SUSPENDED SEDIMENT FLUX IN PERENNIAL RIVER SYSTEMS:
DETERMINANTS OF YIELD LEVELS

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ABSTRACT
The level of suspended sediment flux or sediment yield in rivers has significant implications for river channel development, the growth or decline of estuaries, flood mitigation and fluvial management. This study uses multiple regression analysis to analyze the determinants of sediment flux in a representative set of 57 of the world’s major rivers. The study has three main findings. First, suspended sediment flux yields are strongly driven by precipitation runoff, and an increase in runoff of 1 per cent increases sediment flux by 1.02 per cent. Second, suspended sediment flux yields are strongly driven by sediment concentration, and an increase of sediment concentration of 1 per cent increases sediment flux by 1.00 per cent. Third, suspended sediment levels are weakly driven by the basin size or area, and an increase in area of one per cent increase sediment flux by 0.00016 per cent.

KEY WORDS
Statistical analysis, statistical and probabilistic modelling, environmental modelling, sediment flux, sediment concentration.

1. Introduction
The level of suspended sediment flux or sediment yield in rivers has significant implications for river channel development, the growth or decline of estuaries, flood mitigation and fluvial management. To facilitate comparison across river systems, sediment flux or yield is often expressed in normalized form as kg·km⁻²·day⁻¹. Key drivers of sediment flux or yield include precipitation runoff, area of the relevant river basin and sediment concentration (Brandt [1]).

Several studies have examined the relationships among precipitation runoff, river basin area, sediment concentration, and sediment flux for individual river basins using time-series analysis. Yang et al. [2], Xu [3], Lu [4] and Tiedemann [5] examined sediment concentration and sediment flux in the Yangtze River, China. They found that sediment concentration and sediment flux have fallen significantly since the 1950s, due, in large part, to construction of dams and filling of the associated reservoirs. Bravard et al. [6], Provansal et al. [7] and Arnaud-Fassetta [8] examined long-term geological changes in the Loire Valley of France. They found that significant channel in-filling has taken place when the supply of riverine sediment exceeded the transport capacity of the Loire. Goswami et al. [9] examined changes in the channels of the Subansiri River in India. They found that river increases or decreases in water flow or by increases or decreases in sediment load precipitate changes in the river’s channels. Kondolf et al. [10] used a comparative framework to examine the Pine Creek catchment of Idaho with the Drome catchment in France, with a view to understanding the main drivers of channel change. They found that hard-rock mining and road construction led to increased riverine bedload with channel instability for the Pine Creek catchment, while reforestation and dam construction reduced both erosion and bedrock sediment supply and decreased channel width for the Drome River catchment.

Other studies have examined the relationships among precipitation runoff, river basin area, sediment concentration, and sediment flux for pooled river basins using cross section analysis. Studies by Schumm and Handley [11], Wilson [12], and Syvitski and Milliman [13] found a strong inverse relationship between the size of a river’s drainage basin and the size of sediment yield. However, the research on the effect of climate on sediment yields contradictory results. Most studies including Fournier [14], Jansen and Painter [15] and Hay [16] found that sediment yield increases with increased precipitation runoff. But other studies including Langbein and Schumm [17] and Fournier [18] found that sediment yield decreases with increased precipitation runoff. Relevant general surveys include Walling [19] and Syvitski et al. [20].

One significant gap in this literature is an analysis of the drivers of sediment flux for a representative sample of the world’s rivers using appropriate multivariate statistical methods. The purpose of this paper is to help fill this gap using multiple regression models to estimate the impact of precipitation runoff, sediment concentration and river basin size on sediment flux. Because of the presence of heteroscedasticity in the error terms, we use White’s heteroscedasticity adjusted ordinary least squares which produces unbiased estimates of the significance of the regression coefficients. The focus of this study is on perennial rivers (that is, rivers which do not experience periods of zero flow) and on rivers in a reasonably natural state (that is, rivers which had not been unduly affected...
by dams and their reservoirs for the period of measurement of precipitation runoff and measurement of sediment flux).

2. Model

Using insights from the research cited above, we consider a set of four simple nested models of the determinants of sediment flux. These four nested models are estimated in both the levels of the relevant variables and the logs of the levels of the relevant variables. With the models estimated in levels of the variables, a regression coefficient (or an alpha parameter in the equations below) is interpreted as the change in the dependent variable due to a one unit change in the independent variable. With the models estimated in the logs of the variables, a regression coefficient (or alpha) is interpreted as the percentage change in the dependent variable due to a one per cent change in the independent variable.

