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A global modelling of the climatic, morphological, and lithological control of river sediment discharges to the oceans

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Abstract In this study, we investigate the empirical relationships between river sediment yields and a large number of hydroclimatic, biological, and geomorphological parameters at the global scale. For a set of 60 major world river basins, environmental characteristics were extracted from various global computer datasets, and river sediment fluxes were taken from the literature. Sediment yields can be best correlated by forming the products of hydroclimatic, geomorphological and lithological factors, that is drainage intensity, basin slope, an index characterising rock hardness, and an index characterising rainfall variability over the year. The best correlated parameter combination varies when the rivers are grouped according to their average climatic situation, but it is always a combination of the above-mentioned parameters that yields greatest correlation coefficients. In arid climates, however, regression coefficients are greater than in humid climates, indicating that erodibility is much greater in arid climates. When extrapolated to the total continental area, our models yield a total sediment flux of 14.7 Gt year^{-1} that is discharged to the oceans. About 40% originates from the wet tropics, 21% from wet temperate climates, 5% from the boreal climates, and 34% from dry climates.

INTRODUCTION

River sediment fluxes to the oceans play an important role in various natural geochemical cycles such as the global carbon cycle, as well in for the transport and cycling of many human released pollutants (Walling & Webb, 1985). In order to assess the response of river sediment fluxes to regional and global change, an understanding of the main factors that control river sediment discharges to the oceans is needed. Several attempts have been made to analyse, for example, the relationship between sediment fluxes and mean annual precipitation (e.g. Langbein & Schumm, 1958; Wilson, 1973). Other authors have highlighted the influence of basin elevation and morphology (e.g. Pinet & Souriau, 1988; Milliman & Syvitski, 1992), while again others proposed multiple regression models combining various hydroclimatic, biological, geomorphological, and lithological parameters to predict sediment fluxes worldwide (e.g. Jansen & Painter, 1974; Probst, 1992; Probst & Amiotte-Suchet, 1992).

The purpose of this study is to determine the main factors and relationships that control river sediment discharges at the global scale. Many of the previous investigations suffered from strong data limitations, especially with respect to environmental parameters. Our study makes use of the large number of global environmental datasets that have been developed in recent years in various disciplines for global scale investigations. These datasets give not only a very detailed description of the hydroclimatic, biological, and geomorphological characteristics of the Earth, but they also facilitate extrapolation of the relationships established to the overall continental area. This is important because one can test whether these relationships agree with the variability of observed river sediment fluxes both on regional and global scales.

DATA AND METHODS

Hydroclimatic, biological, and geomorphological characteristics of 60 major world river basins were extracted from various environmental datasets using a set of digitized river basin contours (Ludwig *et al.*, 1996), as well as the contours of the endoreic basins on the continents. The 60 river basins cover about 50% of the total exoreic continental area, and are representative of the major ecosystems on Earth. Their basin areas range between 5903×10^3 km^2 for the largest basin (Amazon), and 9×10^3 km^2 for the smallest basin (Ems). The basins were further classified according to a simple climatic classification based on their average position in the Holdridge life zone classification (for details see Ludwig *et al.*, 1996). They fall into the following classes: tropical wet (12 rivers), tropical dry (16 rivers), temperate wet (19 rivers), temperate dry (three rivers), tundra and taiga (10 rivers).

The environmental data we used are mentioned in the legend of Fig. 1. When no reference is given, the same datasets as in Ludwig *et al.* (1996) were taken. For each basin and each parameter, one area-weighted mean value was determined. All calculations were made at a grid point resolution of $0.5° \times 0.5°$ longitude/latitude. The corresponding water and total suspended sediment fluxes for the river basins were taken from the literature. With very few exceptions, we took them from the recently published LOICZ-IGBP river database GLORI (Milliman *et al.*, 1995). Both parameters were divided by basin area, and only used as specific runoff (*Q*) and specific sediment fluxes (*FTSS*), respectively. For calculations with Q on a grid point scale, we used a rasterized version of the UNESCO runoff map (Korzoun *et al.*, 1977) that we have digitized and gridded. With regard to climatic distinctions, we consider all grid points as dry that fall either into the tropical dry or into the temperate dry climate type, or that are desert. Wet grid points are consequently grid points falling into the other climate types.

