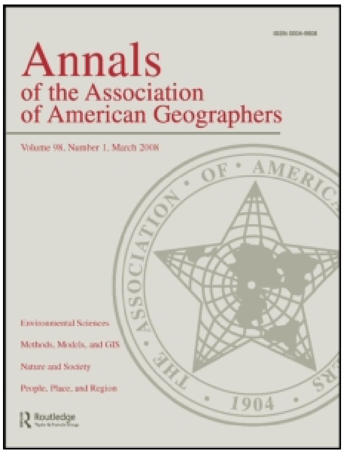

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The Question of Communist Land Degradation: New Evidence from Local Erosion and Basin-Wide Sediment Yield in Southwest China and Southeast Tibet

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Chinese Communist Party doctrine promotes the Confucian belief that the environment should be subjugated to man's will, and modern policies have been identified as compounding environmental degradation caused by historical agricultural practices. In this context, social scientists report massive increases in erosion throughout China, an assertion variously supported and questioned by daily sediment yield data in the Yellow and Yangtze River basins. In this study we used up to twenty-seven-year records of daily sediment yield for stations in southwest China and southeast Tibet to calculate annual and average annual sediment yields over the period of record. We also calculated coefficients for annual sediment rating curves as a way to determine interannual changes in sediment transport, that are insensitive to variations in rainfall. We found no systematic changes in annual sediment yield or rating curve parameters through time. Sediment yield is correlated with upstream area, mean annual rainfall, fraction of land under cultivation, population density, and mean monsoon rainfall but not with mean local relief, basin relief ratio, fraction of cropland from satellite data, or drainage density. Variability in mean annual sediment yield decreases as basin area increases, suggesting that larger basins store sediment more effectively and buffer against extreme events. We propose that anthropogenic changes to sediment yields have been smaller than the magnitude of interannual variability and might be comparable to the effect of the regional rainfall gradient across the basins. In basins with substantial anthropogenic activity, sediment storage might be affecting any signal we might otherwise see. *Key Words: anthropogenic effects, erosion rate, sediment yield, southwest China, Three Rivers Region.*

中国共产党的理论家们鼓吹儒家学说，认为环境应该服从于人的意志，并且现代政策已经被确定为对过去农业实践造成的环境退化进行了清算。在此背景下，社会科学家报告了整个中国大量的日益严重的侵蚀，黄河和长江流域的每日产沙量数据对该论调提供了不同程度的支持和质疑。在本项研究中，我们使用了多达 27 年的中国西南部和西藏东南部记录站的每日产沙量数据，以此计算记录期间每年和年平均泥沙产量。我们同时也计算了每年产沙量变化曲线的系数，以此来确定泥沙输送的年际变化，这个变化和降水变化曲线是不相关的。我们发现，年产沙量和变化曲线参数随时间并没有系统性的变化。产沙量与上游地区范围、年平均降雨量、土地开垦比例、人口密度、平均季风降雨量具有相关关系，但与本地地形、盆地地形比例、从卫星数据得到的农田面积比例、或排水密度不相关。年平均产沙量减少的变化伴随着流域面积的增加，这表明大型盆地对于极端事件能更有效地存储和缓冲沉积物。我们认为，产沙量的人为变化一直小于产沙量的年际变化幅度，并且可能与整个流域区域性降雨梯度的影响相类似。在有大量人类活动的盆地，泥沙存储可能会影响任何我们在其它方面可能看到的信号。*关键词：人类活动的影响，侵蚀率，产沙量，中国西南地区，三江地区*。

La doctrina del partido comunista chino promueve la creencia confucionista de que el entorno ambiental debe estar sujeto a la voluntad del hombre, y que las políticas modernas se han identificado como tolerantes de la degradación ambiental ocasionada por prácticas agrícolas tradicionales. En este contexto, los científicos sociales informan de un incremento masivo de la eriosión en toda China, una afirmación variablemente apoyada y cuestionada por los datos diarios sobre sedimentos que se generan en las cuencas de los ríos Amarillo y Yangtze. En el presente estudio utilizamos los registros de treintisiete años de datos diarios de las estaciones del sudoeste de China y sudeste del Tibet sobre sedimento generado, para calcular el producto total anual y el promedio anual de sedimentos en el período de registro. También calculamos los coeficientes de las curvas de clasificación anual

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de sedimentos como medio para determinar los cambios interanuales en el transporte de sedimentos, que son insensibles a las variaciones de las precipitaciones. No descubrimos cambios sistemáticos en la producción anual de sedimento, ni en los parámetros de la curva clasificatoria a través del tiempo. La producción de sedimento correlaciona con el área de la cuenca de las corrientes, la precipitación media anual, la fracción de la tierra bajo cultivos, la densidad de población yla precipitación monzónica media, pero no con el relieve local, la razón relieve-cuenca, la fracción de tierra en cultivos derivada de datos de satélite, o la densidad del avenamiento. La variabilidad en la media anual de producción de sedimento disminuye a medida que el área de la cuenca aumenta, lo cual sugiere que las cuencas más grandes almacenan el sedimento de manera más efectiva y se protegen contra eventos extremos. Nuestra propuesta es que los cambios antropogénicos sobre la producción de sedimentgo han sido menores que la magnitud de la variabilidad interanual y podrían compararse con el efecto del gradiente regional de precipitaciones a través de las cuencas. En las cuencas que exhiben sustancial actividad antropogénica, el almacenaje de sedimento podría estar afectando cualquier señal que de otro modo puidièsemos percibir. *Palabras clave*: *efectos antropogénicos, tasa de erosión, producción de sedimento, China del sudoeste, Región de los Tres Ríos.*

Let's wage war against the great earth!
Let the mountains and rivers surrender under our feet.
March on Nature,
Let's take over the power of rain and wind.

