The Irrawaddy River Sediment Flux to the Indian Ocean: The Original Nineteenth-Century Data Revisited

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ABSTRACT

The Irrawaddy (Ayeyarwady) River of Myanmar is ranked as having the fifth-largest suspended load and the fourth-highest total dissolved load of the world's rivers, and the combined Irrawaddy and Salween (Thanlwin) system is regarded as contributing 20% of the total flux of material from the Himalayan-Tibetan orogen. The estimates for the Irrawaddy are taken from published quotations of a nineteenth-century data set, and there are no available published data for the Myanmar reaches of the Salween. Apart from our own field studies in 2005 and 2006, no recent research documenting the sediment load of these important large rivers has been conducted, although their contribution to biogeochemical cycles and ocean geochemistry is clearly significant. We present a reanalysis of the Irrawaddy data from the original 550-page report of Gordon covering 10 yr of discharge (1869–1879) and 1 yr of sediment concentration measurements (1877–1878). We describe Gordon's methodologies, evaluate his measurements and calculations and the adjustments he made to his data set, and present our revised interpretation of nineteenth-century discharge and sediment load with an estimate of uncertainty. The 10-yr average of annual suspended sediment load currently cited in the literature is assessed as being underestimated by 27% on the basis of our sediment rating curve of the nineteenth-century data. On the basis of our sampling of suspended load, the nineteenth-century concentrations are interpreted to be missing about 18% of their total mass, which is the proportion of sediment recovered by a 0.45-μm filter. The new annual Irrawaddy suspended sediment load is 364 ± 60 MT. Our revised estimate of the annual sediment load from the Irrawaddy-Salween system for the nineteenth century (600 MT) represents more than half the present-day Ganges-Brahmaputra flux to the Indian Ocean. Since major Chinese rivers have reduced their load due to damming, the Irrawaddy is likely the third-largest contributor of sediment load in the world.

Introduction

The eastern syntaxis of the Himalayas and the Tibetan Plateau contains the most tectonically complex geology in Asia (Socquet and Pubellier 2005). This region is drained by the Red, Mekong, Salween, Irrawaddy, Ganges, and Brahmaputra rivers, and two of these systems, the Ganges-Brahmaputra (G-B) and the Irrawaddy-Salween (I-S), debouch into the Indian Ocean. We consider the Irrawaddy and Salween with the Sittoung and four smaller rivers together because their catchments are adjacent and both flow into the Gulf of Martaban (fig. 1) along a similar length of coastline to the G-B river system. The headwaters of the I-S are undergoing some of the highest rates of landscape adjustment in a region of active orogenesis (Zeitler et al. 2001).

Collision, uplift, and shear zone development since the early Tertiary have resulted in a complex pattern of river capture involving the Irrawaddy, Salween, Red, Yangtze, Mekong, and Brahmaputra rivers (Clark et al. 2004). These large rivers deliver material from the Himalayas to the ocean, and

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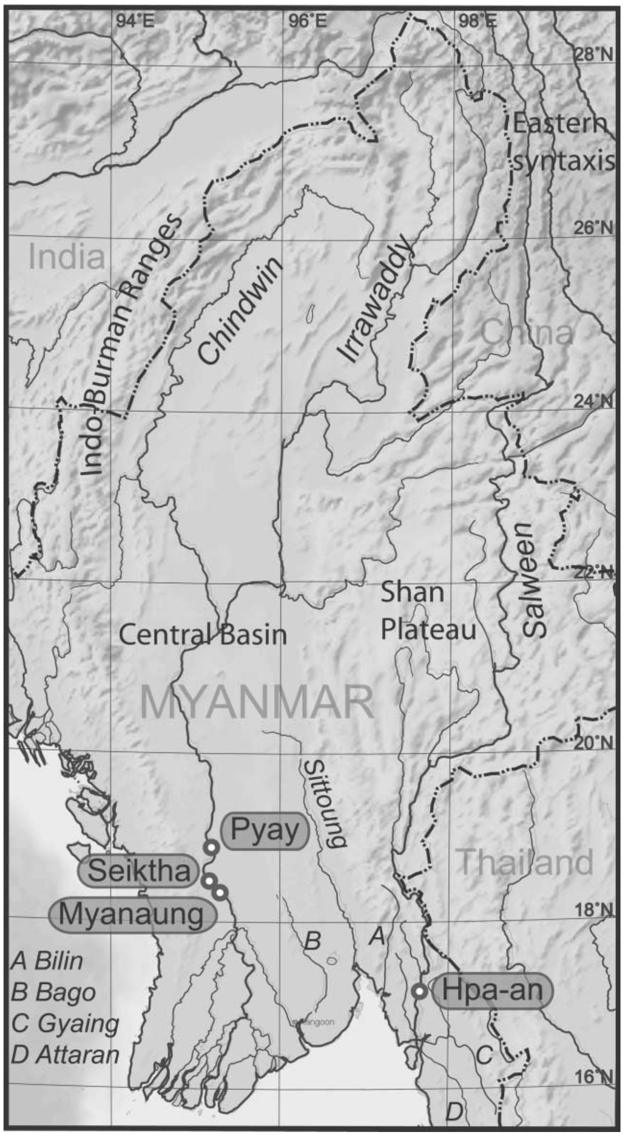


Figure 1. Location of the original Irrawaddy study site of Gordon (1879–1880, 1885) at Seiktha and the rivers included in this article. Our measurement sites for modern discharge and material fluxes are at Seiktha and Pyay on the Irrawaddy and at Hpa-An on the Salween.

knowledge of the magnitude of fluxes, as well as the mineralogical and chemical characteristics of the transported material, is a prerequisite for understanding the impact of Himalayan uplift on global biogeochemical cycles (Raymo et al. 1988) and the impact of human activities on recent-modern sediment yields (Wilkinson 2005). An understanding of denudation rates in areas of active tectonism is critical in assessing the extent to which climate-driven erosion influences large-scale tectonic behavior (An et al. 2001; Zeitler et al. 2001).

