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# Modelling suspended sediment supply to the River Rhine drainage network; a methodological study

**PAUL M. VAN DIJK & FRANS J. P. M. KWAAD**

*Department of Physical Geography and Soil Science, University of Amsterdam, Nieuwe Prinsengracht 130, 1018 VZ Amsterdam, The Netherlands*

**Abstract** In the framework of a climate change research project, an approach and preliminary results are presented of modelling the suspended sediment supply to the drainage network of the River Rhine. Concepts of the GAMES model are used as a basis. In the model, the amount of mobilized sediment that actually reaches the stream network depends on the proximity of the sediment source to the stream, the occurrence of overland flow and on the character of the terrain along the route towards the channel (including surface roughness and slope angle). Attention is paid to problems that are specific to the large size of the studied basin and the spatial resolution of the available data set. Preliminary results show that estimates of sediment supply from hillslope to streams are reasonable. Calculated sediment supply was compared with measured sediment yields at several sampling stations in the Rhine basin. It appeared that suspended sediment supplied in lower parts of the basin is transported more effectively through the alluvial system. A large part of the sediment produced in the Alps and in the Swiss middle mountains is stored in the alluvial system further downstream where stream power decreases.

## INTRODUCTION

Water quality, and in particular, the suspended sediment load of the River Rhine is of great importance for water management in The Netherlands. Deposition of fine, contaminated sediments in embanked flood plains, in the lower delta area and in harbours depends on the suspended sediment input through the river system. Environmental change is expected to have significant effects on the discharge regime of the River Rhine and suspended sediment it carries (Kwadijk, 1993; Van der Drift & Kwaad, 1995; Asselman, 1997).

In the framework of the National Research Programme on Global Air Pollution and Climate Change, research is being carried out which aims to assess the impact of climate change on basin hydrology of the Rhine and the sediment budgets. Concerning the sediment budget, major questions for this research are:

(a) What are the sediment source areas in the Rhine basin?
(b) How much sediment enters the stream channels?
(c) What is the fate of the sediment after it has entered the channel network? and
(d) What are the answers to these questions if the climate changes?

Sediment is supplied to the river by downslope movement of loose soil material on valley side slopes with or without the assistance of overland water flow within the basin. Examples of sediment-producing hillslope processes are soil erosion by overland flow and rain splash, landslides, earthflows and the dispersed clay travelling towards the stream in subsurface flow (Van den Broek, 1989). Sediment can also be produced by channel processes like bed and bank erosion. The sediment supply to rivers varies in space and time for the same reasons the water supply varies, but the variability for sediment is larger, due to fluid and/or gravity force thresholds for downslope movement, and due to the discrete character of mass movement events (Bridge, 1996). The part of the supplied sediment that becomes suspended load travels at the speed of the fluid and settles only in places where turbulence intensity is low (e.g. lakes, reservoirs, flood plains and harbours). The suspended load reaching the Dutch border amounts to about 3.2 Mt year$^{-1}$ and consists mainly of clay, silt and very fine sand (Rijkswaterstaat, 1992).

In terms of quantity, soil erosion on hillslopes is thought to be a primary source for the suspended sediment reaching The Netherlands (Graf, 1971; Richards, 1982; Knighton, 1984). However, Walling (1990) points to the uncertainties in this assumption. Another source is the waste water emission from the potassium mining industry in France (Van der Drift & Kwaad, 1995), which will not be considered in this study. Not all sediment that is produced on hillslopes by soil erosion reaches a branch of the permanent stream network and is subsequently transported out of the catchment. Part of the sediment is stored on the hillslopes and part is stored within the alluvial system. Thus it is not possible to predict basin suspended sediment yield solely from erosion rates in the river basin. Upscaling of the rate of soil erosion to basin sediment yield involves taking into account both colluvial and alluvial sediment storage (Fig. 1).

This paper deals with the first two questions mentioned earlier: mapping of sediment source locations and quantification of the sediment supply from the hillslope to the channel network under present-day conditions. Attention is paid to the quantification of sediment production by soil erosion and hillslope storage for the entire Rhine basin using the available spatial and temporal information. For very large river basins, this is a new area of research. Therefore, in this paper the