Equation (1) assumes that sediment flux $S_i$ is a function of a constant $\alpha_1$, of basin area $A_i$, and of runoff $R_i$

$$S_i = \alpha_1 + \alpha_2 A_i + \alpha_3 R_i.$$  

Equation (2) assumes that sediment flux $S_i$ is a function of a constant $\alpha_1$, of basin area $A_i$, and of sediment concentration $C_i$

$$S_i = \alpha_1 + \alpha_2 A_i + \alpha_3 C_i.$$  

Equation (3) assumes that sediment flux $S_i$ is a function of a constant $\alpha_1$, of runoff $R_i$, and of sediment concentration $C_i$

$$S_i = \alpha_1 + \alpha_2 R_i + \alpha_3 C_i.$$  

Equation (4) assumes that sediment flux $S_i$ is a function of a constant $\alpha_1$, of basin area $A_i$, of runoff $R_i$, and of sediment concentration $C_i$

$$S_i = \alpha_1 + \alpha_2 A_i + \alpha_3 R_i + \alpha_3 C_i.$$  

The relevant literature provides little guidance about the appropriate functional form for the estimated equations. Since it is not obvious which is the appropriate functional form, the equations are estimated in both levels and logs of the relevant variables. As was noted above, models in levels of the variables have the advantage of having a clear physical interpretation, that is, each regression coefficient represents the change in the dependent variable due to a one unit change in the independent variable. Models in logs of the variables have the advantage of being interpretable as elasticities which are dimensionless and can be readily compared across studies, that is, each regression coefficient represents the percentage change in the dependent variable due to a one per cent change in the independent variable.

3. Data and Sample

The data set used in this study is taken from Meybeck et al. [22]. Fifty-nine of the observations in their study have complete data. We use fifty-seven of these fifty-nine observations, with the two observations for the Little Colorado River excluded from this regression analysis because the Little Colorado is dry for much of the year, and it is therefore not a perennial river.

The variables used in regression analysis for this study are sediment yield, river basin area, precipitation runoff, and sediment concentration. Table 1 provides a summary of this data, including definition of the variable, the mean value of the variable, and the standard deviation of the variable.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield (S)</td>
<td>kg·km$^{-2}$·day$^{-1}$</td>
<td>851.1</td>
<td>1,265.1</td>
</tr>
<tr>
<td>Area (A)</td>
<td>km$^2$</td>
<td>139,320</td>
<td>445,650</td>
</tr>
<tr>
<td>Runoff (R)</td>
<td>l·s$^{-1}$·km$^{-2}$</td>
<td>13.1</td>
<td>12.0</td>
</tr>
<tr>
<td>Concentration (C)</td>
<td>mg·l$^{-1}$</td>
<td>1,705.5</td>
<td>3,121.2</td>
</tr>
</tbody>
</table>

Table 2 shows the partial correlations between the variables used in the models. The dependent variable is yield while the independent variables are area, runoff and sediment concentration. The partial correlations present two useful points.

First, the partial correlations between the dependent variable yield and each of the independent variables is consistent with the literature, although as outlined above some studies have found impacts at odds with the bulk of the published literature. An increase in river basin area decreases sediment yield while an increase in precipitation runoff or sediment concentration increases sediment yield.

Second, if the partial correlation between two independent variables is relatively high, the presence of multi-collinearity may make it difficult to obtain accurate estimates of the individual effects of the independent variables on the dependent variable. As a rule of thumb, if the correlation between two independent variables is 0.50 or higher, this may be an indication of multi-collinearity. Since the largest partial correlation is 0.34, there is no evidence that multi-collinearity is a problem.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Yield</th>
<th>Area</th>
<th>Runoff</th>
<th>Concen.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>-0.09</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runoff</td>
<td>0.15</td>
<td>-0.12</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Concen.</td>
<td>0.55</td>
<td>-0.02</td>
<td>-0.34</td>
<td>1.00</td>
</tr>
</tbody>
</table>
4. Determinants of Sediment Flux

The following Table 3 and Table 4 present the results of the regression analysis. The standard errors for the regression coefficients and the significance of the F statistic are shown in parentheses. One, two or three asterisks on the regression coefficient indicate that the regression coefficient is significant at the 10%, 5% or 1% level respectively.