Together, the G-B and I-S are thought to deliver close to half of the current total flux of water, sediment, and dissolved load from the Himalayas and Tibet to the ocean, with ~20% of this attributed to the I-S (Milliman and Meade 1983). The Irrawaddy River ranks fifth in the world in terms of suspended load (265 MT yr^{-1}) and fourth in terms of dissolved load (Milliman and Meade 1983, their table 2); these published sediment and water fluxes are derived from a nineteenth-century data set (Gordon 1885), and the dissolved loads were published in an article by Meybeck and Ragu (1995). Stamp (1940) states that 48 MT yr^{-1} should be added as dissolved load for the Irrawaddy but gives no source for this estimate. Values published by Meybeck and Ragu (1995), Meade (1996), Gaillardet et al. (1999), and Meybeck et al. (2003) equate to combined I-S annual averages of 697 km^3 of water, 365 MT of suspended material, and 162 MT of dissolved material. Although figures for these rivers are widely quoted and used for global flux calculations of carbon (e.g., Subramanian and Ittekkot 1991), there are no measurements of suspended load for the Salween in Myanmar, and the values quoted by Meade (1996, his table 1) are estimates based on the measured suspended load values of the Irrawaddy and Mekong. The increase in damming along the Yangtze (Changjiang) and Yellow (Huanghe) rivers has substantially reduced the sediment load of these rivers (Walling 2006), such that the Irrawaddy may now rank as having as high as the third-largest sediment load in the world after the Amazon and the G-B.

We have reanalyzed the original nineteenth-century Irrawaddy data and subsequent early twentieth-century engineering reports that identify problems with the data collection. In their seminal article, Milliman and Meade (1983) use the Irrawaddy as an example of the potential error that can arise when compiling global sediment budgets using data recycled from previous reports rather than original, often inaccessible, data. Given the very significant contribution of the Irrawaddy River to global sediment budgets, we have begun to compare the revised nineteenth-century water and sediment load values to our own field measurements collected during the onset of the 2005 and 2006 monsoon seasons. We use our preliminary data set here simply to compare the efficiency of Gordon's and our filtering methods; we do not present any comparison of nineteenth-century and modern sediment load values because this is the focus of ongoing research.

Study Area and Methods

The Irrawaddy and Salween rivers are ~2000 and ~2800 km long and have drainage areas of

0.413×10^6 and 0.272×10^6 km^2, respectively (Nyi 1967; Bender 1983). The Irrawaddy catchment rock types include Cretaceous to mid-Cenozoic flysch of the western Indo-Burman ranges, Eocene-Miocene and Quaternary sediments of the Myanmar Central Basin, and the Late Precambrian and Cretaceous-Eocene metamorphic, basic, and ultrabasic rocks of the eastern syntaxis of the Himalayas. The Salween and eastern tributaries of the Irrawaddy drain Precambrian, Oligocene-Tertiary sedimentary, and acidic and metamorphic rocks of the eastern Shan Plateau (Bender 1983; Curray 2005; Najman 2005; Socquet and Pubellier 2005).

Gordon (1885) presented monthly discharge data collected between 1869 and 1879 and 1 yr of sediment load data (1877–1878) to the Royal Geographical Society (RGS) without details of his field methods or sampling locations. Gordon's original report, containing his full daily discharge, rainfall, and sediment concentration data set, survey maps, channel cross sections, and a detailed description of sampling techniques (Gordon 1879–1880), was located in the archives of the RGS in 2005; another copy is located in the British Library in London. These data have been digitally reconstructed using OCR software, and every number has been checked against the original report. The data are of remarkable quality, particularly because there is a full range of flows, including monsoon peak discharge. Sediment concentration was measured at three depths within the water column, including the lower part of the water column. Milliman and Meade (1983, p. 2) note that inadequate sampling at peak flows and from throughout the water column are among the most important sources of error in sediment load data.

Gordon, a civil engineer in charge of river works in Myanmar during the late nineteenth century, investigated the magnitude and duration of flood events on the Irrawaddy for the government of India, in order to calculate the required size and height of flood embankments. Gordon selected Seiktha (fig. 1) as the main measurement site for velocity and sediment concentration because it is the farthest downstream site above the delta that is constrained by bedrock highs on both its western and its eastern banks. Seiktha is 16 mi upstream of Myanaung (fig. 1), where daily stage was recorded from 1869 to 1879 but where the width of the river made multiple cross-sectional measurements of sediment load, velocity, and depth too difficult.

Nineteenth-Century Cross-Sectional Area and Flow Velocity Measurements. Gordon's (1879–1880) hydrological sampling strategy was based on the flotation methods published in an article by Humphreys and Abbot (1861), as used by Caleb Goldsmith Forshey at hydrological stations on the Mississippi River between 1848 and 1855 during the U.S. government's Mississippi Delta Survey. Gordon made daily measurements of flow velocity and depth and recorded stage during 1872–1873 and again in 1875, missing only Sundays, holidays, and days of very bad weather. Channel width at Seiktha ranges from ca. 700 m at low flow to ca. 1600 m at peak flow. Flow depth was measured along a line normal to the main flow from a boat using a lead and line, and the boat position was surveyed by triangulation from the bank with theodolites. Flow velocity was estimated from the time taken for floats to travel between two cross-channel baselines spaced about 60 m apart, and theodolites positioned at the end of each baseline were used to track float trajectories. The starting and final positions of the floats were drafted as scaled drawings, and the downstream component of velocity was resolved trigonometrically from the time of travel.

