Mapping and spatial analysis of suspended sediment yields from the Russian Plain

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Abstract The aim of this paper is to demonstrate the potential use of a GIS and associated database to map and analyse global patterns of sediment yield. Attention focuses on the suspended sediment yield (SSY) data available for the European territories of the Russian Federation and the variation of SSY across part of the Russian Plain. A GIS and database have been developed for the Volga River basin. The GIS system permits the drainage basins for which SSY data are available to be delineated and the database conflates information on sediment yield and the hydrological and physiographic characteristics of the individual drainage basins. A map of the variation of annual sediment yield within the Volga basin is presented.

Key words erosion; suspended sediments yield; GIS; thematic maps; hydrological stations

INTRODUCTION

The development of geomorphology during recent decades has placed increasing emphasis on process dynamics. There is a shift from a morphological paradigm to a process paradigm, reflecting increased interest in the physical and chemical processes responsible for landscape development. For example, an understanding of suspended sediment yields and their controls provides a valuable basis for investigating landscape development. Increased interest in process dynamics within geomorphology is leading to important changes in research methods. There is increasing emphasis on quantifying rates of landscape development and their variation between different morphoclimatic zones, exploring the links between process and form, experimental investigations and numerical and GIS-based modelling. Studies of exogenic processes, and more particularly erosion and deposition, within river basins are attracting increasing attention.

The intensity and spatial variation in the operation of exogenic processes is influenced by many factors, and studies of the magnitude and spatial variability of suspended sediment yield (SSY) in river basins provide a useful means of assessing the impact of such processes. The sediment yield of a river basin provides an important indication of the rate of denudation in the upstream basin, and the conveyance loss associated with the transfer of sediment to the basin outlet reflects the balance between erosional and depositional processes in landscape development. Since it is related to the intensity of mechanical and physical denudation processes, SSY provides a useful variable for comparing different areas or regions. Furthermore, contemporary SSY data provide valuable information for addressing key geomorphological issues related to the role of exogenic processes in landscape evolution.

SSY data possess a number of important features which make them particularly valuable for assessing denudation and landscape evolution. These include the use of standard methods for documenting SSY, the existence of records covering extended periods and the ability to cover large areas and to provide information relating to a range of scales. At present there are about 10 000 stations located around the world where SSY is measured. About 6000 of these provide data which are of limited value for geomorphological purposes, for a number of reasons, including short periods of record, low quality and non-accessibility. Thus, at the present time, data suitable for research purposes are available from published sources for about 4000 stations. These are mostly located in the former USSR, USA, Canada, Germany and some other countries of Western Europe. These data sets provide information on suspended sediment discharge and its variation in both time and space in response to a range of controls.

Spatiotemporal analysis of the structure and intensity of denudation at the global scale based on SSY data provides a basis for studying not only rates of denudation and landscape development, but also the role of both natural and human factors as controls and their relative importance. For a variety of reasons, quantitative analysis of the various factors controlling SSY undertaken to date in both Russia and elsewhere has been primarily at the general level. Development of erosion models and models of exogenic landscape development for different landscape regions of the Earth requires the integration of a wide range of quantitative data. In view of the global scale of such research, it necessitates application of modern information technologies based on geographic information systems (GIS).

Current research in this field within the Institute of Geography and Ecology of Kazan Federal University represents a logical development of the studies of global sediment yield started in the 1970s by Professors A. P. Dedkov and V. I. Mozzherin (see Dedkov & Mozzherin, 1984). At present our primary aim is to develop a custom-built GIS to provide a global-level synthesis of the suspended sediment yields of river basins (Yermolaev *et al.*, 2011, 2012). This will, in turn, provide a basis for spatiotemporal geomorphological analysis of global erosional systems and exogenic relief formation. A GIS database has, for example, been employed for constructing a map of the spatial zoning of SSY within a large area represented by the Volga River basin (Fig. 1).

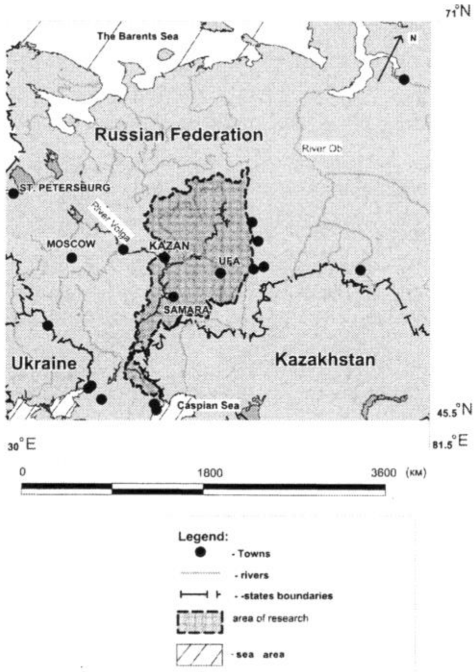

Fig. 1 Location of the study area in northern Eurasia (within the territory of the former USSR).

