Impact of Humans on the Flux of Terrestrial Sediment to the Global Coastal Ocean

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One Sentence Summary: A new GIS modeling system quantifies the significant impact of human modification of the delivery of sediment to our world's coastlines.

Abstract

Global predictions are provided on the terrestrial flux of sediment, on a river-by-river basis, under Modern and pre-Anthropocene conditions. Sediment delivery is influenced by basin characteristics, regional climate, and reservoirs. Pre-Anthropocene sediment flux was likely 15.5 BT/yr. Human activities have increased fluvial sediment erosion by 2.3 BT/yr. Modern delivery of sediment is presently 12.6 BT/yr, due to an estimated trapping of 100 BT of sediment behind reservoirs. Africa and Asia have greatly reduced sediment loads, Indonesia now delivers much more sediment. Seasonal patterns of sediment delivery are conditioned by precipitation patterns, snow-release periods, and human-influenced water release from reservoirs.

Introduction

Coastal retreat is a major concern to human habitat, with >37% (2.1B in 1994) of the world’s population living within 100km of a coastline and approximately 44% live within 150km of a coastline (1). Coastal retreat is directly impacted by the reduction of river-supplied sediment (2). Thus a goal of the International Geosphere Biosphere Program (IGBP) and its core program Land Ocean Interaction in the Coastal Zone (LOICZ) has been a survey of terrestrial sediment supply to the coast along with an analysis of human perturbation of this flux (3). Changes in the flux can greatly impact the benthic
environment of coastal estuaries (4), coral reefs (5), and sea grass communities (6). In addition, nutrient fluxes, particularly carbon, are intimately tied to the flux of sediment (7), with implications to coastal fisheries (8). Sediment delivery will also impact harbor maintenance, and the burial potential for pollutants (9).

Yet even with such environmental importance, <10% of the world-rivers have been monitored for their sediment delivery to the coastal zone, or have observational data available to researchers (3). Of the monitored rivers, most have had their sediment-gauging activities terminated (3). To address this paucity data, we provide a globally consistent method for the estimation of the sediment flux near river mouths. We combine databases and models to determine the pre-Anthropocene and Modern delivery rate of sediment to the coast, including seasonal attributes, on a river-by-river global basis.

Global River Discharge

The Simulated Topological Network (STN-30p) for potential river flow paths (10) provides the spatial framework for organizing environmental data into distinct river basins. STN-30p is comprised of ≈60,000 grid cells at 30' spatial resolution for the continental land mass. These cells define 6292 river basins with drainage areas >10^2 km^2. 4464 of these basins are not covered by ice sheets of the Antarctica, Greenland and portions of the Canadian Archipelago, have a positive discharge to the ocean/sea, and are analyzed in this paper. STN-30p catchment areas have a 7.5% absolute error with a 2% positive bias (11).

The UNH Water Balance and Transport Model (WBTM) based on the STN-30p network provides a fundamental structure for analyzing sediment flux distribution by river basin, continent, climatic zone and receiving ocean or sea. The WBTM runoff (R) is based on climate data fields according the following mass balance:

\[ R = P - E - \left( \frac{\partial W}{\partial t} \right) \]

(1)
Where P is precipitation, E is evapotranspiration, and $\partial W/\partial t$ is the change in soil moisture. The monthly climate fields are derived from 30' gridded data (12). The UNH-WBTM uses a modified Penman-Monteith formula (13) for Potential EvapoTranspiration, and the Thornthwaite soil moisture budget (14). Quasi-daily time steps are used to reduce the temporal aggregation bias arising from monthly climatic values (15). Soil and vegetation characteristics are used in the characterization of evapotranspiration and soil moisture release are based on the FAO/UNESCO soil data bank (11), and the Olson Terrestrial Ecosystem Model (16).