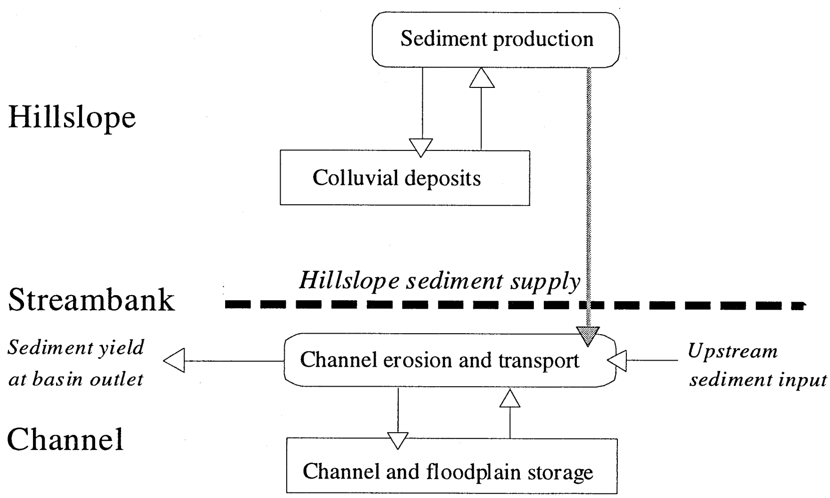


**Fig. 1** Flow chart of hillslope sediment supply and the fate of delivered sediment in channels. Processes are noted as ovals, storage elements as rectangles and transfers as arrows (after Reid & Dunne, 1996).

emphasis lies on the approach, and in particular on the question how to translate global data into parameters which are relevant on the hillslope scale. Because that is where the supply process takes place. An attempt is made to quantify the hillslope sediment supply using a simple, fully distributed model. Preliminary results are presented.