Surface floats, suspended up to ~1 m below the surface to avoid wind and waves, were used initially. Gordon recognized the need for vertical velocity profiles and so sank floats on increasing lengths of line in ~1-m intervals down through the water column; the depth of the river at Seiktha never exceeded 25 m (Gordon 1879–1880). The velocity measurements were usually reported as the average of two or three readings. The float (called a double float) was a solid cylinder of wood (1 ft [30 cm] in height and 6 in [15 cm] in diameter) with a 4 × 4-in (10 × 10-cm) hole on the outside into which was inserted the amount of wet clay ballast needed to sink the cylinder to the required depth (Gordon 1879–1880). Floats were suspended from a thin cord (1/16 in [ca. 1.5 mm] diameter) attached to a smaller wooden cylinder (6 in [15 cm] diameter and 1 in [25 mm] thick) that floated just below the water surface. Gordon grouped similar surface velocity values together to divide the channel cross section into 10 subsections (the sections were altered slightly for overbank floods) and calculated the area of each subsection. He calculated the arithmetic mean velocity for each vertical profile across the channel and mean surface velocity for each subsection. Some subsections had more than one vertical velocity profile (and some appear to have none), and for days of continuous stage height, he calculated the mean of the average vertical velocities for each profile. Gordon (1879–1880) notes that his measurements at any location remained the same on consecutive days with constant stage (and differed with stage) and varied both within a subsection if there were multiple profiles and across the whole cross section. About 10,000 vertical profiles of float velocity were recorded by the

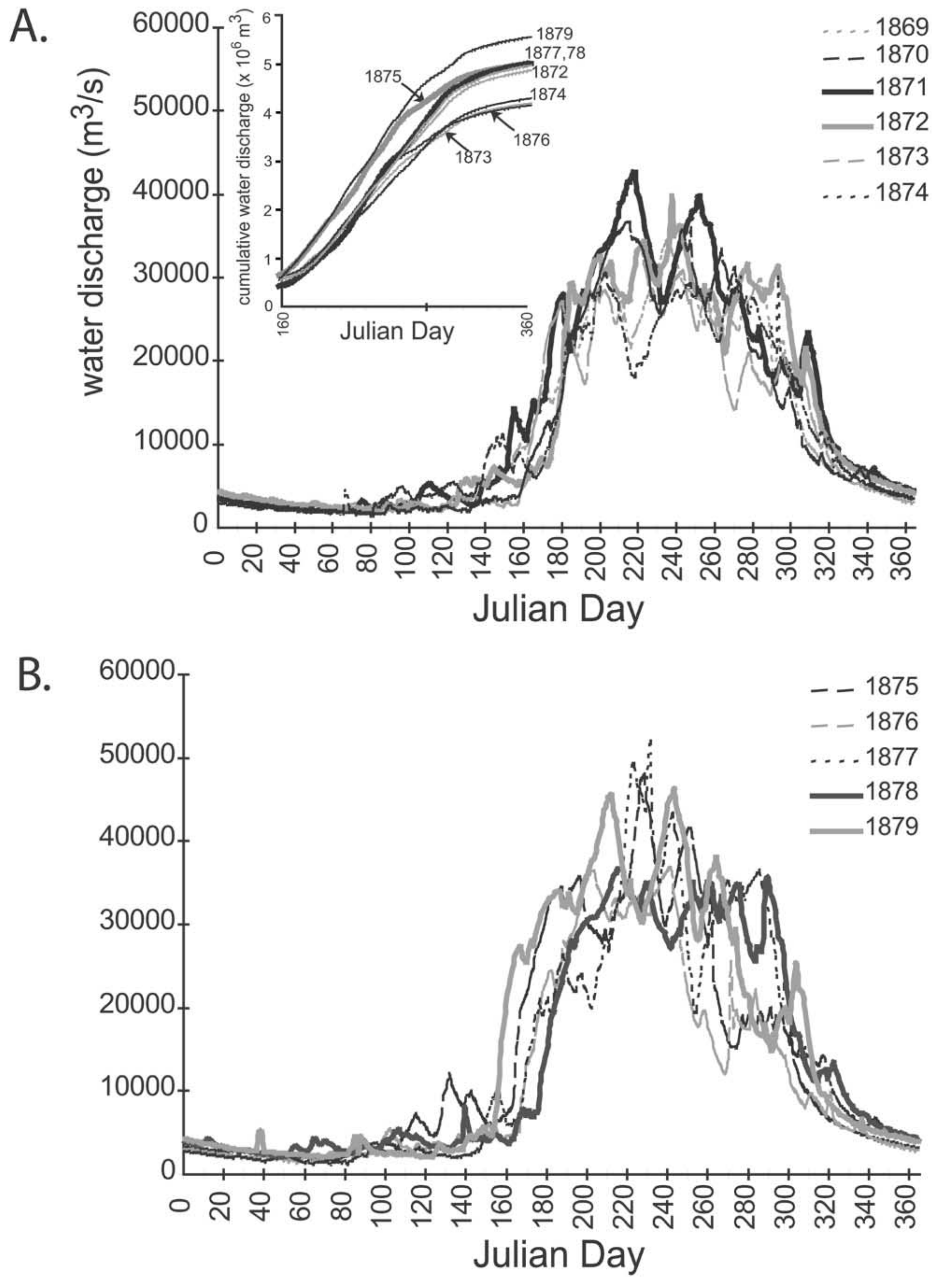


Figure 2. Annual hydrographs at Seiktha, using Gordon's original (1879–1880) data. Daily discharge values for 1869–1874 (*A*) and 1875–1879 (*B*). The timing, duration, and peak value of the monsoon seasons produce total annual discharges that vary by ±11% from the mean (inset in *A*).

end of 1875, and each channel cross section (1 d of measurements) was covered by about 10 profiles (Gordon 1879–1880). He then calculated discharge by summing the velocity-area product of each subsection. He used 2 yr of daily data (excluding Sundays and holidays) and the stage readings to develop stage-discharge rating relationships for rising and falling flows at Seiktha (fig. 2); he presented both the measured and the predicted discharge values and states that in only very few cases do the differences exceed 10% (Gordon 1879–1880, p. 22).

In addition to daily sampling at Seiktha for the periods mentioned above, Gordon used a simple transfer function to match the Myanaung stage record (fig. 1) to that at Seiktha and then calculated daily discharge for the remaining years between 1869 and 1879 at Seiktha from the Myanaung stage measurements (fig. 2). Gordon used the Myanaung record instead of the Seiktha stage record because a sand bar developed downstream of Seiktha between 1873 and 1875, and it raised the water level at the gauging location "by 2–3 feet" (Gordon 1879–1880, p. 22) and because Myanaung had the longer stage record. Gordon (1879–1880, p. 22) compared the Seiktha and Myanaung records for 1872–1873 and stated that the Myanaung record was "with some uniformity about 1/2 foot lower" than at Seiktha and the difference did not vary over a range of flows.