RESULTS AND DISCUSSION

Figure 1 shows that *Q* has the strongest correlation with *FTSS* among all parameters considered. The next highest correlations with *FTSS* include *APPT*, *Four*, *VegC*, *LithMI*, and *Slope*. Correlation of certain variables with *FTSS* does not necessarily indicate a causal relationship, because multicollinearity exists between the various parameters. Strong multicollinearity exists between the different hydroclimatic variables, as well as between the hydroclimatic and the biological variables. The good correlation between *Q* and *VegC* may, for example, explain why there is a positive correlation between *VegC*

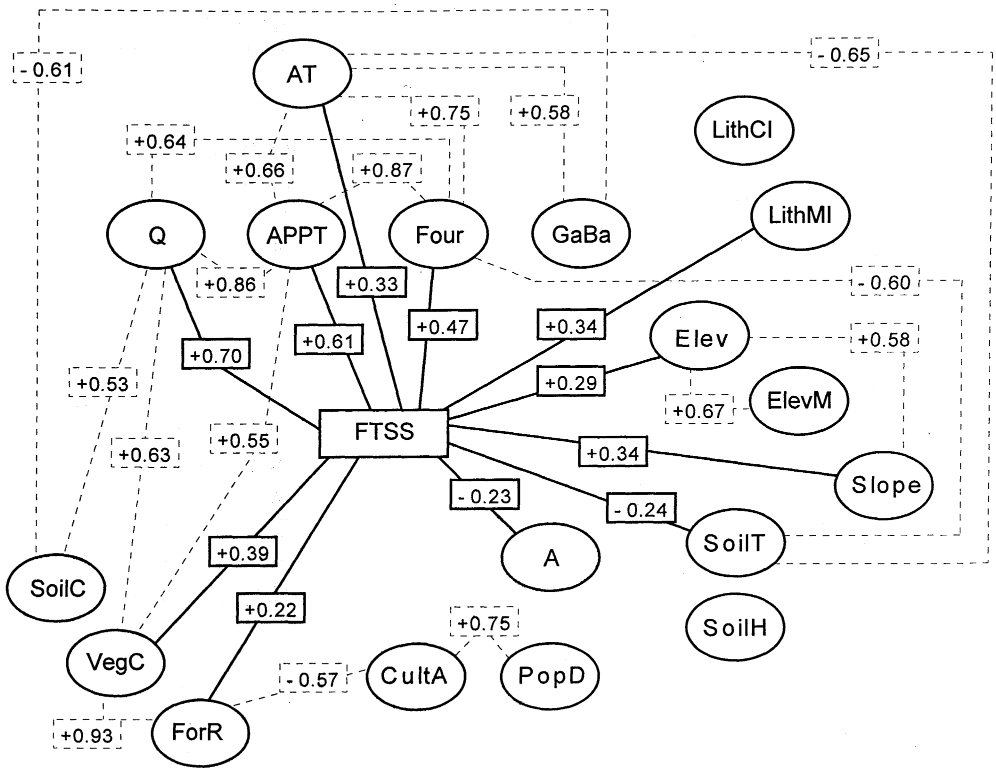

Fig. 1 Correlation between sediment yield (*FTSS*) and different environmental parameters for 60 major world river basins (solid lines; only regressions significant with $P < 0.1$ are depicted), as well as correlation between the environmental parameters (dashed lines; only regressions with correlation coefficients < -0.5 and $> +0.5$ are depicted). *Q* is the specific drainage intensity. *AT* and *APPT* are, respectively, the mean annual temperature and the mean annual precipitation total. *Four* is a modified form of an index originally proposed by Fournier (1960) to characterise the variability of precipitation over the year. It was calculated as the sum of the square of mean monthly precipitation over mean annual precipitation for all 12 month of the year. *GaBa* is the Bagnouls-Gaussen aridity index based on monthly precipitation and temperature data (CEC, 1992). *LithMI* and *LithCI* are two indices for the erodibility of the dominant basin lithology with regard to mechanical and chemical erosion, respectively. For the classification of each rock type and the corresponding lithological maps see Probst (1992) for *LithMI*, and Amiotte-Suchet (1995) for *LithCI*. *Elev* is the mean modal basin elevation, and *ElevM* is the maximum basin elevation. *Slope* is the average basin slope. *SoilT* is an index for the erodibility of the dominant soil type (low, medium, high) based on the average soil texture following the classification proposed by CEC (1992), while *SoilH* represents the average soil depth. *A* is the basin area calculated in this study. *SoilC* gives the average organic carbon content in the soils (data from: USDA-SCS, see Eswaran *et al.*, 1993). *VegC* is the average biomass density, and *ForR* represents the mean forest ratio (from 0 to 1) in the basins (Claussen *et al.*, 1994). *CultA* is the percentage of the cultivated area in the basins, and *PopD* is an estimate of the mean population density in the basins.

and *FTSS*, while one should expect an inverse relationship between both parameters, because of the protection of soils against mechanical erosion by a dense plant cover (Summerfield, 1991; Probst, 1992).