—Zhang Zhimin[1]

Poems such as the one just shown, by a noted revolutionary poet, illustrate poignantly communist-era attitudes toward nature that the Chinese government promoted and that are widely blamed for increased flooding in recent decades along the lower Yangtze River (e.g., Yin and Li 2001). This attitude toward nature is not new. Prior to the revolution, although small villages and isolated regions generally subscribed to Daoist and Buddhist ideals of living in harmony with nature and revering all living things, larger communities, scholars, and the ruling class held the Confucian ideals of controlling nature to suit humanity (Shapiro 2001).

Numerous reports of environmental destruction exist for imperial China. The degradation of the Loess Plateau and the Yellow River basin is one striking example. A thousand-fold population increase (70,000 to 70 million in 400 years) caused grassland and forested land on the Loess Plateau to decrease from 53 percent to 3 percent (Saito, Yang, and Hori 2001). Erosion "carved a maze and labyrinth of enormous gullies, up to 600 feet deep" (Lowdermilk 1924, 13) and increased flooding related to sedimentation resulted in levee building projects as early as 206 BC (Ma 2004). Other early large-scale efforts to control nature include the irrigation projects at Dujiang Yan (Shapiro 2001) and illegal clearing and levee building in the Dongting region of Hunan province during the Ming and Qing dynasties, which were blamed for causing massive Yangtze River floods in 1788 (Perdue 1982).

Environmental destruction is also well documented in modern Chinese history. Three major policies, known as the Three Great Cuttings, are blamed for mass deforestation since 1949: (1) the Great Leap Forward (1958–1960), when fueling widespread "backyard" steel furnaces induced extensive deforestation (Shapiro 2001; Hyde, Belcher, and Xu 2003); (2) the "Grain as a Key Link" policy (1966–1976) to clear land for expanding cropland (Hyde, Belcher, and Xu 2003); and (3) "opening and development" in the early 1980s, when private markets opened and people could benefit financially from trees they cut and sold (Hyde, Belcher, and Xu 2003).

Analysis of regional, quantitative data leads to complicated conclusions regarding the impact of such anthropogenic activity on erosion. For example, annual sediment yield in the Yellow River is second only to the Amazon (Saito, Yang, and Hori 2001), but recent conservation efforts appear to have been somewhat successful at reducing sediment yields (Hassan et al. 2008). Additionally, the Yellow River delta recorded a declining sediment load between 1951 and 1999 (S. J. Wang, Hassan, and Xie 2006). Instead of conservation, this trend might reflect the increased water demand in the basin and the subsequent inability for the river to reach, let alone transport sediment to, the delta; in 1997 the river did not reach the sea during 220 days, an increase from 20 dry days in 1961 (S. J. Wang, Hassan, and Xie 2006).

However, the Yangtze River is more complicated. Up to 40 percent of the forests in Sichuan were cut in modern times (Winkler 1996) and this has been blamed for increased sediment load and subsequent flooding (G. J. Chen 2000; Yin and Li 2001; Yi 2003). In contrast, a number of studies concluded that human activity and modern policies have not, on average, increased sediment yield in the Yangtze River (Lu and Higgitt 1998, 1999; Higgitt and Lu 1999; Lu, Ashmore, and Wang 2003a, 2003b). Some studies even found decreasing sediment yield to the river (Xu 2000; Z. Chen et al. 2001; Xu 2005; Z. Y. Wang, Huang, and Li 2007; Z. Y. Wang, Li, and He 2007). Small-scale studies tell a different story. Several detailed studies found sediment loads increasing in mountainous tributaries and decreasing in urban tributaries (Zhang 1999; Zhang and Wen 2002, 2004). Another set of studies found that in a rural, minority township in Sichuan, the local ethic for conservation did not stop the area from being heavily logged during all three "great cuttings" (Trac et al. 2007), transforming a single-channel river set in a wooded floodplain into a widening channel actively eroding into hillslopes and undercutting roads and houses (Urgenson et al. 2010).

These seemingly contradictory results parallel the broader, international discussion of anthropogenic landscape change in the Himalaya and, more specifically, the theory of Himalayan environmental degradation (THED). This theory postulates a general eight-step process by which upstream anthropogenic changes, such as deforestation, cause enormous changes to the downstream environment (Ives 1987). A popular theory in the late 1980s, THED generally fell out of favor among those who study Himalayan environmental change as an overly simplistic representation of the environment (e.g., Ives 1987). More recent research suggests that although THED does not hold on large scales, over small scales the environmental consequences of human activities can be great (Forsyth 1996; Ali and Benjaminsen 2004). Despite the scientific community moving away from such single-trajectory representations of environmental change, recent Chinese environmental policies are derived from THED. These policies largely ignore subtleties in the relationship between upstream land use and downstream effects, instead favoring blanket policies of controlling all anthropogenic land use as damaging to downstream areas (Blaikie and Muldavin 2004).

This contrast in the results of large-scale and small-scale studies is corroborated by numerous studies showing that not only does extensive deforestation greatly increase erosion but that humans have simultaneously increased storage of sediments, leading to a net effect of decreased sediment yield to oceans (Syvitski et al. 2005). Similarly, in China, Higgitt and Lu (1996) showed that although soil erosion was increasing in the Upper Yangtze watersheds from the late 1940s to the late 1980s, sediment yield in rivers did not increase, suggesting that sediment was stored and did not leave the basins. Thus, given the well-recognized tendency for deforestation to increase erosion, we propose two possible hypotheses for the downstream effects of deforestation: (1) sediment yields increased regionally and, in turn, increased flooding by aggrading channel beds and decreasing channel space for water to flow in without overtopping banks; or (2) sediment yields increased locally but sediment storage in alluvial fans and floodplains upstream buffers downstream reaches from such changes.