Gordon (1879–1880) discussed possible errors with the double float method, including drag associated with the cord, the accuracy of calculated

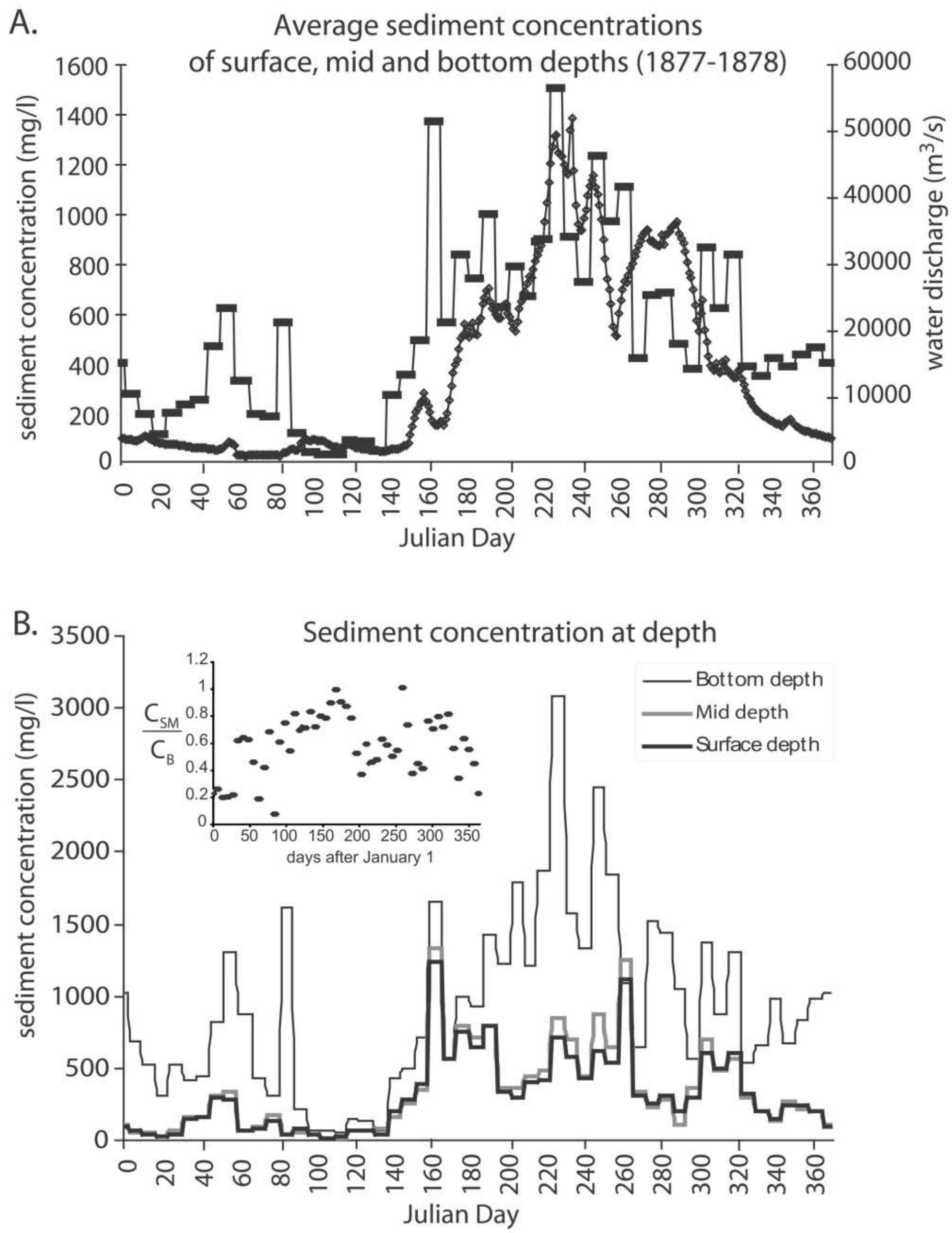


Figure 3. Original discharge and suspended sediment concentrations for 1877–1878. *A*, Concentrations are based on an average of surface, middle, and near-bottom depth suspended sediment sample measurements. *B*, Individual concentrations for each water depth; inset shows the ratio of the average of surface and middle sediment concentrations to bottom concentration.