UNH-WBTM estimates of discharge are constrained by observed hydrographic data (17, 11). Selected (663) gauging stations from the GRDC archive were co-registered to the STN-30p network, and represent 76 Mkm$^2$ (72%) of the world's actively discharging landmass. The accuracy of GRDC discharge measurements is $\approx$10-20%, much higher than what can be achieved from measuring precipitation (18). Differences between station data and simulated WBTM discharge estimates derived from modern climatology were used to develop correction factors, and then revised to account for human-induced losses of water within basins due to inter-basin water diversions, or harvested crops transported out of the basin, estimated to be 6% of the global discharge total of 40,000 km$^3$/yr (19). The resulting composite discharge field is a mix of observed discharge and WBTM simulations where observations are not available, at a 0.5° x 0.5° resolution for monthly climatology.

**Global Pre-Anthropocene Sediment Flux**

To predict the long-term fluvial discharge of sediment to the world's coastal zone, we use a Drainage Basin Flux Model (DBFM), based on relief, drainage area, or averaged discharge, and basin-distributed temperature (20). Unique solutions for each of the major hemispheric climate regions (polar, temperate and tropic), predict the flux of suspended sediment to within the uncertainties associated with global observations. Observational uncertainties can be large, and may range from a factor of two for estimates for well-
monitored rivers, to an-order-of-magnitude for poorly monitored rivers, if important transport events are not captured (20, 21). Measured loads may also be biased if observations fall largely within a single “climate” period: variations in loads between wet and dry intervals of the Pacific/North American climate pattern may vary by a factor of five (22).

To determine the Pre-Anthropocene sediment load of global rivers, we employ the ART version of the INSTAAR-DBTM model (Syvitski et al. 2003), where:

$$Q_s = \alpha_1 A^{\alpha_2} R^{\alpha_3} e^{kT}$$

(2)

$Q_s$ is the long-term sediment flux, $A$ is catchment area, $R$ is maximum basin relief, $T$ is surface temperature averaged across the drainage basin, and $\alpha$’s are empirical coefficients defining major climate zones (20). While the importance of basin area and relief on a river’s sediment load is long accepted (23), [2] incorporates temperature in a secondary role (Note: to overcome recently discovered bias in [2], $e^{kT}=0$ for large tropical basins such as the Amazon). Basin temperature controls polar feedbacks (frozen soils and river beds, snow and ice-melt, predominance of frontal rainfall), temperate feedbacks (spring snowmelt, freeze-thaw cycles, mix of frontal and convective rainfall), and tropical feedbacks (convective rainfall, monsoons, typhoons, chemical weathering and soil formation, tropical canopy, high lapse rates).

The use of the ART model as a pre-Anthropocene estimator of global sediment loads is based on the following considerations. The model was trained on a global database on 340 rivers that cover 70% of the hydrologically-active landmass and includes a majority of rivers either in pristine form, or measurements made before the dominating impact of humans (before sediment sequestering in reservoirs, or increased sediment production from disturbance). Rivers in the database that showed large impact from humans always fell off the line of regression between observation and prediction (20). Based on a smaller database of 145 major rivers (24), monitored across the 20th century, 48% of the
rivers showed little change in their historical sediment loads, 47% showed decreasing loads due to impoundments, and 5% showed increased sediment loads due to disturbance. Walling and Fan (24) note that rivers showing little change in flux may "point to a lack of environmental change within the associated drainage basin, or at least a lack of sensitivity to ongoing changes, [or] ... are buffered by the longer-term storage and remobilization of sediment within the upstream basin, associated with a relatively low sediment delivery ratio."

To test the appropriateness of employing the ART model as a pre-Anthropocene estimator of sediment flux, six to seven rivers from each climatic zone (polar <0°C, cold-temperate 0-10°C, warm-temperate 10-25°C, tropical >25°C) were selected to be representative (small to large area, low to high relief) and be either pristine (largely unregulated) or have observations collected before major human disturbance (Fig. 1): for most rivers the anthropogenic footprint increases sharply after WWII (22). The ART model shows no systematic bias and provides flux predictions within ±25% for these pristine or once pristine rivers. Because the ART model, as applied here, does not take into account variability in geology, the model is not a good estimator everywhere, but the ensemble estimate of landscape erosion before human influence should be reasonable.