The adjusted R-squared and the F-statistic and the Akaike Information Criteria (AIC) are shown. Looking first at the results in levels in Table 3, based on the F-statistic, Model 1 has no explanatory power, while Model 2, Model 3 and Model 4 are all significant at the 1% level. Looking second at the results in logs in Table 4, Model 5 has no explanatory power, while Model 6, Model 7 and Model 8 are all significant at the 1% level.

### Table 3. Determinants of Suspended Sediment Flux in Levels, White’s OLS Estimates (g/l)

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>250.7***</td>
<td>183.2***</td>
<td>-51.1</td>
<td>-43.7</td>
</tr>
<tr>
<td></td>
<td>(99.3)</td>
<td>(52.7)</td>
<td>(82.5)</td>
<td>(86.7)</td>
</tr>
<tr>
<td>Area</td>
<td>-0.000075</td>
<td>-0.000082</td>
<td>-0.00033</td>
<td>-0.000033</td>
</tr>
<tr>
<td></td>
<td>(.000054)</td>
<td>(.000058)</td>
<td>(.000033)</td>
<td>(.000051)</td>
</tr>
<tr>
<td>Runoff</td>
<td>5.38</td>
<td>-</td>
<td>14.5**</td>
<td>14.4**</td>
</tr>
<tr>
<td></td>
<td>(6.87)</td>
<td></td>
<td>(6.8)</td>
<td>(6.8)</td>
</tr>
<tr>
<td>Concen.</td>
<td>-</td>
<td>0.081***</td>
<td>0.10***</td>
<td>0.10***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.024)</td>
<td>(0.027)</td>
<td>(0.027)</td>
</tr>
<tr>
<td>Adj. R²</td>
<td>0.00</td>
<td>0.29</td>
<td>0.41</td>
<td>0.40</td>
</tr>
<tr>
<td>F</td>
<td>0.76</td>
<td>12.2</td>
<td>20.5</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>(0.47)</td>
<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
</tr>
<tr>
<td>AIC</td>
<td>12.3</td>
<td>12.0</td>
<td>11.8</td>
<td>11.8</td>
</tr>
</tbody>
</table>

Note. Standard errors for the regression coefficients and the probability for F are shown in parentheses. One, two or three asterisks means that the regression coefficient is significant at the 10%, 5% or 1% level respectively.

Model 1 includes a constant, an area input variable, and a precipitation runoff input variable, with neither input variable significant. This equation says that an increase in area of one square kilometre reduces sediment flux by 0.000075 kg per square metre per day, while an increase in runoff of 1 litre per square kilometre per second increases sediment flux by 5.38 kg per square kilometre per day.

Model 2 includes a constant, an area input variable, and a sediment concentration input variable, with the area variable not significant and the sediment concentration variable significant. This equation says that an increase in area of one square kilometre reduces sediment flux by 0.000082 kg per square metre per day, while an increase in sediment concentration of 1 milligram per litre increases sediment flux by 0.081 kg per square kilometre per day.

Model 3 includes a constant, a precipitation runoff input variable, and a sediment concentration variable, with both variables significant. This equation says that an increase in runoff of a litre per square metre per day increases sediment flux by 14.5 kg per square metre per day, while an increase in sediment concentration of 1 milligram per litre increases sediment flux by 0.10 kg per square kilometre per day.

Model 4 includes a constant, an area input variable, a precipitation runoff input variable, and a sediment concentration input variable, with the area variable not significant and the precipitation runoff and segment concentration variables significant. This equation says that an increase in area of one square kilometre reduces sediment flux by 0.000033 kg per square metre per day, while an increase in runoff of 1 litre per square kilometre per second increases sediment flux by 14.4 kg per square kilometre per day and an increase of sediment concentration of 1 milligram per litre increases sediment flux by 0.10 kg per square kilometre per day.