In this context, we tested the hypothesis that humans changed the nature of sediment supply to and transport in the large rivers making up the International Rivers of Yunnan and Tibet, China[2] (IRYT; Figure 1). We used three measurements of anthropogenic effects on sediment yield: correlations between sediment yield and metrics of human development (i.e., population density, land cover, and fraction of land under cultivation), changes in the annual sediment yield, and changes in the nature of sediment rating curves. To account for natural spatial variability in sediment yield, we also analyzed correlations between sediment yield and geomorphic parameters (i.e., mean local relief and rainfall). Following Wolman (1967), sediment yield is expected to increase with increasing population density until the point where the area becomes urban and sediment yield sharply decreases, whereas agricultural land use and the fraction of land under cultivation should correlate more directly with sediment yield. We also examined temporal variations in sediment yield reflecting the response of rivers to major changes in sediment supply. Finally, as a control for interannual variability in rainfall, we tested for temporal variations in parameters of the sediment rating curves for each station. When watershed processes are disturbed, resulting in increased sediment delivery to stream channels, the sediment rating curve records changes in the way the river transports sediment by shifting upward—either changing the slope or intercept of the regression (Environmental Protection Agency 2006). Well-documented examples of sediment rating curve shifts as a result of basin degradation include Missouri gully erosion (Piest, Bradford, and Spomer 1975), western Tennessee channelization (Simon and Hupp 1986), and Arizona silvicultural impacts (Lopes, Folliott, and Baker 2001).

The IRYT are the rivers that drain Yunnan and Tibet into foreign countries on their way to the ocean and are mainly in the mountains that make up the eastern and southern margins of the Tibetan Plateau. The region includes the Tsangpo, Salween, Mekong, and Red Rivers[3] and lies between 20°N and 34°N and 80°E and

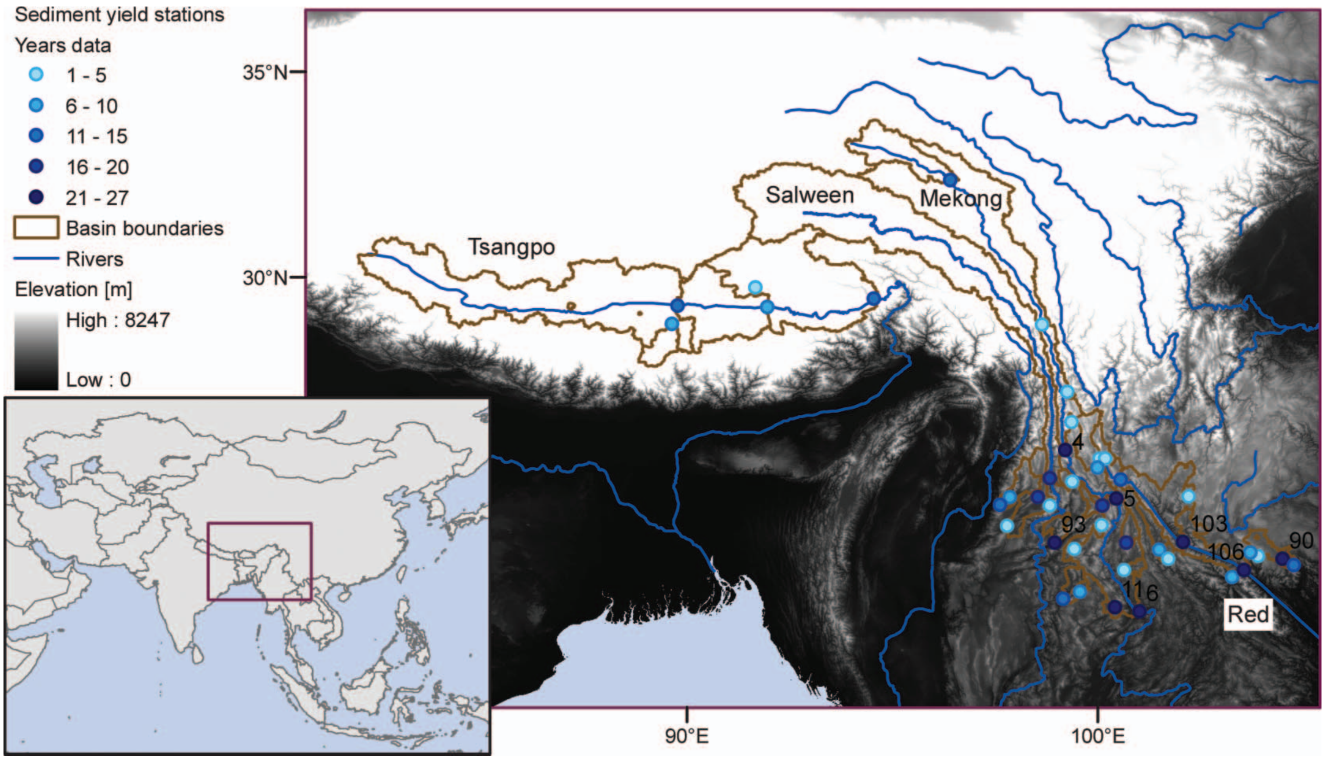

Figure 1. Location of the region we studied in the inset figure and details about that location in the larger figure. Stations for which we analyzed sediment yield are shown with blue circles; the darker colors indicate longer periods of record for the stations. Basin boundaries for the area uniquely sampled by each station are shown with brown. Underlying the image are major rivers in the region and elevations in grayscale.

105°E at elevations ranging from 200 to over 6,000 m. It is characterized by mean annual rainfall as high as 1,500 mm/year and as low as 180 mm/year and local relief ranging from 150 to over 3,000 m measured over 10 km diameter areas.

The IRYT is of particular interest for three reasons: (1) it contains part of the Three Rivers Region UNESCO World Heritage Site[4] and has been reported as possibly being moved to the World Heritage Sites at Risk List (International Union for Conservation of Nature [IUCN] 2006) as a result of proposals for two cascades of dams along the Salween and Mekong Rivers (Feng and He 2004; Magee 2006); (2) the Yangtze River has been extensively studied during planning for and construction of the Three Gorges Dam; and (3) a long record (up to twenty-seven years) exists of daily sediment yield measurements for forty-four stations for the region.