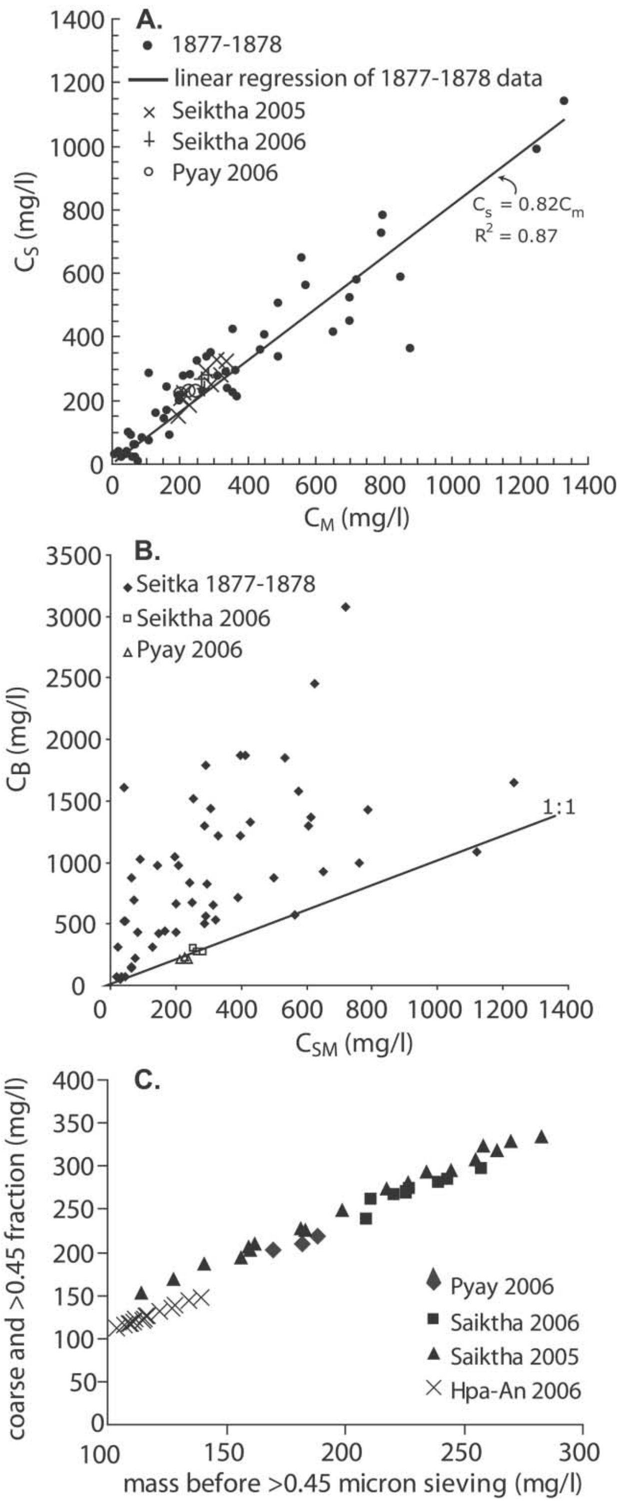


Figure 4. *A*, Relationship between sediment concentration in surface (C_S) and middle depth (C_M) levels of the water column for the 1877–1878 data, shown with our data from 2005 and 2006. *B*, Average of C_S and C_M (C_{SM}) compared with near-bottom concentration (C_B), shown with our 2006 data set. *C*, Relationship between total mass measured in 2005 and 2006 and settled mass before sieving with >0.45-μm nucleopore mesh. Average underestimate of the historical Irrawaddy suspended concentration values inferred from this data is 18%.

time over the short distance, and eye fatigue of the observers. In 1882, Gordon cross-checked the double float method with an electrical Deacon current meter and found that the water velocities from lower parts of the water column were less than his first float measurements and that the difference increased with flood level. He consequently suggested reducing his calculated discharges (Gordon 1879–1880) by 10%, 5%, and 0% for high, medium, and low discharge ranges, respectively, and applied these corrections to the discharge data set presented to the RGS in 1885. He did not discuss the numerical values of high, medium, and low discharges.

Subsequent engineers reevaluated Gordon's data, particularly Samuelson (1913), who took over the Embankment Division in 1913. Samuelson noted several problems with Gordon's data, in particular that the Myanaung and Seiktha stage records varied with changing channel geometry at Myanaung, producing systematic errors in the transfer function between the two locations. One of the features of Gordon's data set (fig. 2) is an apparent increase in discharge for the years after 1875 when the stage records were merged. We discuss this source of uncertainty in "Review of Potential Sources of Error."

Nineteenth-Century Sediment Load Measurements. Gordon measured sediment load for 6 d each week (excluding Sundays, holidays, and storms) for the year of 1877–1878 (52 wk) at three positions across the river: ~90 m from the right bank, in midstream, and ~1220 m from the right bank. At the first two positions, samples were taken at three depths: surface (~1 m depth), middle, and near-bottom (0.5–1 m above the riverbed). The left bank position had only surface and lower measurements as a result of the shallow water depths there. He used a sediment sampler that was based on the device designed for the Mississippi Delta Survey (Humphreys and Abbot 1861). Gordon collected water using a hollow barrel (1 ft [30 cm] long and 6 in [15 cm] diameter) loaded with lead rings to make it sink. The barrel had two large valves on the top and bottom, and its lids were made of leather and lead, and they freely opened upward; as the barrel descended through the water column, the lids remained open, and water entered and passed through it, but the lids closed once the barrel was being lifted out of the water. The sampler thus collected water from the lowest depth to which the barrel descended. Gordon combined 100 g of water and sediment from every bottle collected over 6 d for each of the three water depths to produce 52 weekly measurements of sediment concentration for each depth. He filtered the combined samples (600 g of water) through a double thickness of weighed filter paper, and although he does not mention the quality or grade of paper, it seems unlikely that it was a very small pore size because filtering such large volumes of water and sediment would have been extremely slow. The dried filter papers and sediment were weighed carefully using a Fortin balance; the filter paper alone was reweighed, compared to its original weight, and the sediment mass was calculated. Only the combined weekly concentrations for each depth were reported by Gordon (1879–1880). Measurements were reported in grams of sediment per 100 g of water (1 g per 100 g being equivalent to 10^4 mg L^{-1}) for each depth and week of measurement. The suspended sediment concentration and discharge data are presented in figure 3 and will be discussed in "Reanalysis of Gordon's Original Data." Gordon developed a concentration-discharge relationship for the 1877–1878 data but did not discuss how it was derived. This relationship was combined with the 1869–1879 discharge estimates to calculate annual sediment loads that range from 248 to 352 MT yr^{-1}; the directly measured load for the year of measurement (1877–1878) is 340 MT yr^{-1}. These sediment load values (Gordon 1879–1880, his table 16) are based on the average sediment concentrations from all water depths (fig. 3). Gordon (1879–1880) originally reported that the 10-yr average sediment load for 1869–1879 was 286 MT yr^{-1}; this is close to the number quoted in table 1 of Milliman and Meade (1983). However, as discussed earlier, by 1885, Gordon had reduced the discharge measurements for the monsoon months, and the most frequently quoted annual sediment load value of 261 MT yr^{-1} (i.e., Stamp 1940; Milliman and Syvitski 1992) comes from the 1885 article presented to the RGS (table 1 in Gordon 1885).

Modern Discharge and Sediment Load Measurements. In June 2005, data were collected at Gordon's original site at Seiktha, including 10 bathymetric cross-profiles, 10 vertical velocity profiles (measured using a Valeport velocimeter), and 18 suspended sediment load samples collected using a horizontally deployed, cylindrical 2-L Van Dorn water sampler with openings at each end. We used a sediment sampling protocol similar to that of Gordon (1879), involving collection of water and sediment from surface and middle depths (but not bottom depth) and then settling sediment from 2 L of water for 24 h. We decanted the water and passed it through a 0.45-μm nucleopore filter to determine the likely recovery efficiency of Gordon's protocol. Separate quantification of the settled and filtered components suggests that 18% of the sediment load remains suspended after 24 h of settling and is recovered with a 0.45-μm filter (fig.