## THE STUDY AREA AND BASIC DATA SETS

The Rhine basin upstream of the Dutch border comprises an area of about

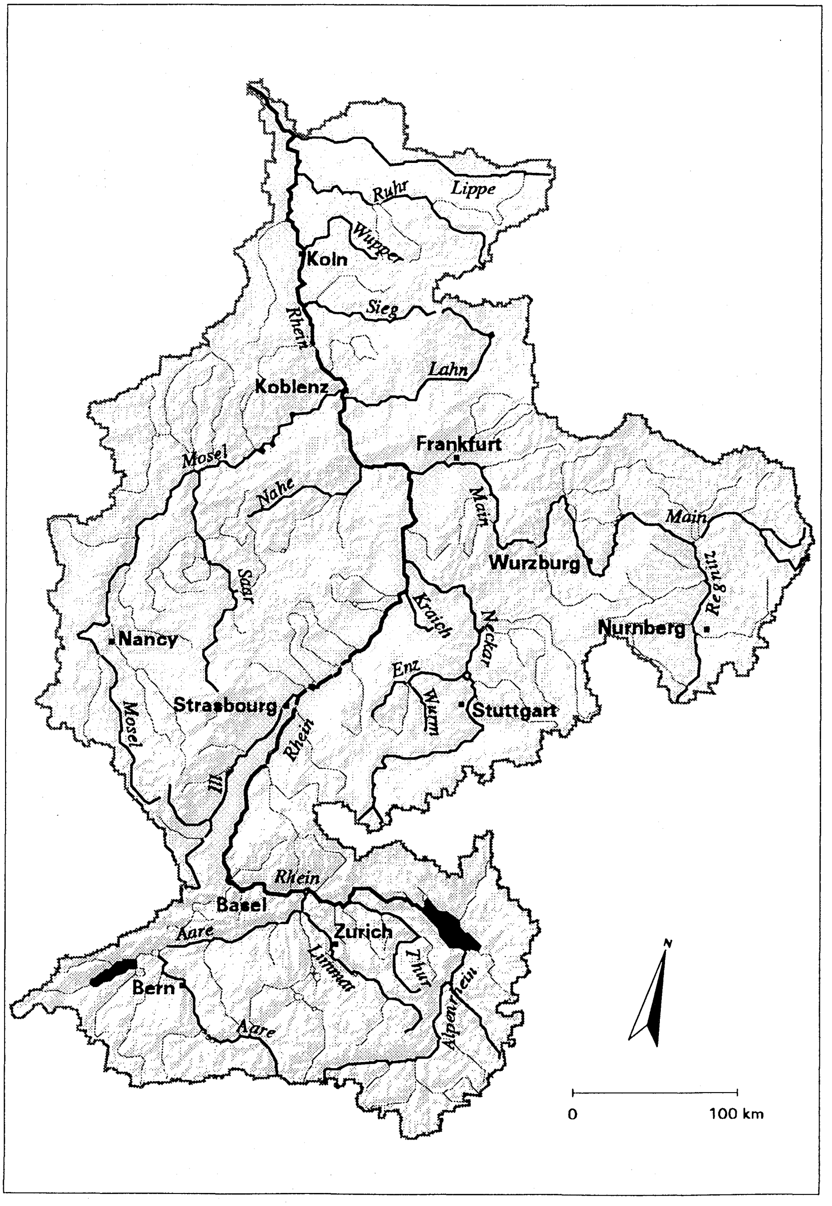


**Fig. 2** The Rhine basin upstream of the Dutch border.

165 000 km$^2$ of which 63% is located in Germany, 17% in Switzerland and 14% in France. The main tributaries of the Rhine are the Aare, Main, Mosel and Neckar (Fig. 2). The climate is mostly temperate and mean annual precipitation varies between 600 mm in the lower parts and 2500 mm in the Alps (CHR/KHR, 1976). During the summer, a large part of the river discharge derives from melted Alpine snow in the southern part of the basin. In winter time, the central part of the basin contributes most water due to soil saturation, while in the Alps discharges are low due to storage of precipitation as snow.

Most of the available spatial data sets for the entire basin are at 1 km$^2$ resolution. A digital elevation model (DEM) was used for the delineation of the borders of the Rhine basin and its sub-basins, for the derivation of a local drain direction network

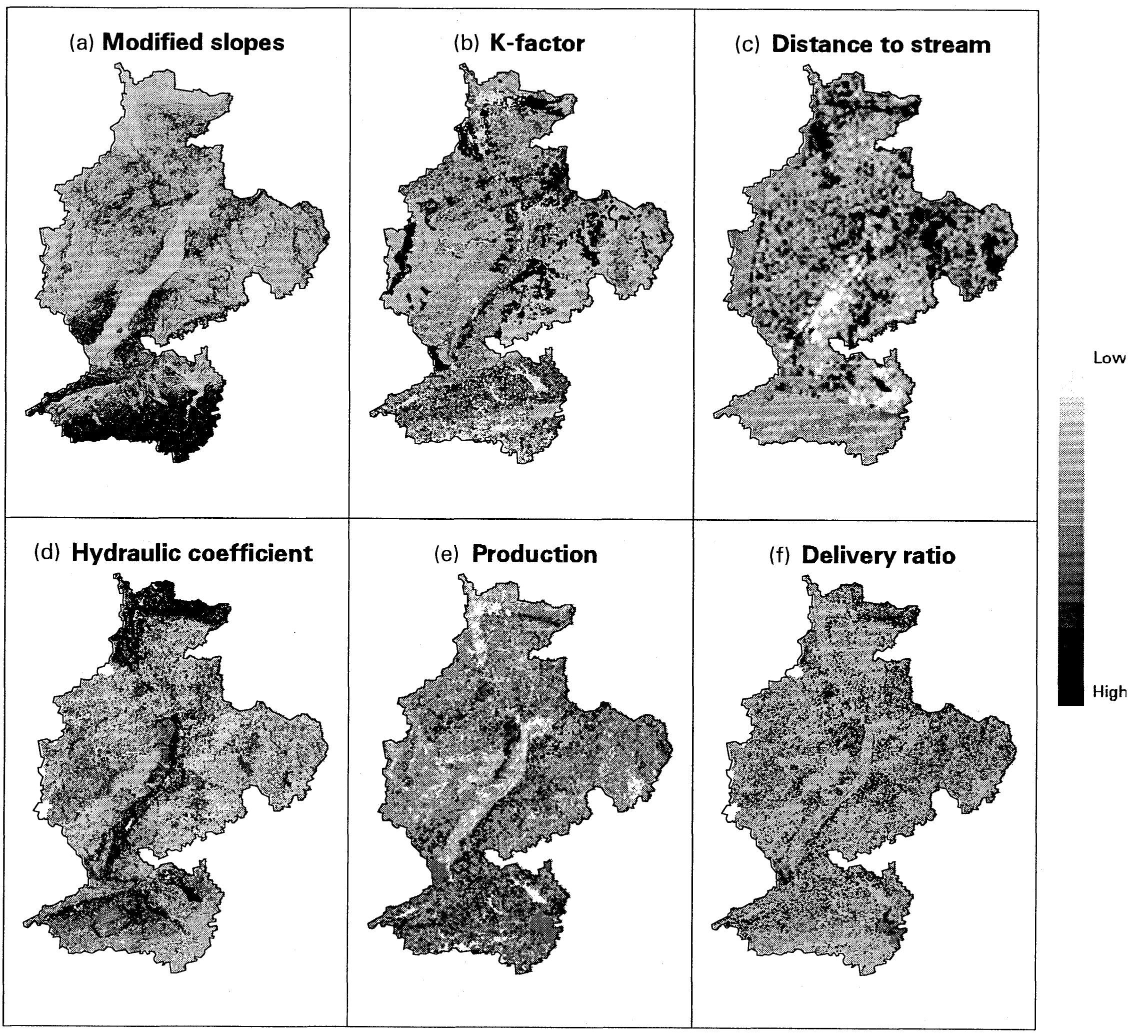


**Fig. 3** Estimated model parameters for the Rhine basin upstream of Lobith: (a) average intra-cell slopes, (b) *K* factor, (c) average distance to nearest channel, (d) hydraulic coefficient, (e) local erosion (ln scale), (f) local delivery ratio.