Linear multiple correlation statistics do not yield a significant increase in the correlation between *FTSS* and the parameters shown in Fig. 1, when compared to the correlation between *FTSS* and Q. However, some improvement is obtained by using the product of certain parameters. The following equation gives the best model to describe the sediment fluxes globally:

$$FTSS = 0.020\ (Q \times Slope \times Four) \qquad (1)$$

$$n = 58;\ r = 0.91;\ P < 0.0001$$

FTSS is in t km^{-2} year^{-1}, Q and *Four* in mm year^{-1}, and *Slope* in radians; r is the correlation coefficient, P is the significance level, and n is the number of river basins considered. Note that the product of Q, *Slope*, and *Four* is calculated as the product of all grid points in the basin, and not calculated as the product of the basin averages. Including *LithMI* in the parameter product can still increase the correlation coefficient ($r = 0.93$), but this leads to a significant positive intercept ($P < 0.1$) in the regression, which makes the model less suitable for regional sediment yield predictions.

In equation (1), we omitted the Huanghe River in China and the Tana River in Kenya from the regressions. Both rivers have by far the greatest specific sediment fluxes of all rivers considered in this study. The extreme sediment yield observed for the Huanghe River is related to one of its tributaries, the Huangfuchuan River, that drains a highly erodible loess-covered terrain, leading to a specific sediment export of more that 50 000 t km^{-2} year^{-1} (Summerfield, 1991). Such local particularities cannot be accounted for in a study such as ours. Also the high sediment load of the Tana River seems to be related to a particular, very erodible region within the basin (Charania, 1988), but the literature value for this river may also be less reliable.

On the basis of the global datasets, equation (1) results in an average global sediment yield of 139.4 t km^{-2} year^{-1} when applied to a total exoreic continental area of about 106×10^6 km^2 (ice-free). The total sediment flux is thus 14.80 gigatonnes (Gt) per year. This figure lies between the recent estimate of Milliman & Syvitski (1992), who suggested that global sediment delivery by rivers may be as great as 20 Gt year^{-1}, and the earlier estimate of Milliman & Meade (1983), who estimated global *FTSS* to be 13.5 Gt year^{-1}.

Forming the product of parameters can lead to large differences between the resulting values, which holds the risk that the regressions are strongly influenced by extreme values. We tested therefore whether the above presented model, or similar models, can be confirmed by making subgroups of the river basins. As a criterion to form the subgroups, the average climatic situation of the basins was selected. Figure 2 provides a plot of mean annual TSS concentration versus specific drainage intensity for all investigated rivers in this study. The rivers are additionally classified according to their average climatic situation. Although concentrations scatter over more than three orders of magnitude, one can see that for a given drainage intensity, the rivers in dry climates tend to have greater concentrations than the rivers in wet climates. Consequently, omitting the dry climate rivers from the regression in equation (1) does not significantly change the regression coefficient, and the correlation coefficient increases ($r = 0.93$). This is indicating that the above presented parameter product is useful for predicting sediment fluxes in the wet climates while in the dry climates sediment fluxes may be controlled differently. Applied to all wet grid points only, equation (1) yields a

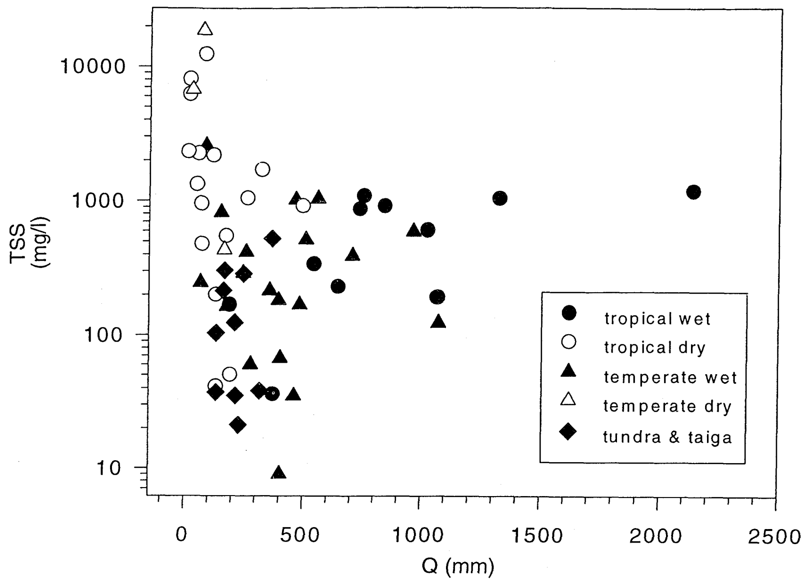

Fig. 2 A plot of mean annual sediment concentration *vs* drainage intensity for 60 major world river basins.