Table 1. Drainage Areas, Water Discharge, and Suspended Sediment Loads for Rivers Entering the Gulf of Martaban, Myanmar

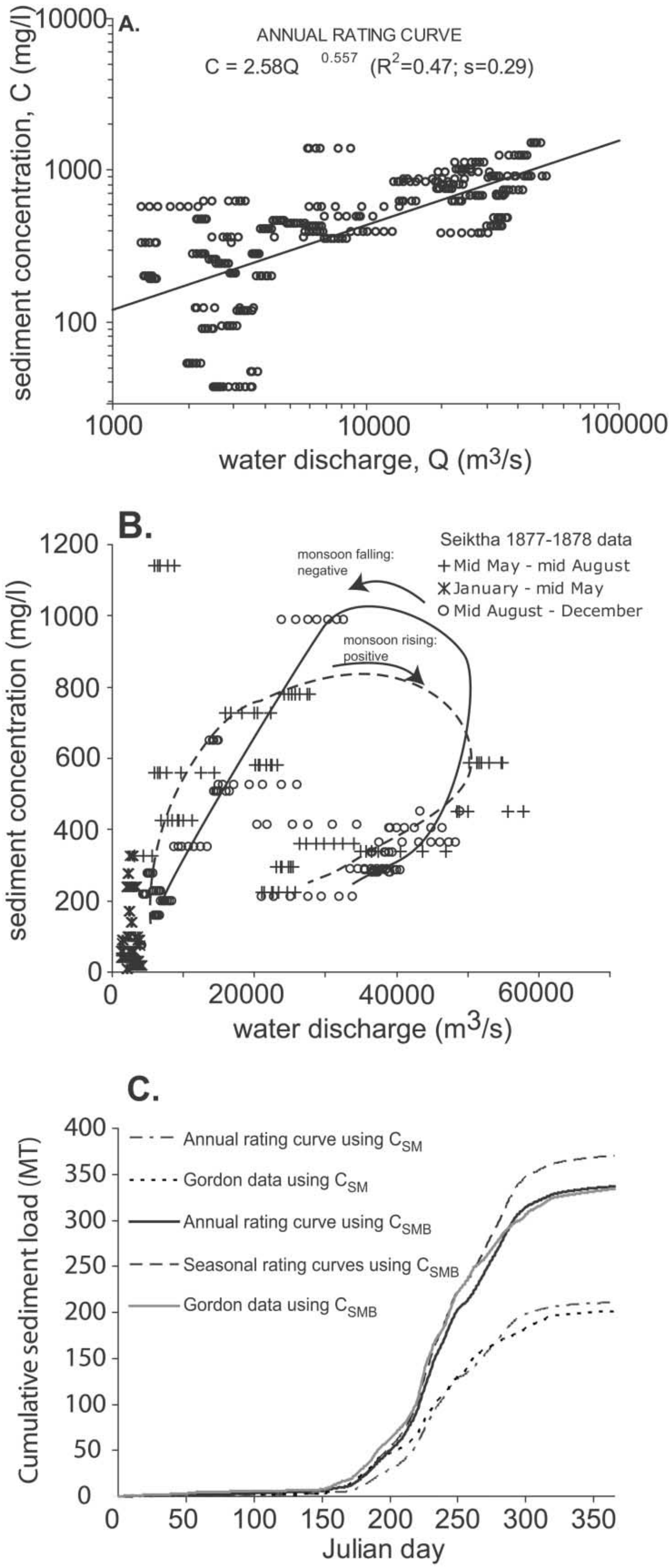
	Drainage area ($\times 10^6$ km^2)	Drainage length (km)	Water flux (km^3 yr^{-1})	Suspended sediment flux ($\times 10^6$ T yr^{-1}): Average surface and middle depth	Suspended sediment flux ($\times 10^6$ T yr^{-1}): Average surface, middle, and bottom depth
Milliman and Meade's (1983) data for I	.43	…	428	…	265 (261[a])
Reanalysis of I data from Gordon (1879–1880)	.413[b]	1985	440 ± 48 (1σ)	…	…
Corrected data after velocity reduction[c]	…	…	422 ± 41 (1σ)	191 ± 32	309 ± 49
Addition due to unmeasured fine fraction (18%)	…	…	…	226 ± 39	364 ± 60
Salween (Thanlwin)	.272[b]	2800	211[b]	110[c]	180[c]
Sittoung, Bago, Bilin, Attaran, and Gyaning	.06[b]	…	119[b]	30[c]	50[c]
Total for I-S system	.745	…	752	370	600
G-B system	1.59[a]	2700	971	1060[a]	1060[a]
Percentage of estimated I-S relative to G-B (%)	47	…	77	35	57

Note. I = Irrawaddy; I-S = Irrawaddy-Salween; G-B = Ganges-Brahmaputra.

[a] From Milliman and Syvitski (1992). Note that the sediment flux is used for the G-B in calculating the ratios of sediment flux for these systems because this is the only value available.

[b] Drainage areas, river lengths, and Salween and Sittoung and smaller river discharge values from Meybeck and Ragu (1995), Bender (1983), and Nyi (1967).

[c] The sediment loads of the Salween, Sittoung, and smaller rivers are estimated proportionally using discharge scaling and the Irrawaddy sediment load values.



A.
ANNUAL RATING CURVE
C = 2.58Q 0.557 (R2=0.47; s=0.29)
sediment concentration, C (mg/l)
water discharge, Q (m3/s)
B.
Seiktha 1877-1878 data
Mid May - mid August
January - mid May
Mid August - December
monsoon falling: negative
monsoon rising: positive
sediment concentration (mg/l)
water discharge (m3/s)
C.
Annual rating curve using CSM
Gordon data using CSM
Annual rating curve using CSMB
Seasonal rating curves using CSMB
Gordon data using CSMB
Cumulative sediment load (MT)
Julian day

4). When we used average velocities and bathymetry for each of our profiles, the velocity-area method gives a discharge of 5058 $m^3\ s^{-1}$ on June 26, 2005, carrying 252 mg L^{-1} of suspended sediments with a median grain size of 10.5 μm.

