***16.4***	***13.3***	***12.5***	***10.6***	***8.9***	***7.9***
Harsova	Danube	***257.2***	***72.8***	***44.5***	***30.2***	***23.8***	***19.5***	***18.5***	***16.0***	***14.0***	***14.5***
Keinstock	Danube	***107.3***	***33.0***	***20.5***	***13.8***	***10.7***	***8.6***	***8.0***	***6.7***	***5.5***	***4.7***
Korneuburg	Danube	***108.4***	***34.0***	***21.3***	***14.2***	***11.1***	***9.0***	***8.1***	***6.7***	***5.4***	***4.6***
Linz	Danube	***112.7***	***34.5***	***21.7***	***14.7***	***11.6***	***9.3***	***8.7***	***7.3***	***6.2***	***5.5***
Lom	Danube	***258.8***	***69.6***	***42.0***	***28.0***	***21.7***	***17.4***	***16.4***	***13.8***	***11.6***	***10.4***
Mohacs	Danube	***190.9***	***57.2***	***35.9***	***24.3***	***19.0***	***15.3***	***14.1***	***11.8***	***9.7***	***8.8***
Orsova	Danube	***227.3***	***65.1***	***40.0***	***26.9***	***21.1***	***17.1***	***16.1***	***13.8***	***11.8***	***10.9***
Regensburg	Danube	***148.3***	***50.8***	***32.8***	***22.6***	***17.9***	***14.5***	***13.5***	***11.3***	***9.4***	***8.6***
Silistra	Danube	***280.4***	***76.9***	***45.8***	***30.4***	***23.3***	***18.7***	***17.4***	***14.7***	***12.1***	***10.7***
Regua	Douro	172.4	80.7	67.0	55.0	55.7	54.3	59.3	56.7	49.2	51.5
Vau Deje	Drin	77.9	20.1	12.9	9.0	8.3	6.7	6.8	7.7	8.0	8.3
Villachica	Duero	338.6	141.3	112.0	92.7	83.7	80.8	90.5	82.9	82.3	110.5
Barby	Elbe	251.9	99.7	70.0	50.8	41.9	35.4	34.2	29.6	25.2	23.8
Neu-Darchau	Elbe	298.2	102.9	69.4	49.9	41.0	34.4	33.1	28.8	24.6	23.4
Wittenberg	Elbe	262.3	103.3	72.7	53.1	43.4	36.2	34.6	29.7	25.1	22.8
Mas d'Agenais	Garonne	122.0	41.4	28.9	22.5	19.7	17.8	19.7	18.7	18.0	20.9
Alcala del Rio	Guadalquivir	121.8	71.6	62.1	58.7	62.7	79.5	109.4	116.2	118.0	192.4
Puente de Palmas	Guadiana	402.1	304.6	323.2	336.6	361.4	406.2	535.4	680.1	954.5	2401.9
Pulo do Lobo	Guadiana	350.0	330.9	443.7	417.3	427.7	376.2	425.2	459.3	473.7	968.5
Blois	Loire	169.5	57.1	39.0	28.8	25.3	23.4	26.1	26.0	26.2	30.6
Montejean	Loire	158.2	62.5	44.9	34.5	31.2	28.8	30.4	29.7	28.2	29.5
Gazdowice	Odra	411.5	133.1	86.5	59.7	47.5	38.9	35.7	30.7	26.5	24.3
Bedford	Ouse	133.8	57.1	39.6	28.6	25.1	22.6	28.5	28.9	24.0	25.3
Piacenza	Po	68.5	27.1	19.4	14.1	11.5	9.5	8.7	7.0	5.7	4.7
Pontelagoscuro	Po	79.5	28.9	19.6	13.8	11.1	9.3	8.8	7.4	6.2	5.3
Paris	Seine	204.5	79.8	59.9	48.4	44.3	41.2	43.0	40.0	37.8	37.1
Poses	Seine	400.8	112.7	70.7	49.9	40.1	32.8	30.0	25.4	21.0	21.0
Bewdley	Severn	79.9	34.7	28.0	23.3	21.6	20.0	21.2	20.0	18.9	18.5
Alcantara	Tejo	203.6	116.0	93.5	83.2	74.6	70.8	78.7	81.1	93.1	133.0
Almouro	Tejo	175.1	79.4	80.6	71.5	67.7	62.7	66.2	67.8	71.0	79.1
De Rodao	Tejo	163.2	88.5	83.8	77.1	79.6	81.4	91.0	103.7	129.9	203.5
Talavera	Tejo	391.8	171.8	135.9	105.6	87.9	78.5	81.8	73.6	71.2	79.3
Roma	Tevere	139.4	45.0	29.7	21.2	17.8	14.6	13.6	11.3	9.0	7.6
Eynsham	Thames	173.1	72.0	55.4	44.7	41.5	42.4	50.7	56.0	61.6	84.2
Sutton Courtney	Thames	44.0	19.0	15.0	12.6	12.4	12.6	15.1	16.2	17.6	21.8
Teddington	Thames	211.1	63.0	41.0	30.3	27.7	25.1	27.2	25.1	23.2	26.8
Polgar	Tisza	182.3	64.8	45.0	32.9	28.3	25.1	25.8	24.4	24.4	25.5
Szeged	Tisza	249.4	82.7	58.7	45.5	40.3	36.2	36.7	33.9	32.8	35.8
Szolnok	Tisza	266.1	91.7	68.2	53.0	47.5	45.2	45.2	39.2	34.6	35.5
Colwick	Trent	69.6	22.8	14.2	9.5	8.0	7.5	7.8	6.5	5.4	4.9
Norham	Tweed	93.4	29.2	18.5	12.8	11.0	11.3	11.9	12.8	13.1	13.2

		mean SSC$_{AREA}$ (mg.l^{-1})									
Location	**River**	**0-10**	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**70-80**	**80-90**	**90-100**
Hann-Muenden	Weser	142.3	63.9	47.4	36.1	30.6	30.9	25.5	22.1	19.2	19.7
Intschede	Weser	160.2	64.2	46.6	34.5	28.9	24.6	24.0	20.8	17.6	16.2
Warsaw	Wisla	261.8	87.3	57.6	41.1	33.5	28.0	26.9	23.4	20.3	19.5
Ddol Farm	Wye	25.1	12.6	10.4	8.9	8.5	8.2	9.0	9.2	9.8	14.2

11.1 DVD info

A DVD was created in order to provide information and data that might be relevant for continuation of this work. The DVD contains spatial and temporal data sets collected for this study. In addition it also contains the calculations performed during the work, results, figures and tables that were used throughout the thesis. Since some of the data were used upon request the DVD is not enclosed here for the public access. For further information and the acquisition of the DVD Prof. Sue White may be contacted:

Prof. Sue White
Institute of Water and Environment
Cranfield University at Silsoe
MK45 4DT
United Kingdom
Tel: +44 (0) 1525 863140
Fax: +44 (0) 1525 863344
Email: sue.white@cranfield.ac.uk