global sediment flux of 14.10 Gt year^{-1} with a corresponding area of 68.91×10^6 km^2.

Taking only the group of river basins with dry climates, no clear correlation between the observed sediment fluxes and environmental parameters or parameter combinations for the river basins can be found. This is also less surprising because the climatic variability can be great for these basins (as shown by Ludwig *et al.*, 1996), making the average basin values extracted from the datasets often less meaningful. Our grouping is based on the average basin situation, but in some basins we classified as dry, the river hydrology is strongly influenced by a particular part of the basin that has quite different environmental characteristics in comparison to the rest of the basin. For the Colorado River, for example, we find that only about 17% of the basin area can be classified as wet, but about 79% of the total runoff of the Colorado originate from this part of the basin.

Table 1 lists the results when the regressions were performed within the individual climate groups of river basins. The temperate dry and the tropical dry climates were still lumped together as one type because only 2 rivers belong to the temperate dry climate (not considering the Huanghe River), and this number is too small for meaningful statistical analysis. When the product of parameters are formed, it is not possible to determine the statistical significance of each parameter in the regressions. For this reason, we tested several parameter combinations, and comparison of the correlation coefficients for each combination can then help to decide whether additional parameters improve the regressions or not. For all 3 wet river groups, high correlation coefficients were found. In the tundra and taiga climate both the products of *Q*, *Slope*, *Four*, and *LithMI* (*P4*) and of *Q*, *Slope*, and *LithMI* (*P5*) show the highest correlations with *FTSS*. *Four* is probably not a very meaningful parameter in this climate type. Because of the temporal storage of water as snow there can be a considerable time lag between precipitation and mechanical

Table 1 Regression of sediment yield versus several parameters and parameter products.

Climate	Number of rivers	Correlation coefficient r:					
		Q	$P2$	$P3$	$P4$	$P5$	$P6$
Tundra and taiga	10	0.65	0.89	0.94	0.98	**0.98**	0.97
Temperate wet	19	0.49	**0.83**	0.75	0.73	0.75	0.76
Tropical wet	12	0.87	0.73	0.92	**0.96**	0.96	0.93
Dry climates	17	0.80	0.55	0.79	**0.81**	0.55	0.63

Climate	Number of rivers	Regression coefficient m ($f(x) = mx$):					
		Q	$P2$	$P3$	$P4$	$P5$	$P6$
Tundra and taiga	10	0.22	*13.13*	0.037	0.00255	**0.125**	-
Temperate wet	19	0.38	**16.52**	0.020	0.00119	0.114	1.97
Tropical wet	12	*0.83*	26.70	0.020	**0.00081**	0.211	5.17
Dry climates	17	1.18	25.73	*0.088*	**0.01176**	1.252	14.36

$P2 = (Four \times Slope)$
$P3 = (Four \times Slope \times Q)$
$P4 = (Four \times Slope \times Q \times LithMI)$
$P5 = (Four \times Q \times LithMI)$
$P6 = (Slope \times Q)$
All regressions are significant at least with $P < 0.05$. The regression coefficient was calculated by forcing the regression to pass through the origin. It is shown when the intercept was not significant in the regressions, which means that for the intercept $P > 0.1$ ($P > 0.05$ for figures in italics).

erosion through the generation of runoff. Also in the tropical wet climate type, *P4* and *P5* yield the highest correlation coefficients with *FTSS*. In the temperate wet climate, however, it is the product of *Four* and *Slope* (*P2*) that is best correlated with sediment fluxes, and neither the inclusion of *Q* nor of *LithMI* in any of the parameter combinations improves the regressions with respect to this correlation. One can suppose that *Four* should especially contribute to mechanical erosion when the soils are periodically in an intermediate position between field capacity and severe water limitation over the year. High *Four* values can then cause a short-term overflow of the soils which may enhance sheet erosion. Among the three wet climate types, it is probably in the temperate wet climate where soil moisture corresponds most closely to this condition. In the tropical wet climate, for comparison, there is generally a greater water excess and the soils should be on average closer to field capacity throughout the year.