Other recent attempts to create a global GIS aimed at analysing the spatial variation of SSY include that reported by Syvitski *et al*. (2003). However, in that work the emphasis was on sediment transfer from the land surface of the globe to the oceans. It was therefore based on measuring stations located at the outlets of river basins, rather than measuring stations located within individual drainage basins that could provide more detailed information on the spatial variability of SSY across the land surface of the globe. Other local hydrological GIS databases have been created for particular countries, mostly in Europe.

METHODS

The creation of a global GIS involves a number of interrelated stages. The first step is to develop software for processing a digital elevation model (DEM) of the Earth. This is needed to produce quantitative data concerning the contemporary relief of the planet (in particular its morphometry), and for computer-aided delineation of drainage basins under various relief conditions and to determine their order. The second step is the development of a global system of operational areal units represented by two types of basin geosystem, namely, planar basins of a given order and basins for which records of suspended sediments transport are available. The third step is the creation of a geospatial database of the river basins of the Earth, which contains both suspended sediment yield data and other basin characteristics or parameters (hydrometeorology, topography, geology-geomorphology, degree of anthropogenic impact, etc.). The fourth step is to develop a methodology of computer-aided thematic and more complex zoning based on Artificial Neural Networks technology. The final stage is the creation of a set of electronic thematic maps (thematic Atlas) showing the spatial variability of SSY and the contemporary denudation of the river basins of the Earth.

It is clear that even where the necessary data are available, the creation of a global GIS is a difficult procedure, both in terms of the labour input and the technology involved. Therefore, for the first stage of our research we focused attention on a more limited area, namely, northern Eurasia (within the former USSR). This region incorporates about 2000 river basins, for which SSY data are available. Figure 2 indicates that the suspended sediment yield data are distributed fairly uniformly over the land area.