(Wesseling *et al.*, 1997), and for estimating slope angles (see also Fig. 3(a)). For soil information, use was made of the digital Soil Map of the European Communities, Version 2 (CEC, 1985; INRA/JRC, 1992; King *et al.*, 1994). In this research, the soil texture class is one of the most important soil attributes in the database. A land-use map was provided by the CHR/KHR (1976). As this map aggregates all agricultural land use into one class, information on land-use statistics from the administrative regions was added. The modified land-use map discriminates between forest, grassland, maize, cereals, beets, potatoes, pulse crops, vineyards, open water, towns/urban areas, bedrock and glaciers. A drainage density map of the permanent stream network was created by combining information from the following sources (Van Dijk, in Asselman *et al.*, 1997): (a) a scan of the "Gewässernetz" of the Hydrological Atlas of Germany (1979), (b) a drainage network derived from the DEM and (c) several topographic maps at a scale of 1:25 000. In this analysis, those streams that can be recognized as exterior links on topographic maps at scale 1:25 000 were assumed to be first-order streams. The River Rhine at Lobith was estimated to be a ninth-order stream (Kwaad & Van Dijk, in preparation) and the average drainage density was estimated to be 0.75 km km$^{-2}$. The analysis showed that the first- and second-order streams could not be resolved within the cell size of the DEM. The spatial patterns in the resulting drainage density map were taken from the scan of the "Gewässernetz", which showed more variation in drainage density than the DEM-derived network.

## METHODS

### The model

Sediment supply to the stream network was estimated using the concepts of GAMES, the Guelph model for evaluating effects of Agricultural Management Systems on Erosion and Sedimentation (Dickinson *et al.*, 1986, 1992). This Canadian model was developed from the starting point that sediment source areas do not necessarily coincide with major soil erosion areas, due to variations in the capacity of different parts of the basin to transport particulate materials (Dickinson *et al.*, 1986). The model was designed for a seasonal or annual time frame and consists of two major components: (a) a sediment production module, and (b) a module that accounts for sediment storage on the hillslope through a delivery ratio expression.

To calculate sediment production, we used the German equivalent of the USLE called ABAG (Allgemeine Bodenabtragsgleichung; Schwertmann *et al.*, 1987) and equations from the Revised Universal Soil Loss Equation (RUSLE; Renard *et al.*, 1991). The average annual sediment production within each grid cell is calculated with:

$$A = R\,K\,LS\,C\,P \tag{1}$$

where: $A$ is soil loss (t ha$^{-1}$ year$^{-1}$), $R$ is the rainfall erosivity factor (N h$^{-1}$), $K$ is the soil erodibility factor (t h ha$^{-1}$ N$^{-1}$), $LS$ is the topographic factor (-), $C$ is the cropping management factor (-) and $P$ is erosion control practice factor (-).

The sediment delivery ratio, $D_r$ (-), is supposed to depend on the surface roughness and the slope gradient along the length of the flow path towards the stream and on the probability of a land cell to generate runoff:

$$D_r = \alpha \left( \frac{H_c \sqrt{s}}{n\,l} \right)^{\beta} \qquad 0 \le D_r \le 1 \tag{2}$$

in which $\alpha$ and $\beta$ are empirical parameters of about 9.53 and 0.79 respectively (Dickinson *et al.*, 1986), $H_c$ is the hydraulic coefficient which is an index for the probability of overland flow occurrence and is called the hydraulic coefficient (-), $s$ is slope gradient (%), $n$ is Manning's roughness coefficient (s $m^{-1/3}$ ) and $l$ is the length of the flow path between the cell and its downstream cell or to the stream channel (m).

The sediment delivery, *SD* (t $ha^{-1}$ $year^{-1}$), from each cell to the next cell downstream is calculated by multiplying $A$ with the local delivery ratio:

$$SD = D_r\,A \tag{3}$$

Hillslope sediment supply to the streams is now determined by accumulating the cell *SD* values over the local drain direction map (LDD) until a stream channel is reached. The model was written in PCRaster dynamic modelling language (Van Deursen, 1995; Wesseling *et al.*, 1996).