Methods

We used daily mean total suspended sediment and discharge data compiled for forty-four stations in the IRYT operated by the Ministry of Hydrology of the People's Republic of China from 1953 to 1987 (Ministry of Hydrology 1962–1989); data after 1987 are not publicly available. We photocopied all data for the Yangtze River–Jinsha and Yalong Regions, the Yellow River–Fen He Region, and all of the IRYT District from the original books. The organization of the books required us first to transliterate (into Pinyin) the names of all stations, rivers, and river basins so that we could match the stations between different years. As the numbers of the stations change from year to year, we matched stations based on their Chinese name and renumbered them such that each station has a unique number. The location of the stations is tied to the year the location was reported because stations sometimes moved around or the location was misreported. After the stations were renumbered and the station information pages were entered into the database, we entered the daily data into the database. Information about the relational database structure and how to access it is available at http://depts.washington.edu/shuiwen/.

Xu and Cheng (2002) reported that the data were collected using standard procedures as described by the Ministry of Water Conservancy (1962) and the

Ministry of Water Conservancy and Electric Power (1975); that is, sediment concentration data were collected daily using a Jakowski sampler and the 0.2–0.8 method. A comparison of sediment concentration and discharge results confirmed that the data were measured daily and not calculated using a rating curve, which assumes a linear relationship between sediment concentration and discharge. In general, a wide range of sediment concentrations are associated with any given discharge, as is apparent, for example, in one year of data at a representative station along the Mekong River (Figure 2A). Each of the stations exhibits interannual variability in the relationship between sediment concentration and discharge, and r^2 values for sediment rating curves calculated for individual years at individual stations are generally between 0.5 and 0.7.

The Ministry of Hydrology does not report errors for the data, and thus we estimated errors conservatively on the basis of previous sediment yield studies. Singh and France-Lanord (2002) showed that point sampling does not adequately sample the distribution of suspended sediment in a river. We estimate that the errors in erosion rates calculated from the sediment data measured by the Ministry of Hydrology could be as high as 50 percent due to errors in point sampling and the fact that these rates do not include bed load or dissolved load (Galy and France-Lanord 2001).

Using data presented in Tables 1 through 6, we calculated sediment yield (tons sediment $\cdot$ km$^{-2}\cdot$ year^{-1}) for each of the stations, which individually have one to twenty-seven years of data available. For the eighteen stations with additional stations upstream of them in the same basin, we calculated the sediment yield for both the intermediate reaches between stations and the entire upstream area. Although reported station locations are accurate to the nearest minute, this resolution is insufficient to extract upstream basin areas from a digital elevation model (DEM), and thus we adjusted the station locations, placing each station on the nearest river of approximately the correct size. The adjustments were minor, with the revised locations placing the stations on rivers in approximately the same location and with nearly identical areas to those originally reported (Figure 2B).

We compared mean annual sediment yields (both basin-wide and for reaches between successive stations) to three metrics of development in the region: population density, land cover, and fraction of land cultivated. We attempted to compare data for overlapping periods of time, but sediment yield data available to us only extend through 1987, the population density data are from 1990 (Deichmann 1996), the land cover data are based on satellite imagery from 1992 and 1993 and are classified using U.S. Geological Survey (USGS)

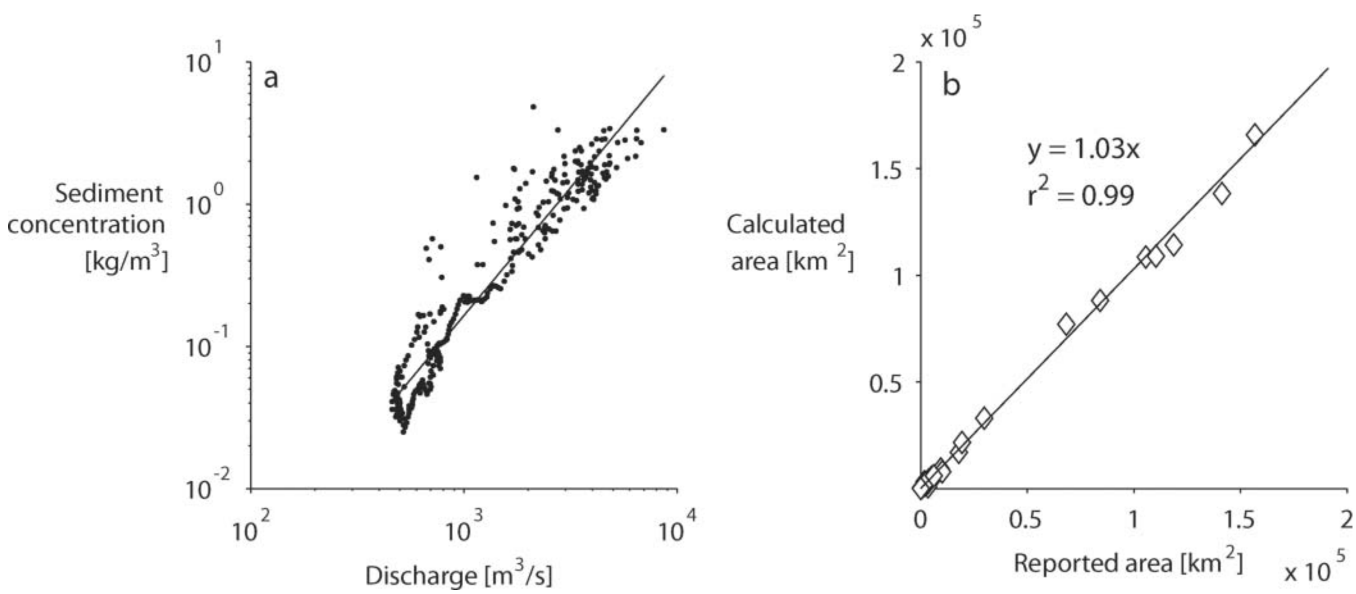

Figure 2. (A) Total suspended sediment as a function of discharge for station 6 in 1969. The scattering of data strongly supports the hypothesis that total suspended sediment was measured daily rather than calculated from a rating curve. This figure also shows how we calculated the slope and y-intercept for Figure 5 and the time series analysis. For each year of data we calculated the best fit line in log-log space for concentration of suspended sediment as a function of discharge. The slope and intercept for that best-fit line are used in subsequent analysis. (B) Area above a station calculated from where we located stations against the upstream area reported in the original data books. The correlation has a slope just above one and an r^2 value > 0.99, suggesting that we placed the stations in the correct locations.