For the group of dry river basins, the statistics were performed in a different way. As mentioned above, large amounts of total runoff in these basins can originate from small wet parts of the basins, which should also considerably influence the total sediment fluxes from these basin. We therefore calculated for the wet basin parts a theoretical sediment flux according to the best regression models found in the wet river groups (boldface regressions in Table 1), and subtracted the values from the observed total sediment flux. The resulting *FTSS* values were then used for regression with the basin characteristics that were calculated on the basis of the dry basin grid points only. For the group of dry climate rivers, we find *P4* to be best correlated with sediment fluxes. Note that the regression coefficients in nearly all regressions are much greater than for the corresponding regressions in the wet climate types, and that is in agreement with the general picture in Fig. 2. This means that erodibility in dry climates is much greater than in wet climates. One explanation for this could be that the water limitation in dry climates leads to vegetation covers that afford a much less efficient protection of soils against mechanical erosion. However, since we include modelled and observed *FTSS* values in the regressions, the results must naturally be used with more caution. More data especially for river basins that are dry over the complete basin area are needed to confirm such a trend.

Taking the most significant regressions in Table 1 (boldface regressions), the global sediment flux to the oceans can be determined on the basis of the global datasets used in this study. This yields the following values: tundra and taiga, 0.78 Gt year^{-1} (A = 27.10 $\times$ 10^6 km^2), temperate wet, 3.08 Gt year^{-1} (A = 16.91 $\times$ 10^6 km^2), tropical wet, 5.82 Gt year^{-1} (A = 24.90 $\times$ 10^6 km^2), and dry climates, 5.03 Gt year^{-1} (A = 37.34 $\times$ 10^6 km^2). In the tundra and taiga regression, we included also the climate type that was classified by Ludwig *et al.* (1996) as ice-free polar climate type (A = 3.89 $\times$ 10^6 km^2), and the regression for the dry climates include also the climate type that was classified by Ludwig *et al.* (1996) as desert (A = 5.94 $\times$ 10^6 km^2). Although these types cover considerable parts of the continents, they contribute little to the total sediment flux (0.05 Gt year^{-1} for the ice-free polar climate, and 0.03 Gt year^{-1} for the desert climate) because of their generally very low drainage intensities. The total sediment flux is thus 14.71 Gt year^{-1}.

Summing the sediment fluxes for the wet climate types only results in a value of 9.68 Gt year^{-1}, which is considerably lower than the value that was calculated with equation (1) for all wet continental grid points. This is mainly due to the fact that *LithMI* was included into the regressions both for the tundra and taiga and for the tropical wet climates. Lithologies that are less resistant to mechanical erosion are over represented in our set of river basins. Taking for these climates the *P3-FTSS* correlations instead, which also still have high correlation coefficients, the corresponding sediment fluxes would increase to a value of 14.94 Gt year^{-1}. Further investigations should be devoted to the role of lithology in influencing global sediment fluxes.

The results of Table 1 indicate that present-day river sediment fluxes are mainly controlled by a combination of hydroclimatic and geomorphological factors such as Q, *Slope*, and *Four*. Our results are in good agreement with the results of Phillips (1990) who found that slope gradient, runoff, and precipitation factors should together account for most of the global variation in soil erosion rates. Our models are quite similar to the Universal Soil Loss Equation (USLE) developed by Wischmeier *et al.* (1958). The USLE also includes rainfall intensity and slope as principal controlling factors, but additional parameters are needed for the USLE, including soil erodibility as a function of soil properties such as soil texture, and the density and structure of the vegetation cover. The USLE was originally designed for local scale assessments of soil loss by rainfall from agricultural land, but our results indicate that similar approaches could be applied in order to assess the response of global sediment delivery for different scenarios of global change, as well as for palaeoclimatic studies. Of course, such simple models cannot cover all aspects of the complex relationships controlling mechanical erosion rates and river sediment fluxes in river basins. One shortcoming of our approach is probably the fact that it is based on a summing up of individual grid point characteristics to larger scales. Therefore it cannot account for sedimentation processes taking place in river basins because of basin subsidence or sediment trapping in internal reservoirs such as lakes. Improved knowledge of the processes of sediment delivery interposed between on-site erosion and the sediment yield at the outlet of the drainage basin is needed (Walling & Webb, 1987).

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