### Table 4. Determinants of Suspended Sediment Flux in Logs, White’s OLS Estimates (log g/l)

<table>
<thead>
<tr>
<th></th>
<th>Model 5</th>
<th>Model 6</th>
<th>Model 7</th>
<th>Model 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>4.92***</td>
<td>0.68</td>
<td>-3.51***</td>
<td>-3.52***</td>
</tr>
<tr>
<td></td>
<td>(1.08)</td>
<td>(0.60)</td>
<td>(0.033)</td>
<td>(0.031)</td>
</tr>
<tr>
<td>Larea</td>
<td>-0.11</td>
<td>-0.078*</td>
<td>-</td>
<td>0.00016</td>
</tr>
<tr>
<td></td>
<td>(0.092)</td>
<td>(0.042)</td>
<td></td>
<td>(0.0018)</td>
</tr>
<tr>
<td>Lrunoff</td>
<td>0.26</td>
<td>-</td>
<td>1.02***</td>
<td>1.07***</td>
</tr>
<tr>
<td></td>
<td>(0.21)</td>
<td></td>
<td>(0.016)</td>
<td>(0.016)</td>
</tr>
<tr>
<td>Lconcen</td>
<td>-</td>
<td>0.77***</td>
<td>1.00***</td>
<td>1.00***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.064)</td>
<td>(0.034)</td>
<td>(0.034)</td>
</tr>
<tr>
<td>Adj. R²</td>
<td>0.02</td>
<td>0.70</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>F</td>
<td>1.58</td>
<td>66.7</td>
<td>27.126</td>
<td>17.750</td>
</tr>
<tr>
<td></td>
<td>(0.22)</td>
<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
</tr>
<tr>
<td>AIC</td>
<td>1.3</td>
<td>0.1</td>
<td>-5.6</td>
<td>-5.5</td>
</tr>
</tbody>
</table>

Note. Standard errors for the regression coefficients and the probability for F are shown in parentheses. One, two or three asterisks means that the regression coefficient is significant at the 10%, 5% or 1% level respectively.

Model 5 includes a constant, a log area input variable, and a log precipitation runoff input variable, with neither input variable significant. This equation says that an increase in area of one per cent reduces sediment flux by 0.11 per cent, while an increase in runoff of 1 per cent increases sediment flux by 0.26 per cent.

Model 6 includes a constant, a log area input variable, and a log sediment concentration input variable, with the log area variable and the log sediment concentration variable significant. This equation says that a one per cent increase in area reduces sediment flux by 0.078 per cent, while an increase in sediment concentration of 1 per cent increases sediment flux by 0.77 per cent.

Model 7 includes a constant, a log precipitation runoff input variable, and a log sediment concentration variable, with both variables significant. This equation says that an increase in runoff of one per cent increases sediment flux by 1.02 per cent, while an increase in
sediment concentration of 1 per cent increases sediment flux by 1.00 per cent.

Model 8 includes a constant, a log area input variable, a log precipitation runoff input variable, and a log sediment concentration input variable, with the log area variable not significant and the log precipitation runoff and log segment concentration variables significant. This equation says that an increase in area of one per cent increase sediment flux by 0.00016 per cent, while an increase in runoff of 1 per cent increases sediment flux by 1.02 per cent and an increase of sediment concentration of 1 per cent increases sediment flux by 1.00 per cent.

AIC is a model selection criteria based on the log likelihood of the model penalized by the number of variables in the regression. A smaller value of AIC indicates that the regression is preferred. Model 3 is preferred in Table 3, and Model 7 is preferred in Table 4.

5. Discussion

Since the 1970s, there has been increased interest in modelling the determinants of suspended sediment loads in rivers. The reasons for this interest include a wide range of scientific, environmental and economic issues including: trends in soil erosion and nutrient availability; trends in water supply and water quality; transport and dispersion of contaminants; and channel, reservoir, and harbor siltation (Walling [23], Ferguson [24], de Vries and Klavars [25] and Horowitz [26]).

A key relationship is that between water supply, represented either by precipitation or precipitation runoff, and sediment flux. Several studies have used regression models to examine the impact of precipitation on sediment flux, and it is useful to compare the results of this previous work with the current study.

Table 5 summarizes some key features of the studies including the author(s), the climate zones(s) or rock type(s) covered by the study, the outcome variable, the precipitation driver, the regression coefficient on the precipitation driver, and R-squared. It is worth noting that with the exception of the present study, the regression models used in previous work did not correct for heteroscedasticity in the residuals.