Table 1. Watershed, river name, station name, and stations upstream

Station number	Watershed	River name	Station name	Stations immediately upstream
87	Bu Gu Jiang	Bu Gu Jiang	Zhong Ai Qiao	None
84	Da Ying Jiang	Da Ying Jiang	La He Lian	None
85	Da Ying Jiang	Da Ying Jiang	Xia La Xian	84
96	Dong He	Dong He	Bing Ma	None
55	Lan Cang Jiang (Mekong)	Za Qu He	Xiang Da	None
57	Lan Cang Jiang (Mekong)	Lan Cang Jiang	Liu Tong Jiang	55
35	Lan Cang Jiang (Mekong)	Yong Chun He	Tang Shang	None
4	Lan Cang Jiang (Mekong)	Lan Cang Jiang	Jiu Zhou	35, 57
75	Lan Cang Jiang (Mekong)	Xi Er He	Tian Sheng Qiao	None
43	Lan Cang Jiang (Mekong)	Xi Er He	Si Shi Li Qiao	75
86	Lan Cang Jiang (Mekong)	Hei Hui Jiang	Tian Kou	43
5	Lan Cang Jiang (Mekong)	Lan Cang Jiang	Ga Jiu	86, 4
11	Lan Cang Jiang (Mekong)	Liu Sha He	Meng Hai	None
32	Lan Cang Jiang (Mekong)	Nan Bi He	Meng Sheng	None
49	Lan Cang Jiang (Mekong)	Jing Gu Da He	Jing Gu	None
70	Lan Cang Jiang (Mekong)	Pu Er He	San Ke Zhuang	None
89	Lan Cang Jiang (Mekong)	Jin Ping He	Xiao He Gou	None
97	Lan Cang Jiang (Mekong)	Ku Ke He	Ke Jie	None
110	Lan Cang Jiang (Mekong)	Bi Jiang	Yun Long	None
6	Lan Cang Jiang (Mekong)	Lan Cang Jiang	Yun Jing Hong	5, 11, 32, 49, 70, 89, 97, 110
100	Long Chuan Jiang	Long Chuan Jiang	Teng Chong Qiao	None
99	Long Chuan Jiang	Long Chuan Jiang	Ga Zhong	100
105	Lv Shui He	Lv Shui He	Lv Shui He	None
108	Lv Shui He	Lv Shui He	Zuo Bei Wu	None
261	Nan Ding He	Nan Ding He	Da Wen	None
93	Nan Ding He	Nan Ding He	Gu Lao He	261
94	Nan Lei He	Nan Lei He	Meng Lian	None
98	Nan Wan He	Nan Wan He	Ma Li Ba	None
109	Nan Xi He	Nan Xi He	Nan Xi Jie	None
15	Nu Jiang (Salween)	Nu Jiang	Dao Jie Ba	None
90	Pan Long He	Pan Long He	Long Tan Zhai	None
91	Pan Long He	Pan Long He	Tian Bao	90
88	Si Nan Jiang	Si Nan Jiang	Da Qiao	None
95	Su Pa He	Su Pa He	Chao Yang	None
102	Yuan Jiang (Red River)	Pa He	Shui Gou	None
104	Yuan Jiang (Red River)	Pa He	Mu Gou	102
101	Yuan Jiang (Red River)	Zha Jiang	Da Dong Yong	None
103	Yuan Jiang (Red River)	Yuan Jiang	Yuan Jiang	101, 104
106	Yuan Jiang (Red River)	Yuan Jiang	Man Hao	103
306	Ya Long Zang Bu Jiang (Yarlung Tsangpo)	Nian Chu He	Jiang Ze	None
301	Ya Long Zang Bu Jiang (Yarlung Tsangpo)	Ya Long Zang Bu Jiang	Nu Ge Sha	306
311	Ya Long Zang Bu Jiang (Yarlung Tsangpo)	La Sa He	Kang Jia	None
302	Ya Long Zang Bu Jiang (Yarlung Tsangpo)	Ya Long Zang Bu Jiang	Yang Cun	301, 311
305	Ya Long Zang Bu Jiang (Yarlung Tsangpo)	Ya Long Zang Bu Jiang	Nu Xia	302

classification schemes (USGS 2008a), and the percentage land under cultivation estimates are from 1997 county data from provincial yearbooks (China Data Center [CDC] 2009a, 2009b). In addition to these metrics of development, we compared mean annual sediment yields to three geomorphic metrics (mean local relief, basin relief ratio, and drainage density) and two climate metrics (mean annual rainfall and mean monsoon rainfall) as indicators of geomorphic parameters that might influence sediment yields independently of anthropogenic factors. Mean local relief was used as a proxy for hillslope steepness, as it is relatively insensitive to quality or scale of topographic data (Montgomery and Brandon 2002). Topographic information, including relief and elevations, was derived from Satellite Radar Topography Mission (SRTM) data. River networks and hydrologically correct DEMs published by the World Wildlife Fund with the HydroSheds data set (USGS 2008b) were used for drainage density calculations and to extract watersheds. Mean annual and monsoon rainfall were derived from Tropical Rainfall Measuring Mission (TRMM) satellite data. TRMM data capture daily variability in rainfall but not total amount of rainfall and therefore likely underestimate actual rainfall by 15 to 25 percent but portray accurate spatial distributions of rainfall (Anders et al. 2006).

For the temporal variations in sediment yield and sediment rating curves, we calculated the annual sediment yield and sediment rating curve parameters (i.e., slope and intercept) for every year through the period of record for stations with over twenty years of data (eight stations).