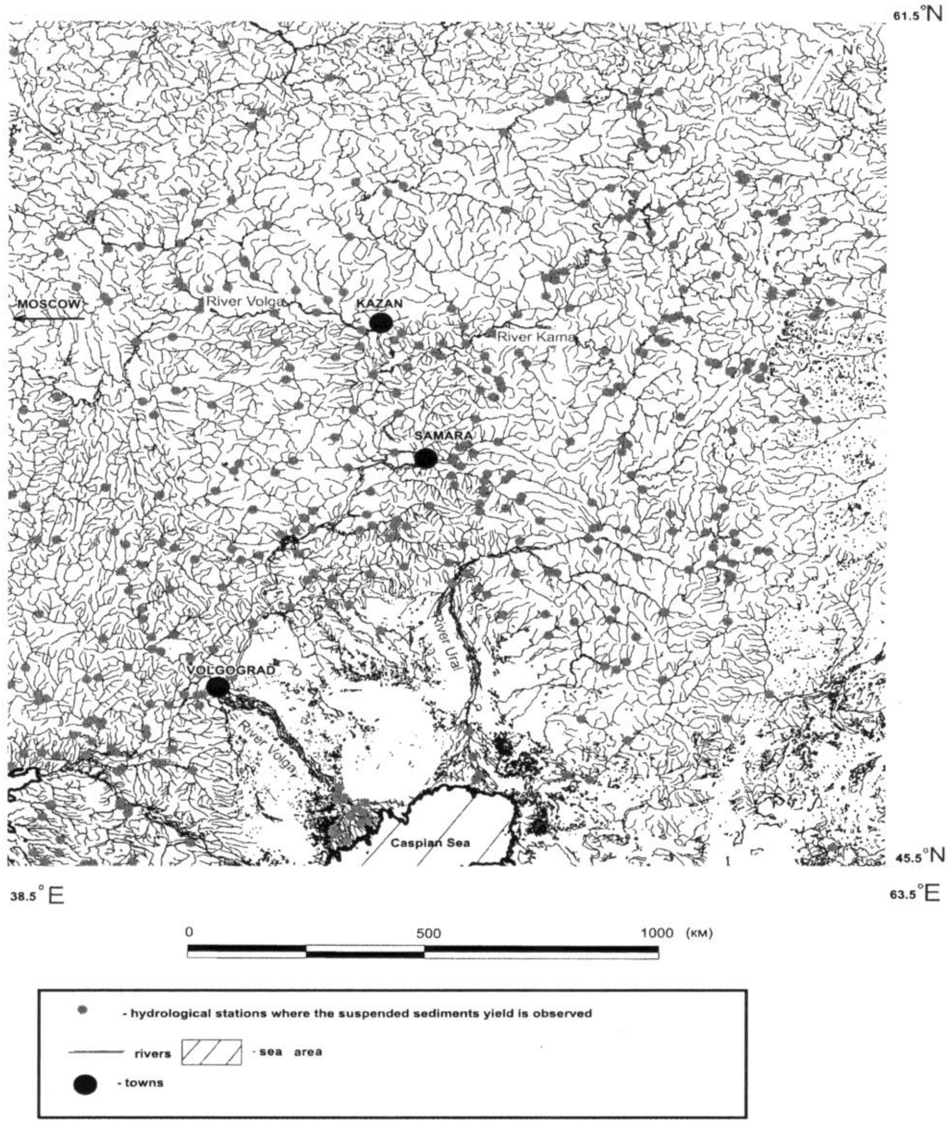

Fig. 2 Distribution of the hydrological measurement stations across the study area.

Establishment of a system of operational-territorial units (OTU) within the geo-information system is a task of key importance, since all the information is associated with river basins. The various components of this work are discussed in more detail below.

In a GIS context, relief is usually represented by either a raster or a vector digital elevation model (DEM). We have selected the raster model for our research. The vector model has certain advantages over the raster model, but one of its significant drawbacks is the increased complexity of the analytical operations. The absence of a verified global-scale vector model is also an important constraint.

There are many national and global raster DEMs of the Earth's relief. However, one of the most accessible and widely used for research purposes is the "GTOPO30" model which was used as the basis for computer-aided delineation of the river basins in our research.

In addition to these data, the "TAS" (Terrain Analysis System) software, developed at the University of Western Ontario by Lindsay (2005), was used. This software was created primarily for hydrological and morphometric analysis of raster relief models, including automated identification of drainage basin boundaries. Automated delineation of drainage basins can be divided into two main stages: (1) the preparation and assembling of the data required for computer-aided basin modelling; and (2) the operations related more directly to delineating drainage basins.

The preparation of data involves correction of the topographic database to eliminate areas with no flow connection within a drainage basin. Many local depressions frequently exist on the base model, and, depending on the algorithm selected, these can interrupt flow pathways and lead to incorrect delineation of drainage basin boundaries and significant areal distortions.

The creation of a model of both the ephemeral and perennial drainage systems involves calculation of flow directions. The algorithm employed is based on searching around the grid node for a node with the minimum altitude value and vectoring the flow to the given grid node. The model of the drainage basin is derived simultaneously with the calculation of flow directions. It involves a raster grid where the cells represent the contributing area of the drainage basin.

The result of the work described above is a model of the hydrographic network. It is based on the flow direction model and a model of cumulative catchment areas. To distinguish temporary and permanent flows, we used the empirical assumptions that perennial streams should have a runoff contributing area of at least 6 km^2 (a minimum basin size) and a length of at least 3 km. The given threshold values have been validated for reference areas for which the necessary medium-scale topographic maps were available. In the majority of cases the general arrangement of the drainage system shown on medium-scale topographic maps closely matched the results of the modelling.

Finally, the boundaries of basins with hydrological stations and available SSY data are constructed (Fig. 3). A two-stage evaluation of the accuracy of the river basin mapping system includes: (1) qualitative evaluation – visual confirmation of drainage basin boundaries; (2) quantitative evaluation – statistical comparison of the drainage basin areas derived from the computer-aided modelling with published information on drainage area for same drainage basins. The errors associated with computer-aided delineation of drainage basins in the European part of Russia are primarily accidental and do not exceed 5–7%. Here it should be noted that catchment areas of reservoirs and closed lakes are included in the watershed above a hydrological station. No information is available regarding sediment deposition in lakes and reservoirs, and attention focuses on the SSY measured at a hydrological station.