In May 2006, we remeasured discharge with an acoustic Doppler current profiler and collected water and sediment samples using the same protocol as in 2005, including sampling near-bottom water depths (0.5–1 m above the riverbed) from Seiktha and Pyay (40 mi upstream) and at Hpa-An on the Salween. Measurements of water discharge (and sediment concentration) made between May 23 and May 30, 2006, were 5370 $m^3\ s^{-1}$ (271 $\pm$ 16 mg L^{-1}) at Seiktha, 5030 $m^3\ s^{-1}$ (210 $\pm$ 9 mg L^{-1}) at Pyay, and 2270 $m^3\ s^{-1}$ (127 $\pm$ 11 mg L^{-1}) at Hpa-An. Our total sediment concentrations (settled and filtered fractions) for June 2005 and May 2006 are plotted together with Gordon's data in figure 4. This article makes no statements about possible changes in sediment load between the nineteenth century and today because we have insufficient data on which such comparisons can be based. We do, however, discuss how sampling and filtering methods can affect measured sediment loads in "Review of Potential Sources of Error."

Reanalysis of Gordon's Original Data

We have recalculated discharge (fig. 2) and suspended sediment load from the data in Gordon's 1879–1880 report (fig. 3; table 1). Our 10-yr average of total annual discharge is calculated as 440 $\pm$ 48 $km^3\ yr^{-1}$ (table 1), which is higher than Gordon's (1879–1880) value of 425 $km^3\ yr^{-1}$, as a result of arithmetic errors in his calculations. However, Gordon's (1885) later publication includes a reduction of the original discharge measurements. Gordon does not discuss exactly how he adjusted his discharge measurements, and the data are not complete enough to allow a correction factor to be calculated. He states that high, medium, and low flow measurements were reduced by 10%, 5%, and 0%, respectively, and by comparing the 1879 and 1885 publications, we estimate that "low flows" are below 10,000 $m^3\ s^{-1}$, "medium flows" are between 10,000 and 35,000 $m^3\ s^{-1}$, and "high flows" are greater than 35,000 $m^3\ s^{-1}$. This reduces our calculation of mean annual water flux by ~4%, from 440 $\pm$ 48 to 422 $\pm$ 41 $km^3\ yr^{-1}$ (table 1); Gordon's 1885 reduced discharge value is 400 $km^3\ yr^{-1}$, which represents an ~6% reduction. We intend to quantify the uncertainty that should be attributed to Gordon's double float method in future field seasons in order to objectively correct the original nineteenth-century discharge values.

The daily concentration measurements for 1877–1878 are presented as an average of surface, middle, and near-bottom depth concentrations (C_{SMB}; fig. 3*A*); as individual surface (C_S), middle depth (C_M), and near-bottom depth measurements (C_B; fig. 3*B*); and as ratios of C_{SM} to C_B (fig. 3*B*). Figure 4 demonstrates that the values of C_S are ~80% of those measured at C_M and that the values of C_B are between two and four times higher than those in the upper parts of the water column and display more variability. Gordon suspected that some of his measurements of C_B were overestimated because of bed disturbance. Our small data set collected in May 2006 during the onset of monsoon (days 144–151) has ratios of C_{SM}/C_B in the range of 0.86–1.1, which may suggest that Gordon's C_B measurements are too high (fig. 4*A*). However, Gordon's data set also shows that the ratio of C_{SM}/C_B approaches 1 during the onset of monsoon (May–June), which is when we sampled (fig. 3*B*). In the absence of a modern sediment concentration data set that covers the full range of flows, which would allow us to evaluate whether Gordon overestimated near-bottom suspended concentrations, C_{SM} will be used as a lower limit for the mean sediment concentration and C_{SMB} will be used as an upper limit. It is worthwhile repeating here that Gordon's (1885) quoted sediment load values are the average of the three depth concentration measurements.

We have calculated new sediment rating curves for the adjusted discharge and sediment concentration values for 1877–1878 (fig. 5) based on a regression of the log-log plot of discharge and sediment concentration and including a bias correction

Figure 5. Sediment rating curves for 1877–1878 measurements. *A*, Regression of data derived from log-log plot using average of surface, middle, and bottom depths (C_{SMB}). *B*, Linear plot showing interpretation of positive hysteresis for early monsoon period and negative hysteresis for late monsoon period. *C*, Cumulative annual and seasonal rating curves based on concentrations averaged over surface and middle depths (C_{SM}) and C_{SMB} compared with Gordon's measured values. Modeled rating curve values of sediment concentration deviate from measured values for the late monsoon period.

factor to account for the inherent underestimation in total load that comes from using a log-log data transformation; this implicitly makes allowance for the poor fit of the regression to sediment concentrations at low discharges (Ferguson 1986). The sediment-discharge relationships are different for early and late monsoon periods; the former exhibits "first flush" positive hysteresis behavior with a steeper rating curve, while negative hysteresis is displayed for the late monsoon period (fig. 5*B*). We compared sediment concentrations calculated using one annual rating curve (fig. 5*A*) with those calculated using two seasonal curves (fig. 5*C*). Despite the clear visual differences in the sediment concentration-discharge behavior between early and late monsoon periods, a seasonal (two-curve) relationship overpredicts sediment concentrations for both C_{SM} and C_{SMB}, compared with the measured values (fig. 5*C*). We have therefore used the annual curve to calculate sediment concentrations for the remaining 9 yr of the discharge records. Notably, our single annual sediment rating curve predicts a sediment load of 337 MT for 1877–1878, which is the same as the measured value of 340 MT (fig. 5*C*) reported by Gordon (1879–1880).

Our filtered sediment concentration data from 2005 and 2006 suggest that the concentrations calculated by Gordon did not include the >0.45-μm particulate fraction. We therefore use an increase of 18%, derived from our data set, as an estimated increase to sediment load (a filtered correction). The raw and adjusted Gordon data, using both C_{SM} and C_{SMB}, are presented in table 1. With no correction for the missing particulate fraction, the Irrawaddy transported 422 ± 41 km^3 yr^{-1} of water and 309 ± 49 MT yr^{-1} of sediment load (10-yr averages). With our 18% increase for the missing fine particulate fraction, the sediment load becomes 364 ± 60 MT yr^{-1}.