Results

The sediment yields range from –8,400 to 173,750 tons · km^{-2}· $year^{-1}$) (M = 3,992, *SD* = 22,304 tons · km^{-2}· $year^{-1}$)) for the region and the measured basins range in size from 4 to 133,796 km^2 (Figure 3A, Tables 2 and 3). Four reaches have apparently negative sediment yield. This is the result of subtracting the downstream sediment yield from the upstream sediment yield to get the sediment yield for just the reach in question. If sediment flux exiting the reach is less than the flux entering it, the resulting sediment yield will be negative, indicating sediment storage. The lowest sediment yields are along the Mekong River between 26° and 29°N, where the river has negative net sediment yield (area upstream of station 4 and downstream of stations 53 and 57). Although other reaches with negative net sediment yield exist (upstream of stations 43, 104, and 302), they record much smaller amounts of sediment accumulation, fewer years of data, or significantly smaller basin areas. The area upstream of station 302 is mapped by Finnegan et al. (2008) as having extensive valley bottom sediment storage, which they interpreted to reflect high sediment supply and low transport capacity. This valley bottom sediment storage is likely the reason sediment yield in the region is negative. The highest sediment yield is for station 311, a 14-km^2 station in Tibet that operated for five years and had an annual sediment yield of 173,750 tons · km^{-2}· $year^{-1}$). This station has a sediment yield more than six standard deviations above the mean, and so we omitted it from future discussion as an outlier; no other station has a yield greater than one standard deviation from the mean. Aside from this station, the highest sediment yields are in the southern reaches of the study area.

Drainage areas for the basins we examined span five orders of magnitude, and we find that basin size influences the degree to which sediment yield is correlated with the metrics of development, geomorphology, and climate we examined. Basin area and sediment yield are correlated ($r^2 = 0.08$, $p < 0.05$), but the low r^2 value indicates that basin area exerts little influence on basin sediment yields (Figure 4A). The variation in sediment yield decreases as basin area increases, suggesting that larger basins buffer more effectively against changes in sediment yield. In the following, we discuss the correlations between sediment yield and each of our geomorphic, climatic, and anthropogenic parameters. We first present results for the data set taken as a whole and then for basins grouped by size ($< 10^3$ km^2 [$n = 15$], 10^3–10^4 km^2 [$n = 24$], 10^4–10^5 km^2 [$n = 13$], and $> 10^5$ km^2 [$n = 7$]). Results are summarized in Table 7. As an additional evaluation of the effects of scale, we used the residuals from a best fit of sediment yield as a function of area as the dependent variable in correlation analyses with the same geomorphic, climatic, and anthropogenic parameters. No improved correlations (when compared to either the entire data set or the data set separated by basin area) emerge.

We examined the influence of relief (using two metrics) on sediment yield in the study area and found that indicators of hillslope steepness are not strong predictors of sediment yield, regardless of basin size. Mean local relief measured over a 10-km-diameter circle and averaged over each basin analyzed ranges from 347 to 1,505 m (Figure 3B). The highest relief basins are in the narrow part of the Mekong River. For the data set as a whole, relief is not a strong predictor of sediment yield ($r^2 = 0.07$, $p < 0.05$; Figure 4B), suggesting that hillslope steepness is not the major factor controlling modern sediment yields in this region. Relief is a poor predictor ($p > 0.05$) of sediment yield for all sizes of basins. Basin relief ratio, a measure of main stem channel steepness calculated as the ratio of total basin relief (maximum minus minimum point in the basin to longest main stem channel length), ranges from 0.002 to 0.13 m/m (Figure 3C). The highest basin relief ratios are in the southern parts of the study area. Total basin relief is also not a strong predictor of sediment yield ($r^2 = 0.09$, $p < 0.05$; Figure 4C) when considering the entire data set. As with mean local relief, predictive power decreases when considering the basins grouped by area ($p > 0.1$ in all cases).