## Assessment of the model parameters

Maps of all necessary parameters were created. Several difficulties arose due to the spatial resolution of our data sets (1 $km^2$). The original model was designed for basins up to 3000 ha, using data with a much higher spatial resolution. According to the drainage density map of the Rhine basin, most of the grid cells contain a stream. This means that hillslope sediment delivery (Fig. 1) is often a "within cell" process instead of a "between cell" process. Thus, for most cells accumulation of *SD* over the LDD map is not necessary to determine supply. However, the input parameters must now describe the "within cell" situation.

True slope lengths and angles cannot be derived directly from the DEM. This hampers the derivation of the *LS* factor. An approximation of "within cell" slope angles was based on a link between the slope map published by Richter (1965) and the slopes derived from the DEM. DEM slopes were classified in such a way that the resulting map resembles the slope map of Richter. A regression between the slope class boundaries of both maps was carried out and the result was used to compute the modified slope map on the basis of the DEM. The modified map is supposed to represent the average of the slope angles within a raster cell (Fig. 3(a)). The *LS* factor was calculated using the modified slope map. The basin average contributing slope length was set to 75 m; spatial variations were related to drainage density patterns.

The *R* map was prepared by Asselman (1997) who extended the data of Sauerborn (1994) for Germany to other locations within the Rhine drainage basin. In total, about 330 precipitation values were used. The rainfall erosivity values were interpolated using universal block kriging, with relief as an additional variable. Rainfall erosivity increases from north to south. High values are found in the Vosges and the Black Forest. Maximum *R* values are found in the higher parts of the Alps (Asselman, 1997).

The $K$ map (Fig. 3(b)) is based on soil texture and organic matter content. The map with texture classes was converted into three maps showing clay, silt and sand fractions. Within each texture class, texture was allowed to vary within the class boundaries instead of taking the average fractions. A multiple regression equation was used to compute $K$ from the clay and silt fraction. The equation was derived from $K$ data of 37 different "Bodenarten" published in the *Geologisches Jahrbuch*, Heft 31. The $K$ map was corrected for the organic matter content. The organic matter content of soils under forest was assumed to be three times higher than under other types of land use (Van der Drift & Kwaad, 1995). High $K$ values often coincide with the occurrence of loess because of the high silt content of loess soils.

The $C$ map was derived from the land-use map using crop factor values taken from the literature. High $C$ values coincide with vineyards and maize fields, low values with forests and grass surfaces. Conservation practices were assumed to play a minor role ($P$ map = 1).

The $l$ parameter of equation (3) could not simply be determined from the distance of a cell to the next downstream cell, because often sediment is supplied within the raster cells. Therefore, $l$ was related to the drainage density. For this, relationships between drainage density and the mean distance to a stream were established. This was done by using $10 * 10\ m^2$ artificial DEMs covering $1\ km^2$ (= one cell in the Rhine database) on which drainage networks were draped with different densities. For each drainage density, the average distance of each $10 * 10\ m^2$ cell to the nearest stream was determined. This information was used to calculate a map with the average distance to the stream on the basis of the drainage density of each $1\ km^2$ cell (Fig. 3(c)). This distance is supposed to relate to $l$. The procedures are described in detail in Kwaad & Van Dijk (in preparation).

Manning's $n$ was determined from the land-use map using tables from the literature. The hydraulic coefficient (the $H_c$ map) was computed with the curve number method. The main parameter in this model is the retention parameter $s_w$, which was calculated using routines from SWRRB (Arnold *et al.*, 1990). $s_w$ depends on the curve number, but also varies in time due to changes in the soil water content. Curve numbers were derived from the land-use map and a map with hydrological soil groups, using the SCS tables (Chow, 1964). The hydrological soil groups were based on the FAO soil subgroups and drainage classes taken from Batjes (1997). The actual soil water state was calculated on a monthly basis using the RHINEFLOW model (Kwadijk, 1993; Van Deursen, 1995). RHINEFLOW calculates the soil water content by accounting for monthly precipitation, snow storage, snowmelt, drainage to groundwater and actual evapotranspiration. The yearly average $H_c$ map is shown in Fig. 3(d). For this simulation, rainfall and temperature data (of 16 and 26 stations, respectively) for the period 1956–1980 were used.