Table 1 provides the Pre-Anthropocene fluxes of sediment load as differentiated by landmass, ocean basin or sea, climate zone, and elevation class. The global flux of suspended sediment is 14BT/yr, or 15.5BT/yr when a bedload estimate is included. Asia is the largest producer of fluvial sediment followed by the Americas. The highest sediment yield (load divided by area) is from Indonesia and Oceania, both of which receive the highest hydrological runoff (discharge divided by area). The lowest sediment yield is from the polar terrain draining into the Arctic Ocean. Warm temperate regions have the highest sediment yield compared to other climates and accounts for nearly 2/3 of global sediment delivery. Close to 60% of global sediment delivery to the coastal zone is derived from basins draining high mountains (>3000 m).
Global Modern Sediment Flux

With the increase in human activities, much has changed in terms of sediment delivery, with variances in both directions \((24, 25)\). Changes in surface runoff affect the transport agent of the fluvial load, and include aquifer mining, surface water diversion, volume changes of inland lakes, desertification, wetland drainage, soil reservoir storage, deforestation and dam building \((19)\). While these changes are almost in balance, with \(1.41 \text{ Mkm}^3\) in increased runoff balanced by water retention behind artificial impoundments of \(1.40 \text{ Mkm}^3\), the global pattern sees large regional differences \((19)\).

Reservoir operations also impact the timing of runoff, for example winter release for hydroelectric power generation, and summer release for agricultural purposes, in differences to the more normal spring and fall wet periods in the temperate regions of the world. To address these contemporary issues, we use the GRDC-UNH/WBTM composite discharge fields that define the modern Anthropocene world.

In addition to human impacts on global runoff, there are many anthropogenic influences on global sediment yield, including urbanization, deforestation, agricultural practices, mining, and retention by reservoirs. These changes can affect both small river systems, where human activities can over-whelm pristine conditions, and large systems such as the Mississippi, Colorado, Yellow and the Nile \((3, 24, 25)\). The magnitude of the composite anthropogenic effect is a moving target. For example, historic land use and sediment discharge response have come full circle for the eastern seaboard of the USA where peak fluxes occurred along with 18th century deforestation, but have returned to back-ground conditions through reservoir construction \((26)\).

To model the Anthropocene period, we merge observations \((1960-1995)\) on sediment loads of rivers that drain 70% of the land surface, and “QRT” predictions \((20)\) for basins with missing observations. The QRT model is similar to the ART model in development, bias and accuracy, and likewise could be considered to represent pre-Anthropocene
values. However the QRT model employs discharge rather than basin area, and is thus able to incorporate changes in runoff due to humans, with:

\[
\overline{Q}_i = \alpha_6 \overline{Q}^\alpha_i R^\alpha_i e^{\beta T} \tag{3}
\]

Where \( \overline{Q} \) is the composite GRDC/UNH-WBTM human-influenced discharge, and \( \alpha \)'s defining major climate zones with \( \alpha_6 \) able to account for trapping of sediment in reservoirs (27). The load database includes both pre-dam and post-dam values of sediment load (see Fig. 1 for reservoir influence on the Ebro, Orange and Nile Rivers), and estimates of sediment trapping from both large and small reservoirs for the ungauged rivers (27).

Figure 2 shows the human impact on the natural sediment load estimates, using 217 global rivers with good observational data (pre/post dam). When pre-dam values are examined, the analysis indicates that rivers are globally getting dirtier and would otherwise move more sediment to the coast if not for the impact of reservoirs. Two curves factoring out reservoir trapping are provided: one with, and one without Yellow River (Huang He) loads. The Yellow is an example of a river's sediment load being a moving target. In the 1950-1977 period, the Yellow River had a load of 1.6 BT/yr, largely related to poor farming practices on the loess plateau (23). Since the 1980's, the sediment load of the Yellow has dropped to <50% of this earlier period due to a reduced hinterland precipitation, increased water abstraction, and improved sediment control practices in the loess region (24). Other curves in Figure 2 show the impact of sediment impoundment behind reservoirs. One curve demonstrates the basin-wide trapping of suspended sediment flux by the large (>15m deep) reservoirs that account for about 70% of the impoundment storage volume filed with the International Commission on World Registry of Dams (27). Another curve highlights the impact of the millions of smaller reservoirs that have much lower trapping efficiencies due to their size but still significantly decrease the flux of sediment to the coast due to their number.
The global "modern" sediment flux is calculated to be 12.6 BT/yr, or 10% less than the "pre-Anthropocene load" (Table 1). Given that reservoirs trap 20% of the global sediment flux by large reservoirs, or 26% including small reservoirs (Table 1), then in a modern world without reservoirs the global annual flux would be \((0.26 \times 14\text{BT} + 12.6\text{BT})\) 16.2 BT of suspended sediment, or 17.8 BT including bedload. This value is smaller than the 20 BT/yr estimated by Milliman and Syvitski (23) who included a larger landmass in their analysis (i.e. the glaciated Arctic), and did not undertake a basin-by-basin upscaling of their missing data.