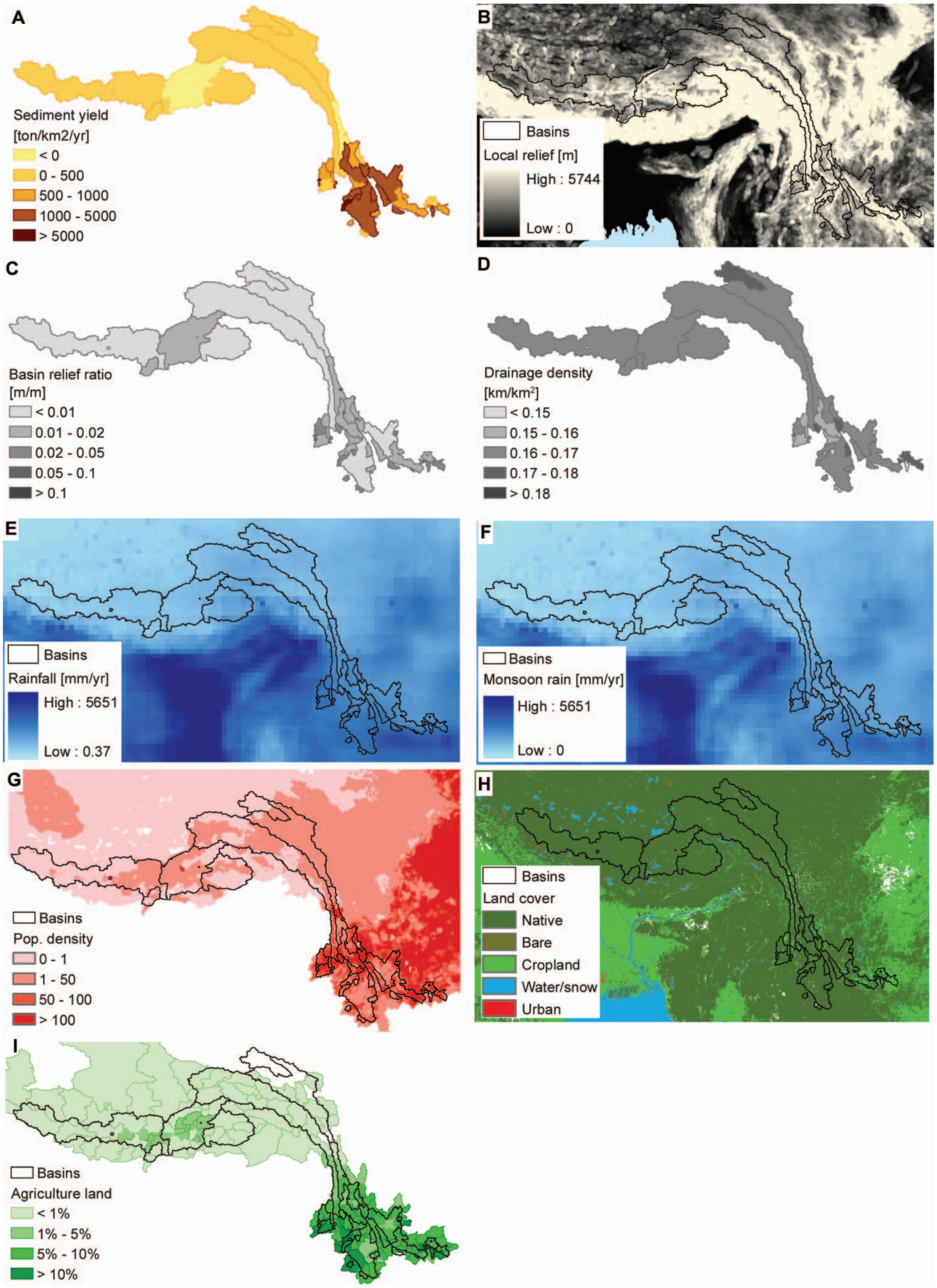

Figure 3. Geomorphic and anthropogenic data about the region. (A) shows the mean annual sediment yield for unique areas sampled by stations. (B), (C), and (D) show geomorphic parameters, which are proposed to correlate with sediment yield data: local relief (B), basin relief ratio (C), and drainage density (D). (E) and (F) show rainfall parameters that are proposed to correlate with sediment yield data: mean annual rainfall (E) and monsoon rainfall (F). (G), (H), and (I) show the anthropogenic parameters predicted to be related to sediment yield: population density (G), land cover from satellite data (H), and fraction of land under cultivation by county from Chinese records (I).

Table 2. Reported station location, our best location for the station, and upstream area

	Reported location				Where we put the station		
Station number	Latitude	Longitude	Entire upstream area (km^2)	Years data	Latitude	Longitude	Entire upstream area (km^2)
87	23.35	101.50	3,564	17	23.35	101.50	3,610
84	24.70	97.97	4,225	6	24.75	98.05	4,022
85	24.68	98.27	5,476	17	24.69	97.92	4,243
96	25.00	99.40	N/A	2	25.00	99.40	3,641
55	32.30	96.20	17,909	20	32.35	96.43	16,959
57	28.82	98.82	68,280	4	28.83	98.65	77,090
35	27.17	99.63	247	18	27.15	99.32	199
4	25.83	99.38	84,220	26	25.81	99.20	88,177
75	25.62	100.20	2,513	2	25.62	100.22	2,519
43	25.60	100.10	2,591	6	25.56	100.10	2,693
86	25.35	100.02	9,394	12	25.35	100.01	9,209
5	24.60	100.47	105,660	23	24.60	100.47	108,522
11	21.95	100.42	1,032	23	21.95	100.43	1,056
32	23.38	99.42	1,766	5	23.38	99.42	1,746
49	23.50	100.70	2,773	20	23.55	100.71	1,891
70	22.88	100.70	1,372	2	22.89	100.70	1,381
89	22.65	103.30	109	10	22.85	103.14	231
97	24.87	99.77	1,755	17	24.52	100.49	3,235
110	25.90	99.37	211	1	25.85	99.51	182
6	21.88	101.07	141,380	22	21.85	101.03	138,301
100	24.63	98.83	3,487	18	24.64	98.63	3,684
99	24.00	98.43	10,084	6	24.07	97.98	7,905
105	23.00	103.27	181	6	23.29	103.73	285
108	23.03	103.45	63	7	23.26	103.63	318
261	23.95	100.10	657	1	23.68	99.24	690
93	23.68	99.23	3,628	20	23.95	100.10	3,924
94	22.33	99.58	775	16	22.33	99.58	746
98	24.42	97.97	294	2	24.42	97.98	280
109	22.65	104.05	3,476	18	22.82	103.90	907
15	25.10	99.15	118,760	23	25.11	98.85	114,158
90	23.45	104.28	3,410	27	23.40	104.22	2,704
91	22.95	104.77	5,123	14	22.98	104.79	5,299
88	22.97	101.90	2,083	9	23.10	101.85	1,610
95	24.43	98.80	459	1	24.43	98.78	441
102	24.67	102.27	691	10	24.69	102.24	537
104	24.65	102.22	691	6	24.68	102.23	610
101	25.10	100.57	2,373	23	25.07	100.56	2,611
103	23.63	102.15	19,320	21	23.63	101.99	21,660
106	22.85	103.55	29,889	25	22.85	103.57	32,983
306	28.90	89.60	6,200	10	28.85	89.65	5,980
301	29.38	89.78	110,415	11	29.30	89.79	108,957
311	29.88	91.78	20.367	5	29.89	91.82	14
302	29.30	91.97	156,808	10	29.26	91.97	165,838
305	29.45	94.57	191,222	12	29.46	94.56	203,904

We also examined the predictive power of drainage density on sediment yield. Drainage density is frequently used as a parameter in models that forecast sediment output from a basin and it is expected that higher drainage density should correlate with higher sediment yield (Garde and Ranga Raju 2000). Drainage density ranges from 0.132 to 0.359 km/km^2 (Figure 3D) with the highest values in the south and the far north of the Mekong drainage. Drainage density has no predictive power with respect to sediment yield for either the entire data set or for any basins smaller than 10^5 km^2 ($p > 0.05$). For the basins with areas greater than 10^5 km^2, drainage density is a good predictor of sediment yield ($r^2 = 0.70$, $p < 0.05$).