## PRELIMINARY RESULTS AND DISCUSSION

### Sediment production

The sediment production map, based on the USLE is shown in Fig. 3(e). High values are found in Switzerland, along parts of the edges of the Rhine rift valley (especially between Basel and Strasbourg), in the downstream part of the Neckar basin with agricultural land use and highly erodible soils, and in the downstream part of the Mosel basin. Low sediment production mostly coincides with forested areas on sandy or clayey soils and with flat areas (e.g. the Rhine rift valley itself).

## Sediment supply to the stream network

The map of the yearly average sediment delivery ratio calculated with equation (3) is

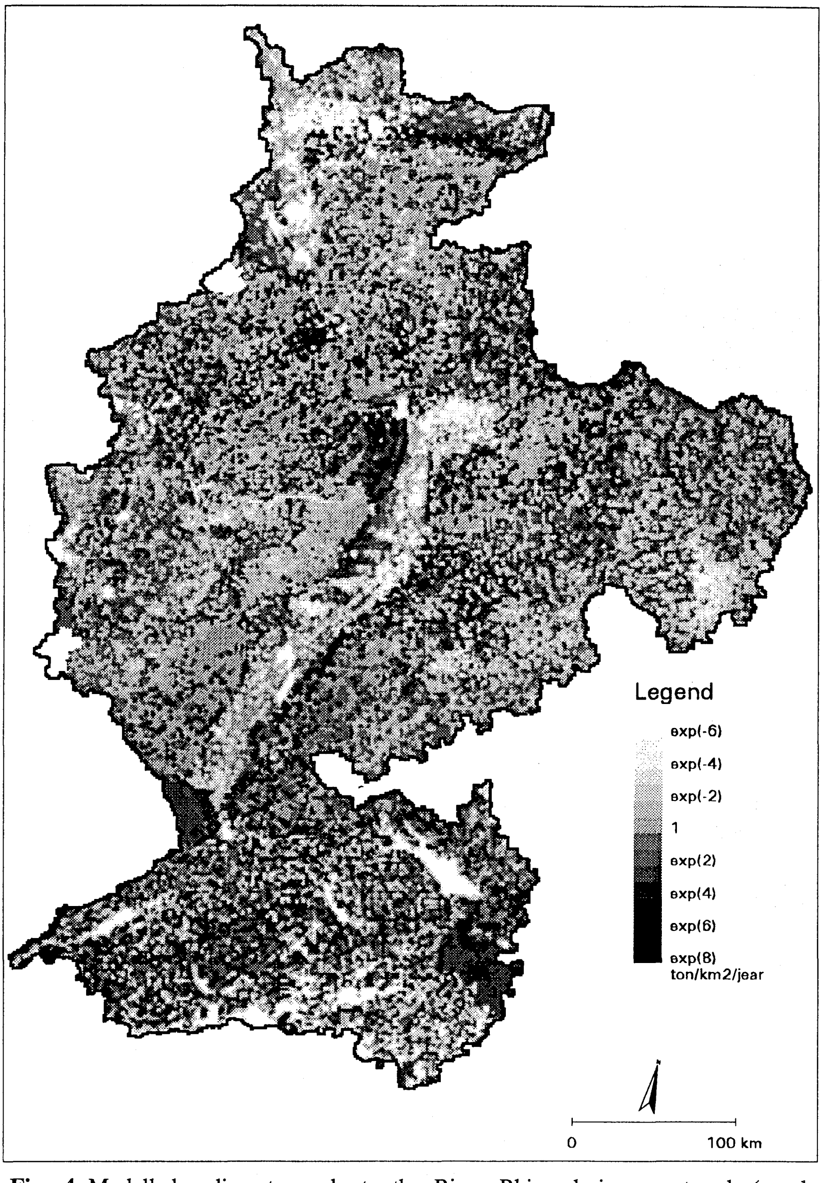


**Fig. 4** Modelled sediment supply to the River Rhine drainage network (yearly average) using meteorological data of 1956–1980.

shown in Fig. 3(f). The yearly average sediment supply to the streams is shown in Fig. 4. The speckled character of this map is mainly due to land use. A number of important supply areas can be identified: (a) the entire Aare sub-basin, (b) the southern Rhine valley especially at the eastern flank, (c) downstream along the Neckar and the Mosel, (d) south of the large river bend near Mainz, (e) the loess area between the Lippe and the Ruhr.