In summary, the recalculated sediment load data differ from Gordon's (1885) values because (1) there were minor arithmetic errors in the original nineteenth-century discharge calculations (accounting for an ~4% decrease in discharge); (2) our sediment rating curve produces a 27% increase in the 10-yr average annual sediment load measurement, even though our rating curve correctly estimates the measured value for 1877–1878; and (3) our filtered correction that accounts for a missing particulate fraction in Gordon's concentration measurements increases the loads by 18% (table 1).

Review of Potential Sources of Error

There are four sources of potential uncertainty in Gordon's Irrawaddy data set: (1) the velocity measurement technique, (2) the missing >0.45-μm filtered fraction in the sediment concentration data, (3) the merging of two stage-discharge relationships developed at two different locations, and (4) the contribution of C_B to the daily depth-averaged concentration values. We have adjusted the raw discharge values to account for the uncertainty due to the velocity measurement technique (an ~4% reduction in the 10-yr average of total annual discharge) but recognize that Gordon's method of measuring velocity needs to be independently verified. Sediment concentrations have been increased based on our estimation of the missing particulate fraction (an 18% increase). Our analysis of the stage records from Seiktha and Myanaung suggests that the merging of two stage records from different locations introduces an uncertainty of about 8%. Finally, the largest uncertainty in the data set is the values for C_B. It is possible that some of the C_B measured by Gordon overrepresents the true bottom suspended sediment concentration. The barrel used in Gordon's sampling probably had a larger internal diameter than the openings that let the flow move through: therefore, as the barrel descended through the column, sand-sized particles in suspension may have been trapped inside, thus resulting in oversampling of the suspended sand-sized material. The amount of this oversampling would increase with depth because the barrel collects sand for a longer period of time in deeper flows and because the sand concentration increases toward the bed. Another possibility is that during sampling, the barrel could have disturbed the bed, producing bottom concentration values that are not entirely due to suspended load. We intend to address all these sampling issues in future field campaigns by comparing various devices for measuring suspended load concentrations, including a barrel with a design similar to that of Gordon's (i.e., that of Humphreys and Abbot [1861]) and the Van Dorn sampler.

Implications

In order to estimate the suspended sediment load debouched into the Gulf of Martaban, we have combined the new Irrawaddy load values with estimates for the Salween and Sittoung, as well as four smaller rivers (Bilin, Bago, Attaran, and Gyaing) that terminate in the gulf (fig. 1). Their estimates are based on a scaling of the Irrawaddy annual sediment load values in proportion to their annual discharge relative to the Irrawaddy, and we recognize that this is a crude estimate in the absence of more data; we therefore present these values, and the total combined flux, as rounded to the nearest two significant digits (table 1). Our lower value of suspended sediment load for the Salween is 110 MT yr^{-1}, similar to the 100–MT yr^{-1} estimate of Meade (1996), which was based on scaling values for the Irrawaddy and Mekong. Our upper value of 180 MT yr^{-1} is similar to an annual suspended load of 164 MT, calculated from the yield value presented by Meybeck et al. (2003) for the Salween in Thailand. The total annual suspended sediment load to the eastern Indian Ocean for the Irrawaddy-Salween-Sittoung system is potentially as large as 600 MT, representing 57% of the modern G-B sediment flux (table 1); this represents sediment loads calculated from three depths (average of C_S, C_M, and C_B) for the Irrawaddy. In comparison, because of the uncertainty surrounding the near-bottom concentration measurements, total annual sediment load for the Irrawaddy based on averaging just the upper and middle depths is 370 MT and represents 35% of the G-B flux.

Over the past century or more, many rivers worldwide have undergone substantial declines in sediment export as a result of damming and irrigation, but the results of Syvitski et al. (2005) suggest that the Irrawaddy has undergone the largest relative increase in sediment delivery to the ocean of any major river as a result of land use and population changes and the absence of dams on its mainstem or major tributaries. The majority of the Irrawaddy load was thought by Stamp (1940) to have been derived from below Mandalay from the unconsolidated and rapidly eroding "dry zone" (<800 mm annual rainfall) of the Central Basin of Myanmar (fig. 1), where recent population and agricultural changes have produced significant land use changes. We are currently developing modern mass flux records for the Irrawaddy and Salween, as well as methods that allow us to hindcast sediment loads back to the nineteenth century, in order to address how land use and climate have influenced sediment loads. The sparsely inhabited nature of the Salween catchment means that land use change has had less of an impact on this river, but an extensive damming and hydroelectrical scheme is scheduled to begin in 2007 (Mizzima News 2007), which will have a significant effect on future sediment flux. Measuring the sediment load of the, as yet, longest nondammed river remaining in southeast Asia at the present time is absolutely critical.

Conclusions

The existing sediment flux data for the Irrawaddy River, one of six major systems draining the eastern Himalaya, come from a comprehensive nineteenth-century hydrological study, but these original data have not been reevaluated since recognition of the significance of these river systems to global climate change and the evolution of the Himalayan orogen. To date, only recycled values from early twentieth-century summaries of the work have been incorporated in global river sediment load and discharge databases. We have evaluated the sampling strategies, reanalyzed the original data, and recalculated discharges and sediment loads and find that the typically quoted sediment flux values (e.g., Milliman and Meade 1983; Meade 1996) are underestimated.

We therefore believe that the significance of the I-S contribution to "natural" Himalayan denudation and land-ocean fluxes has not been fully appreciated because (1) reanalysis of the original nineteenth-century data (Gordon 1879–1880) for the Irrawaddy suggests that the often-quoted flux of 261 MT yr^{-1} may be a significant underestimate, with the true value as high as 364 ± 60 MT yr^{-1}, which would place the Irrawaddy as third-largest contributor of sediment load after the Amazon and G-B (due to reduced loads on the major dammed Chinese rivers), and (2) the I-S system may contribute 35%–57% (370–600 MT yr^{-1}) of the G-B load.

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