The next step of GIS creation involved developing the associated database. Each river basin had to be linked with the relevant information on SSY and its controlling factors in a database. The database integrates the essentially homogeneous data published in hydrological reference books and in the monograph published by Dedkov & Mozzherin (1984). However, the database was considerably expanded in terms of inclusion of data relating to the primary controls on SSY. The information about landscape characteristics was supplemented through the use of remote sensing imagery related to the period of SSY measurement. In addition, meteorological data and data from several thematic maps were added.

The GIS and associated database developed for the study arguably represents the largest body of hydrological and geomorphological information related to SSY and its controlling factors currently assembled in the world. This is in terms of not only the number of river basins included, but also the range of other data included. The database consists of several independent components, each of which could be used separately (Fig. 3). The first component consists of general data about the hydrometric stations, for which SYY data exist, and their location. It contains the names of the hydrological stations and the rivers and also information on river basins belonging to particular natural and political units. Information on latitude and longitude which can be used for precise location of the measuring stations is also included.

The second, and the most extensive component of the database contains a range of information for the river basins relating to both the natural conditions and the degree of anthropogenic modification. This includes information about the topographic characteristics of the basin, climatic parameters, geological conditions and land use. Imagery of the landscape and agricultural activity is also included.

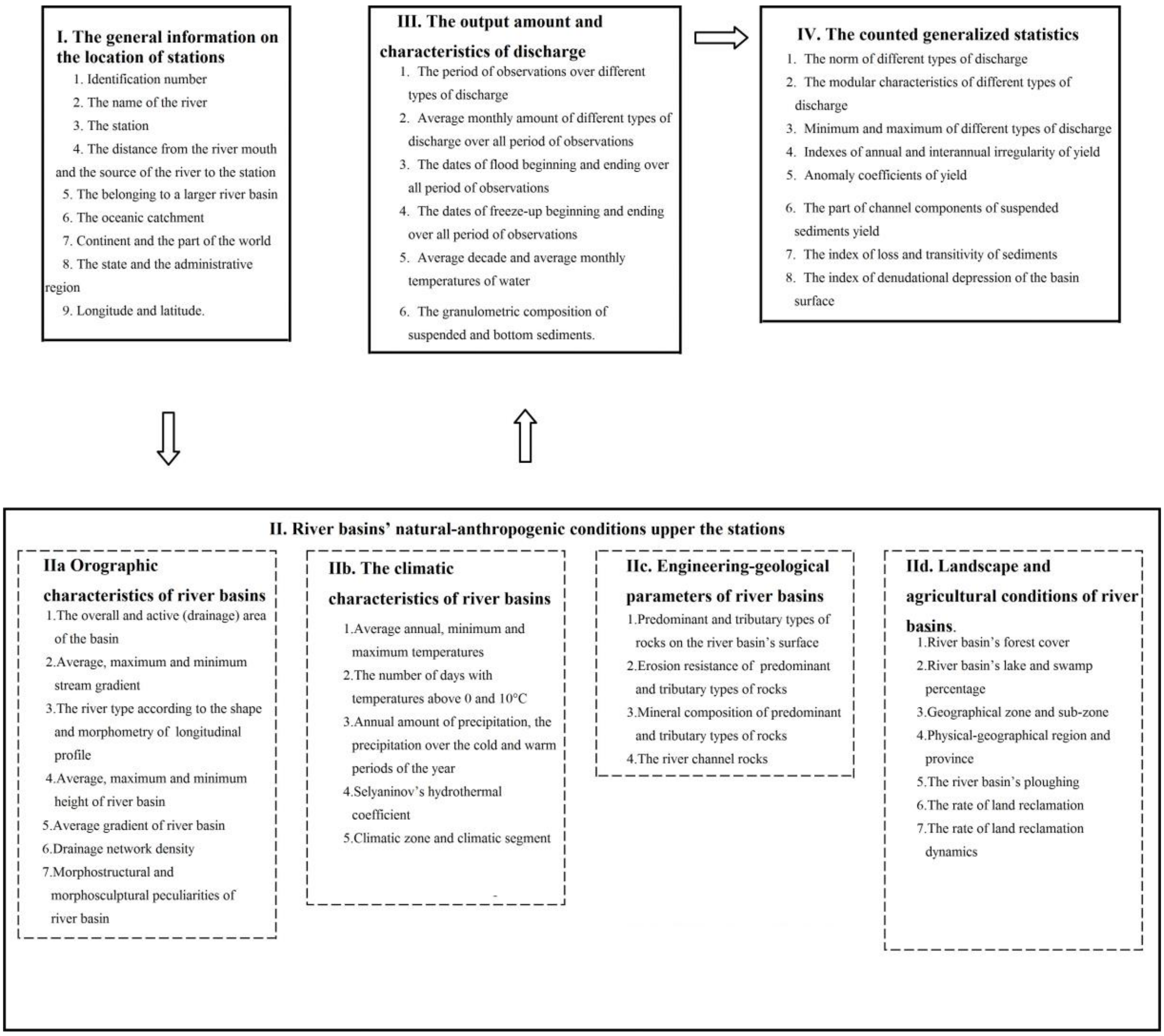

Fig. 3 The structure of the database containing information on both suspended sediment yield and its key controls integrated into the global GIS.

The third component contains data on the measurements of water discharge, and suspended sediment and dissolved solids transport for monthly or less frequent intervals. Finally, the fourth component provides summary statistics for the sediment and dissolved solids transport, including mean, minimum/maximum, indices of intra- and inter-annual variability, anomaly coefficients, the relative contribution of the channel and catchment surface to the SSY, and various indices representing the denudation rate. The summary statistics and indices are calculated automatically from the assembled data using generally accepted formulae. Addition or removal of data, due to extension or correction of a row, leads to revision of the entire set of summary statistics. These statistics are used as the basis for the development of both spatial and temporal mathematical-statistical models of river basin sediment yield, investigation of controlling factors, and defining the character and intensity of mechanical and chemical denudation within in river basin.