The total sediment production for the entire basin is estimated to be 53 Mt year$^{-1}$, while total supply to the drainage network amounts to approximately 7.3 Mt year$^{-1}$ (13.8% of the production). The amount of suspended sediment which passes the Rees Emmerich sampling station near the Dutch border equals 3.2 Mt year$^{-1}$ or 44% of the supply. Modelled sediment supply was compared with suspended sediment yield measured at six sampling stations in the basin (Fig. 5). Results show that supply is

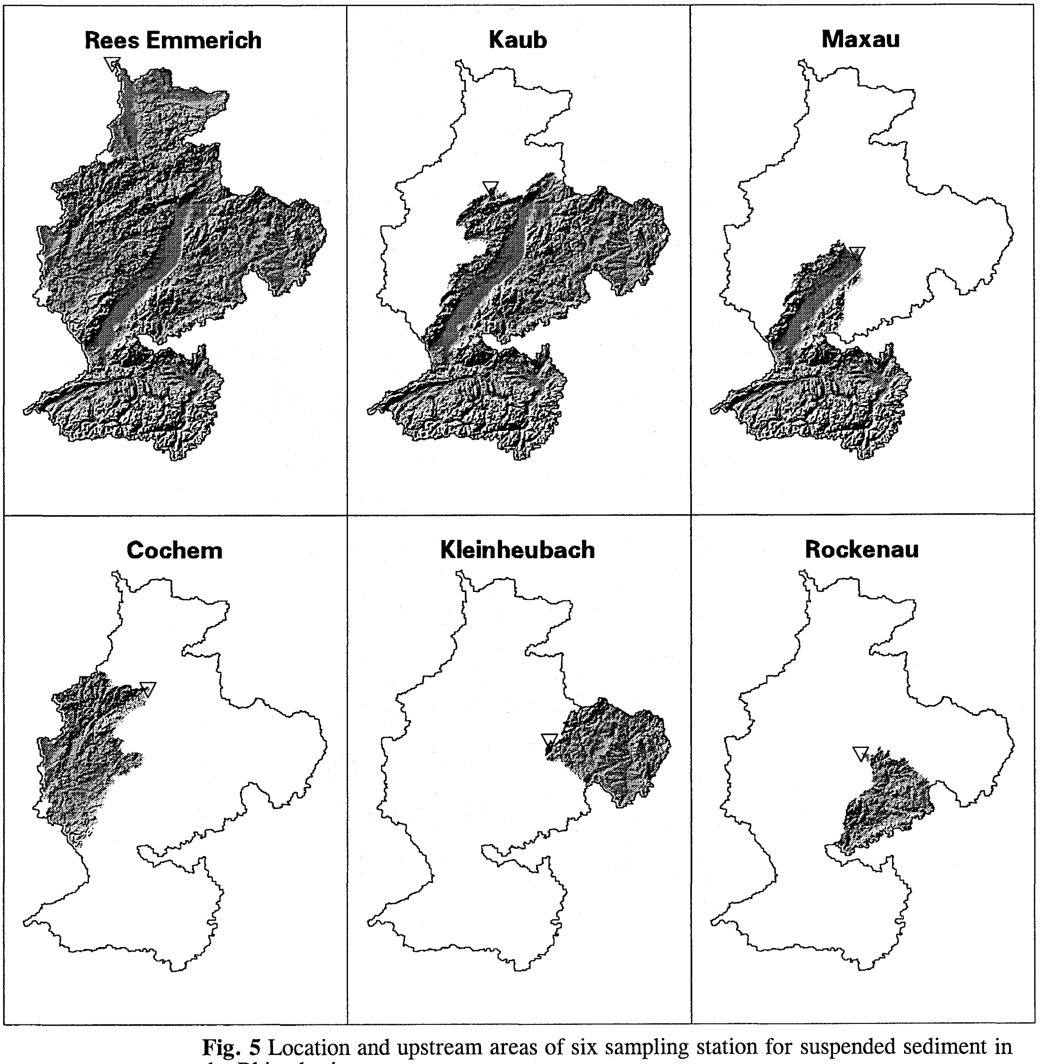


**Fig. 5** Location and upstream areas of six sampling station for suspended sediment in the Rhine basin.

reasonably balanced by yield for the locations Cochem, Kleinheubach and Rockenau (Fig. 6(a)). However, for the sampling stations which have upstream areas located in the Alps and the Rhine rift valley (e.g. Maxau, Fig. 6(b)), supply is much higher than the output.

The difference between modelled supply of sediment to the channels and measured suspended sediment yield at the basin outlet may be due to alluvial processes, which stand between sediment supply and basin sediment yield. However, it is too early to draw such a conclusion, as the uncertainty of our model predictions has not yet been quantified. An analysis of the uncertainty in model predictions is an essential next step in this research. Prediction errors may be due to model errors, errors in input parameters and omission of processes. An example of an omitted process is supply of sediment in subsurface flow. Also, the model does not cope with the role of vegetated riparian zones as sediment sinks. However, research of Bach *et al.* (1994) has shown that in most cases water enters these zones at point inlets due to concentration of overland flow on the hillslope. As a result, there was no remarkable effect of vegetative filter strips on input to streams.