Africa and Asia see the largest reduction in sediment flux to the coast (Table 1, Fig. 3), highlighting the Nile, Orange, Niger, and Zambezi in Africa, and Chang Jiang, Indus, and Huang He in Asia. Inland seas, the Mediterranean and the Black, are the bodies of water most affected by reservoirs (Table 1) (2). The cold temperate zone encompasses the industrialized countries where power consumption is highest, and host reservoirs that trap 47% of the regional sediment flux. As expected, mountain-draining rivers show decreased sediment fluxes on average, due to the proliferation of impoundments (Table 1), in contrast to non-mountainous drainage basins where sediment flux has increased (Table 1, Fig. 3) (28). The tropics in general and Indonesia in particular, are the regions most influenced by increased sediment loads (Table 1, Fig. 3), largely due to deforestation (29).

**Global Modern Seasonal Sediment Flux**

To predict sediment discharge at the dynamic (daily) level, Morehead et al. (30) recast the classic rating curve \(Q_{S(i)} = aQ_{(i)}^{C}\), where \(Q_{S(i)}\) is instantaneous sediment load, \(Q_{(i)}\) is instantaneous discharge, \(a\) and \(C\) are the rating coefficients) in a non-dimensional form (the PSI model) to account for inter-daily and inter-annual variability:

\[
\left(\frac{Q_{S(i)}}{Q_s}\right) = \psi_{(i)}F\left(\frac{Q_{(i)}}{Q}\right)^{C_a}
\]

(4)
ψ_{(i)} \text{ is intra-daily deviation from the rating curve related to flood dynamics and variable sediment sources and } E(ψ)=1, \sigma(ψ)=f(\overline{Q}), \ C_0 \text{ is the annually-variable rating coefficient and } E(C)=f(T,R,\overline{Q}_s), \ \sigma(C)=f(\overline{Q}) (31), \text{ and } F \text{ is a constant of proportionality. The PSI model has successfully captured the behavior of both large and small rivers, e.g. rain-dominated Eel, CA (32), ice-melt dominated Kliniklini, BC (30), cyclone-dominated Lanyang, Taiwan (33), agricultural Po, Italy (34), and snowmelt Liard River (31).}

To apply the PSI model [4] to global rivers, we use the Anthropocene values of monthly discharge from the GRDC/UNH-WBTM time series (1960-1995), and the merged observations/QRT-simulations of long-term sediment load (e.g. Fig. 3). Figure 4 shows details of the result when applied to three type rivers. Monthly averages of the modeled discharge compare well with measured values and lie within the observed inter-annual variability. The Po is an exception and highlights the coarseness of the STN-30p grid not able to separate two adjoining river basins (Po and the Adige, see Note 1 on Fig. 4). As a consequence, modeled discharge is larger than observations for the Po alone. Modeled monthly averages of suspended load compare well for many rivers (e.g. Fraser, Fig. 4), but show deviations for strongly impacted rivers: 1) For the Mississippi, the modeled load is over-predicted in the spring and under-predicted in the fall as the full impact of the basin's 65,000 reservoirs is not adequately captured (Note 2 on Fig. 4); and 2) For the Po, the modeled load does not capture the 2-D effect of different water sources: relatively clean water released from large Alpine reservoirs during winter months compared to the unfiltered Apennine load (Note 3 on Fig. 4). These variances are clearly seen on the time series of sediment discharge (Note 4 on Fig. 4). Below seasonal averages were calculated to reduce these within-month variances.