The application of the GIS described above has four main aims. The first is linked to the development of computer-aided databases and their use. Thematic databases (topography, hydrology, climate, landscape, lithology, etc.), which are of great interest to different fields of Earth Science, will involve a huge data array (representing more than 4000 hydrological stations located throughout the world). The second is connected with geostatistical investigations, which can readily make use of the available databases. This could involve detailed mathematical-statistical analysis of SSY and denudation data, incorporating the geographical factors. Such analysis could be used to develop a global geographical-statistical model represented by mathematical equations and aimed at providing a higher degree of explanation of the available data. This would make it possible to predict the SSY at any point on the land surface of the Earth. It could be based on existing empirical models, developed using global and regional data, such as ART, DBFM, BQART, etc. (Syvitski & Kettner, 2007; Liquete *et al.* 2009; Mozzherin & Mozzherin, 2011).

The third area of application and that most connected with geo-information technologies aims to provide a computer-cartographic visualization of the SSY distribution across the surface of the Earth, at scales ranging from local and regional to global levels of generalization. The fourth aim represents the distribution of the results to other scientific centres and groups, not only within our own country, but worldwide. Publication of the results on the Internet represents an effective means of achieving this. Access to the databases, the results of geostatistical processing of the data and version of the global GIS adapted for use by the network would be provided for authorized users.

RESULTS AND DISCUSSION

To demonstrate the potential application of the GIS and associated database in mapping the spatial variation of SSY, an example relating to 110 river basins located in the middle and lower reaches of the Volga basin is presented (Figs 1 and 4).

The total area covered by the study is 757 000 km^2 and extends 1000 km from east to west and 1500 km from north to south. It involves 53% of the total area of the Volga basin.

Our analysis employed the following key indicators:

$$R = W / S \quad (1)$$

where R (t km^{-2} year^{-1}) is the mean annual suspended sediment yield from the entire area upstream of a measuring station, S (km^2) is the catchment area upstream of the measuring station and W (t year^{-1}) is the mean annual suspended sediment load for the measuring station:

$$R_d = (W_2 - W_1) / (S_2 - S_1) \quad (2)$$

where R_d (t km^2 year^{-1}) is the differentiated mean annual SSY for the part of the upstream basin between the measuring station and the next measuring station upstream, where $W_2 - W_1$ is the difference between the mean annual suspended sediment load at the two stations and $S_2 - S_1$ is the difference between the catchment areas of the same measuring stations (Dedkov *et al.*, 2001).

Considering the pattern of sediment yield presented in Fig. 4, the zones mapped include areas of taiga, mixed and broad-leaved forest, forest-steppe, steppe and semi-desert. The majority of the basins delineated are located within the Russian Plain, although approximately one fifth are located on the western slopes of the Ural Mountains.