Then, what can we say about the model results we have obtained so far? The GAMES model was applied without recalibration to an entirely different basin size. Estimated yearly supply values are close to measured yields for three of the six locations (Fig. 7(a)). The suspended sediment at the other three locations is strongly affected by the presence of large lakes, reservoirs, weirs and dams in the upstream area. Studies have shown that much of the sediment in the Alpine streams is trapped in the many large lakes in front of the Alps (Van der Drift & Kwaad, 1995). Furthermore, about 40% of the total suspended load in the Rhine section between Breisach and Iffezheim is deposited (upstream of Maxau) due to weirs, dams and reservoirs (Gölz, 1990). If we subtract these losses from modelled supply, the resulting amount of sediment passing the stations Maxau, Kaub and Rees is much closer to the suspended load measured (Fig. 7(b)), but still higher. If we now interpret the results with reservation, the following can be argued. A large part of the sediment supplied under high stress conditions (due to steep slopes and/or high rainfall erosivity) becomes stored somewhere downstream in the alluvial system where stream power decreases. Initially, supplied sediment may be transported in suspended mode in streams with a high flow velocity, but a part may become bed-

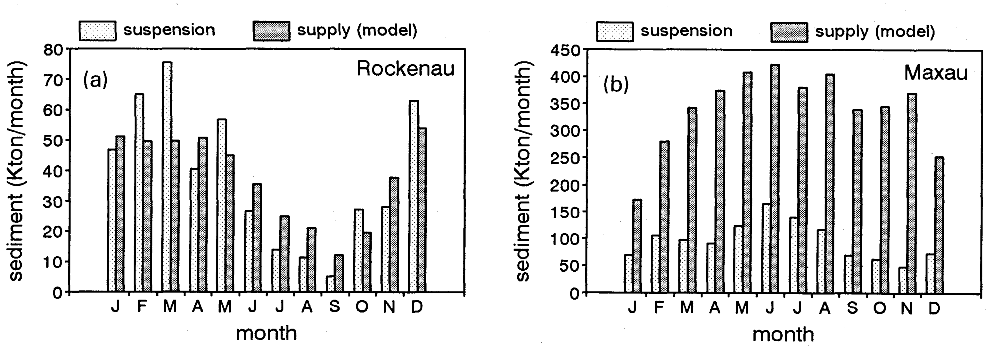


**Fig. 6** Comparison of modelled monthly sediment supply and measured sediment yield for (a) the Rockenau and (b) the Maxau sampling stations.

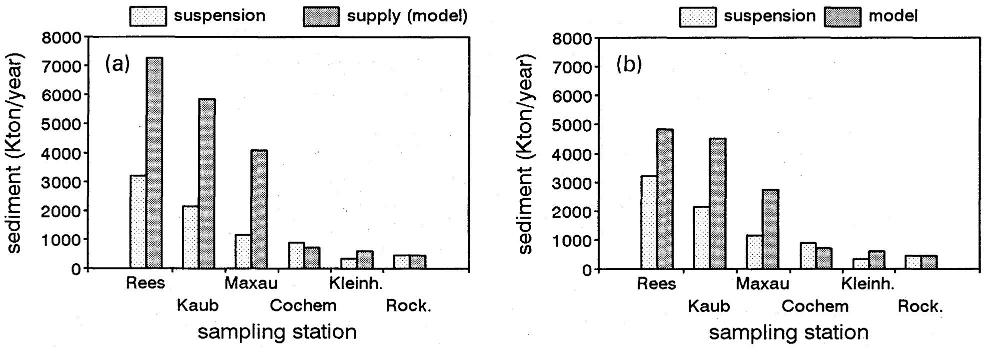


**Fig. 7** Comparison of measured suspended sediment yield with (a) modelled sediment supply and (b) modelled supply minus known deposition upstream of Maxau (see text).

load transport when flow velocities reduce downstream. Sediment supplied to streams under low stress conditions, in undulating areas with highly erodible soils, is more effectively transported through the alluvial system. Under these conditions, a larger part of the sediment delivered to the streams remains in suspension.

## CONCLUSION

It can be concluded that the spatial database for the Rhine basin in combination with a simple model can be used to identify sediment supply areas. Validation of the quantitative estimates is very difficult, because supply data are scarce. The sediment supply model should be combined with a model for the alluvial processes to get a hold on the entire sediment budget.

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