To calculate the global seasonal sediment load, we apply the composite observation/WBTM-QRT-PSI model to produce global monthly averages of sediment loads. The monthly values are summed across March-May (MAM), June-August (JJA), September-November (SON) and December-February (DJF) to produce the seasonal
values (Table 1, Figure 5). The effect of geographic asymmetry of the world's landmass is superimposed on the patterns of the monsoonal discharge (i.e. Dec-Apr in the southern tropics vs. Jun-Oct in the northern tropics), temperate discharge (winter/spring rain and snowmelt), and arctic discharge (summer rain mixed with snow and ice melt) (Fig. 5). Table 1 presents which coasts are dominated by highly-seasonal fluxes of sediment and those that receive more constant albeit episodic flux of material. Rivers affected by monsoons are highly seasonal in their sediment fluxes (e.g. Indonesia, Asia). Figure 5 also highlights the east coast of the Americas, where flux patterns show similarity to global seasonal patterns, but also deviations that reflect the size distribution of drainage basins in relation to mountain chains and climate zones. As expected the Arctic Ocean, Polar region, and rivers draining high mountains demonstrate the largest seasonality in their sediment flux (Table 1).

Summary
This study provides the first attempt to predict the global flux of sediment on a river-by-river basis (4462 rivers >100 km²) under Modern conditions, and before human influence (Pre-Anthropocene). The method allows global hotspots to be located on a 0.5° grid of the global coast. These hotspots of high or modified sediment flux should allow land-atmosphere models to be better calibrated. Humans are simultaneously increasing the river transport of sediment through soil erosion activities, while decreasing this flux to the coastal zone through sediment retention in reservoirs. The net result is a global reduction in sediment flux by about 1.4BT/yr over pre-Anthropocene loads. This impact on coastal erosion will be further accelerated as sea level rises, as anticipated by human-induced climate change (35). Given the time history of dam construction (27), and the increase in fluvial sediment loads, then over 100 BT of sediment including carbon (≈1 to 3%) is being sequestered behind man-made reservoirs. Where reservoir construction remains limited, such as in Indonesia, then much of the "extra" sediment production and transported carbon is being buried on the surrounding continental margins. The seasonal pattern in the global delivery of sediment to the coast is displayed for the first time and as
a valuable aid to those investigating the dynamics of nutrient fluxes to the coast, and those monitoring coastal fisheries, coral reefs and sea grass communities.

Future improvements include use of a finer grid (i.e. 1km$^2$) to address problems associated with smaller rivers (e.g. Po Fig. 4), and allow for the contribution of rivers of <100 km$^2$ to be assessed. By including water routing in the modeling scheme, large-river discharge hysteresis could be addressed. By including within-basin variability in sediment yield sediment hysteresis could be effectively studied. To accomplish these advances, higher resolution grids must be obtained for precipitation, temperature, soil type, vegetation and population and the geo-location of small reservoirs.

References
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29. D. Hu, Y. Saito, S. Kempe, in *Asian Change in the Context of Global Climate Change: Impact of Natural and Anthropogenic Changes in Asia on Global*


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<table>
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<th>Discharge km³/yr</th>
<th>Pre-Anthro Qs MT/yr</th>
<th>Modern Qs DJF MT/yr</th>
<th>Modern Qs MAM MT/yr</th>
<th>Modern Qs JJA MT/yr</th>
<th>Modern Qs SON MT/yr</th>
<th>Modern Qs Total MT/yr</th>
<th>Retention in Reservoirs</th>
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<td>225</td>
<td>174</td>
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<td>888</td>
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<td>200</td>
<td>41</td>
<td>32</td>
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<td>640</td>
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<td>1454</td>
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<td>505</td>
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<td>1,328</td>
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<td>216</td>
<td>522</td>
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| Elevation Class |                   |                  |                     |                     |                     |                     |                     |                       |                         |
| High Mountain >5000m | 21 | 12,499          | 5,116               | 439                 | 753                 | 1799                | 1107                | 4,098                 | 31%                     |
| Mountain 3000-5000m | 30 | 6,415           | 2,970               | 440                 | 607                 | 673                 | 468                 | 2,188                 | 22%                     |
| Low Mtn. 1000-3000m | 36 | 12,794          | 4,674               | 970                 | 1119                | 1486                | 1223                | 4,799                 | 12%                     |
| Upland 500-1000m | 10                | 3,668            | 905                 | 256                 | 257                 | 299                 | 247                 | 1,061                 | 4%                      |
| Lowland 100-500m | 8                 | 2,556            | 332                 | 77                  | 122                 | 96                  | 70                  | 364                   | 2%                      |
| Coastal Plain <100m | 1 | 602             | 33                  | 27                  | 40                  | 20                  | 13                  | 100                   | 0%                      |