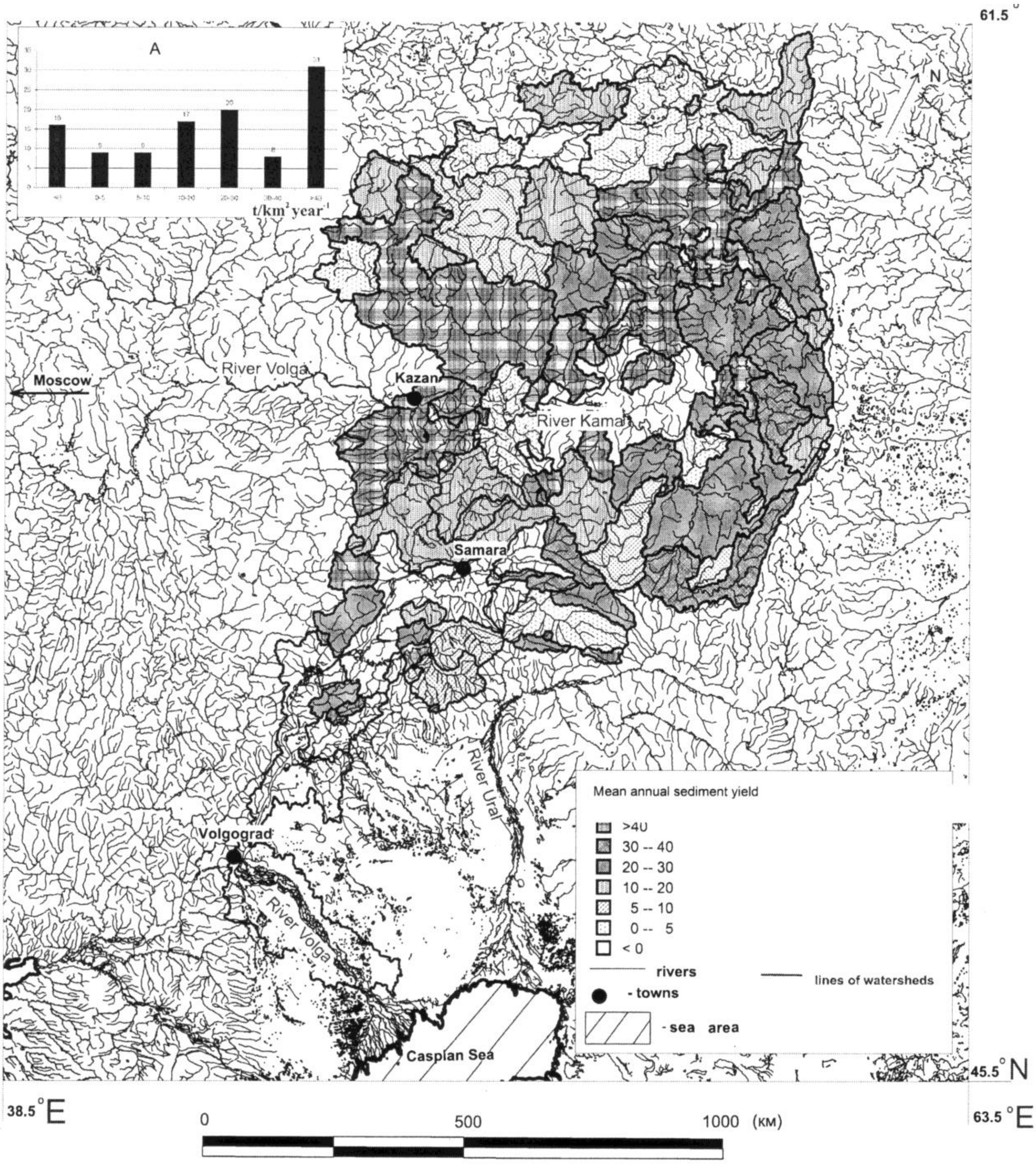

Fig. 4 Variation of mean annual differentiated suspended sediment yield across the river basins delineated automatically for the measuring stations located in middle and lower Volga basin. (**A** presents a histogram of the values of mean annual SSY.)

The majority of the basins (about ⅔ of the total) are characterized by a mean SSY in the range 0–50 t km^{-2} $year^{-1}$. No major change is apparent across the different natural zones. The highest values of mean SSA (>50 t km^{-2} $year^{-1}$; 20% of all basins) are primarily associated with the smaller basins (< 5000 km^2) and the basins located in foothills of the Ural Mountains.

For 16 of the measuring stations (15% of the total) a negative differentiated sediment yield was found. This demonstrates the potential importance of sediment deposition within the river network. In general, such basins are located below large reservoirs.

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