<table>
<thead>
<tr>
<th>Study</th>
<th>Type</th>
<th>Outcome variable</th>
<th>Driver</th>
<th>Coeff.</th>
<th>R-sq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jansen [27]</td>
<td>All climates</td>
<td>Lyield</td>
<td>Lrainfall</td>
<td>1.10</td>
<td>0.58</td>
</tr>
<tr>
<td>Probst [28]</td>
<td>All climates</td>
<td>Lyield</td>
<td>Lrunoff</td>
<td>0.69</td>
<td>NA</td>
</tr>
<tr>
<td>Probst [29]</td>
<td>Weekly cohesive rocks</td>
<td>Lyield</td>
<td>Lrunoff</td>
<td>1.99</td>
<td>0.83</td>
</tr>
<tr>
<td>Probst [29]</td>
<td>Average cohesive rocks</td>
<td>Lyield</td>
<td>Lrunoff</td>
<td>1.44</td>
<td>0.32</td>
</tr>
<tr>
<td>Probst [29]</td>
<td>Highly cohesive rocks</td>
<td>Lyield</td>
<td>Lrunoff</td>
<td>1.16</td>
<td>0.44</td>
</tr>
<tr>
<td>Ludwig [30]</td>
<td>Tundra and taiga</td>
<td>Yield</td>
<td>Runoff</td>
<td>0.22</td>
<td>0.65</td>
</tr>
<tr>
<td>Ludwig [30]</td>
<td>Temperate wet</td>
<td>Yield</td>
<td>Runoff</td>
<td>0.38</td>
<td>0.49</td>
</tr>
<tr>
<td>Ludwig [30]</td>
<td>Tropical wet</td>
<td>Yield</td>
<td>Runoff</td>
<td>0.83</td>
<td>0.87</td>
</tr>
<tr>
<td>Ludwig [30]</td>
<td>Dry climates</td>
<td>Yield</td>
<td>Runoff</td>
<td>1.18</td>
<td>0.80</td>
</tr>
<tr>
<td>Syvitski [31]</td>
<td>Polar</td>
<td>Lyield</td>
<td>Lrunoff</td>
<td>0.55</td>
<td>0.78</td>
</tr>
<tr>
<td>Syvitski [31]</td>
<td>Temperate North</td>
<td>Lyield</td>
<td>Lrunoff</td>
<td>0.53</td>
<td>0.49</td>
</tr>
<tr>
<td>Syvitski [31]</td>
<td>Tropics North</td>
<td>Lyield</td>
<td>Lrunoff</td>
<td>0.45</td>
<td>0.54</td>
</tr>
<tr>
<td>Syvitski [31]</td>
<td>Tropics South</td>
<td>Lyield</td>
<td>Lrunoff</td>
<td>0.65</td>
<td>0.76</td>
</tr>
<tr>
<td>Syvitski [13]</td>
<td>All climates</td>
<td>Lyield</td>
<td>Lrunoff</td>
<td>0.31</td>
<td>0.95</td>
</tr>
<tr>
<td>This study</td>
<td>All climates</td>
<td>Lyield</td>
<td>Lrunoff</td>
<td>1.02</td>
<td>0.99</td>
</tr>
</tbody>
</table>

6. Conclusion

Understanding the evolution of erosion and deposition within a fluvial system has implications for river channel development, estuary growth or decline, flood mitigation and fluvial management. This study provides an analysis of the determinants of sediment fluxes or yields for a representative set of 57 of the world’s major rivers. To facilitate comparison across river systems, sediment flux or yield is expressed in normalized form as kg·km⁻²·day⁻¹.

The statistical framework employed is based on previous research, and it uses White’s OLS estimator to deal with the heteroscedasticity present in the initial OLS regressions. This study has three main findings.

First, suspended sediment flux yields are strongly driven by precipitation runoff. Using the models in levels of variables, an increase in runoff of 1 litre per square kilometre per second increases sediment flux by 14.4 kg
per square kilometre per day. Using the models in logs of variables, an increase in runoff of 1 per cent increases sediment flux by 1.02 per cent.

Second, suspended sediment flux yields are strongly driven by sediment concentration. Using the models in levels of variables, an increase of sediment concentration of 1 milligram per litre increases sediment flux by 0.10 kg per square kilometre per day. Using the models in logs of variables, an increase of sediment concentration of 1 per cent increases sediment flux by 1.00 per cent.

Third, suspended sediment levels are weakly driven by basin size. Using the models in levels of variables, an increase in area of one square kilometre reduces sediment flux by 0.000033 kg per square metre per day. Using the models in logs of variables, an increase in area of one per cent increase sediment flux by 0.00016 per cent.

References