| Global       | 106               | 38,537           | 14,029              | 2,208               | 2,899               | 4,372               | 3,129               | 12,608                 | 20%                     |

**Area:** hydrologic-active drainage area with runoff > 3 mm/yr

**Discharge:** 35 yr mean using the GRDC-WBTM method to determine composite runoff

**Pre-Anthropocene Qs:** ART model predictions for determining a river's long-term sediment load

**Modern Qs:** observed sediment loads where available (70% of global drainage), and QRT model predictions for the remaining 30% of world drainage with sediment retention in large reservoirs taken into account.

**Retention in Reservoirs:** sediment flux trapped behind large reservoirs as percent of modern flux. Trapping in small reservoirs increases regional trapping by another 30%, i.e. global trapping of 20% would increase to 26%.
Figure 1 Comparing sediment loads observations with ART model predictions (20) for selected pristine (largely unregulated) rivers (e.g. South, Colville, Indigirka, Pyasina, Squamish, Kuskowin, Mae Klong, Orinoco), or rivers with observations before major human impacts (e.g., compare post-dam values of Ebro, Nile, Orange with pre-dam values). Data are from (20). Largest difference between predictions and observations is 63% (Negro). Errors associated with observational data are of the same magnitude as those associated with predictions.
Figure 2: Comparison between Pre-Anthropocene (Fig. 1) and Modern sediment loads, using 217 global rivers with good observational pre/post-dam data. Data is presented as cumulative curves ranked by decreasing river discharge (e.g. first value to left is the Amazon). 1:1 line represents no impact by humans. Two curves (with/without Yellow River) had trapping by reservoirs removed and represents the increased sediment yield due to human activity (e.g. deforestation). Two other curves show the impact of sediment sequestering in large or small reservoirs. Inserts include the global geography of basin-wide trapping of sediment by large reservoirs (27).
Figure 3. **Top:** Global distribution of Pre-Anthropocene sediment flux based on ART model (20) predictions (Fig. 1). **Bottom:** Differences between Pre-Anthropocene and modern sediment load (observations merged with QRT model predictions accounting for anthropogenic impacts) (Fig. 2).
Fig. 4 Observed and modeled monthly discharge and sediment load for three type rivers that highlight model capabilities and problems (see text for discussion on “notes”). Horizontal panels represent three rivers: Top 3,220,000 km$^2$ Mississippi, USA; Middle 220,000 km$^2$ Fraser, Canada; Bottom 77,000 km$^2$ Po, Italy. **Left Panels:** Observed water discharge with 35yr mean ± 1 standard deviation (dashed lines) and the composite WBTM discharge values. **Middle Panels:** Observed sediment discharge with 35yr mean ± 1 standard deviation (dashed lines) and QRT-PSI model predictions. **Right Panels:** Time series of observed monthly sediment load, and QRT-PSI predictions.
Figure 5: Modern seasonal sediment load for global rivers. **Left:** Seasonal flux as percent of annual flux for rivers draining from the Americas into the Atlantic Ocean: green for March-May; red for June-August; yellow for September-November; blue for December-October. Superimposed is the annual flux averaged across 1° of latitude, with major rivers that contribute to hot spots of sediment discharge. **Right:** Seasonal flux to worlds coastal zone, as percent of annual flux. Superimposed is the annual flux as percent of global total, averaged across 1° of latitude, with major rivers that contribute to hot spots of sediment discharge.