Table 3. Sediment yield, mean local relief, basin relief ratio, drainage density, mean annual rainfall, and mean monsoon rainfall

Station number	Mean annual sediment yield (ton/km^2/year)	Mean local relief (m)	Basin relief ratio ($\times 10^{-2}$; m/m)	Drainage density (km/km^2)	Mean annual rainfall (mm/year)	Mean monsoon rainfall (mm/year)
87	1,790	869	1.38	0.168	1,160	935
84	589	862	2.44	0.167	1,285	1,000
85	1,074	870	2.08	0.167	1,284	999
96	472	594	2.80	0.176	1,034	815
55	211	617	0.56	0.174	505	473
57	404	806	0.38	0.169	532	483
35	167	1,000	12.71	0.141	799	682
4	261	890	0.34	0.168	570	507
75	14	854	1.50	0.168	986	820
43	11	861	1.48	0.169	986	819
86	395	887	0.79	0.167	995	830
5	413	922	0.25	0.171	660	575
11	113	486	2.41	0.155	1,252	1,012
32	21,919	850	3.17	0.167	1,231	972
49	1,196	790	1.89	0.179	1,184	979
70	720	551	1.85	0.162	1,386	1,128
89	950	1,334	8.87	0.143	1,372	1,049
97	709	896	1.27	0.151	1,039	828
110	2,198	729	9.12	0.163	1,007	826
6	566	895	0.19	0.169	783	667
100	507	874	1.43	0.157	1,239	976
99	476	833	0.90	0.158	1,260	991
105	913	574	7.26	0.172	973	745
108	90	368	1.84	0.184	968	745
261	1,027	763	3.06	0.146	1,153	921
93	1,624	1,071	1.44	0.162	1,130	888
94	593	600	2.96	0.166	1,356	1,154
98	2,266	932	7.84	0.132	1,270	998
109	2,879	1,090	3.81	0.146	1,200	917
15	212	944	0.34	0.170	614	531
90	252	347	1.36	0.177	974	758
91	419	466	1.19	0.176	1,076	844
88	1,252	844	2.34	0.160	1,286	1,038
95	1,455	631	3.26	0.170	1,218	959
102	205	558	2.15	0.151	925	773
104	127	549	1.85	0.176	927	775
101	1,139	716	1.83	0.173	935	759
103	1,076	818	0.62	0.170	955	785
106	1,038	889	0.45	0.170	989	798
306	191	712	1.41	0.168	402	332
301	119	736	0.25	0.165	371	321
311	173,750	1,266	N/A	0.000	574	504
302	60	773	0.23	0.166	411	356
305	74	854	0.22	0.165	466	399

Climate metrics (mean annual rainfall and mean monsoon rainfall) are also correlated with sediment yield. Mean annual rainfall values averaged over the basins analyzed range from 369 mm/year to 1,386 mm/year (Figure 3E). The highest rainfall values are in the southern basins of the region, which are those most affected by the Indian monsoon. A weak correlation exists between the mean annual rainfall for each basin and the mean annual sediment yield ($r^2 = 0.27$, $p < 0.001$; Figure 4E). Mean annual rainfall does not predict erosion rates in basins between 10^3 and 10^5 km^2 ($p > 0.05$) but does for smaller ($r^2 = 0.27$, $p < 0.05$) and larger ($r^2 = 0.79$, $p < 0.01$) basins. Mean monsoon rainfall values averaged over the basins analyzed range

Table 4. Mean population density, fraction cropland, and fraction agricultural land

Station number	Mean population density (people/km^2)	Fraction cropland (from satellite satellite data)	Fraction agricultural land (from Chinese data)
87	55	0.03	0.06
84	105	0.07	0.08
85	105	0.08	0.01
96	132	0.11	0.10
55	2	0.01	0.00
57	4	0.02	0.00
35	148	0.08	0.05
4	12	0.03	0.00
75	235	0.14	0.08
43	251	0.13	0.01
86	140	0.07	0.04
5	34	0.04	0.01
11	55	0.13	0.07
32	50	0.05	0.10
49	54	0.00	0.06
70	47	0.02	0.05
89	192	0.33	0.08
97	91	0.13	0.10
110	69	0.01	0.05
6	38	0.04	0.01
100	106	0.22	0.07
99	107	0.12	0.05
105	42	0.38	0.10
108	70	0.38	0.12
261	48	0.05	0.09
93	59	0.07	0.08
94	51	0.03	0.13
98	102	0.00	0.11
109	55	0.69	0.09
15	9	0.03	0.02
90	108	0.46	0.09
91	97	0.61	0.04
88	47	0.10	0.05
95	55	0.01	0.10
102	107	0.07	0.07
104	109	0.08	0.01
101	235	0.08	0.09
103	89	0.10	0.06
106	96	0.15	0.02
306	1	0.00	0.01
301	3	0.00	0.01
311	9	0.00	0.01
302	4	0.00	0.00
305	4	0.01	0.00

from 320 mm/year to 1,154 mm/year (Figure 3F), suggesting that a large percentage of the annual rain falls during the monsoon in the majority of the basins. On average, 82 percent of the annual rain falls during the monsoon, with some basins receiving as much as 90 percent of their annual rain during these six months. The highest monsoon rainfall values are in the southern parts of the study region. As with mean annual rainfall, monsoon rainfall is a modest predictor of sediment yield for the entire data set when basins of all sizes are considered together ($r^2 = 0.22$, $p < 0.001$; Figure 4F). However, monsoon rainfall does not predict sediment yields for any of the subsets of basins sorted by area ($p > 0.05$).

The population density in the region ranges from < 1 to 516 people/km^2 averaged over the basins studied (Figure 3G). Qualitatively, the highest population densities are in the southwestern portions of the region with highest sediment yields. However, the annual sediment yield as a function of mean basin-averaged population density shows no trends ($p > 0.1$; Figure 4G). When basins are considered grouped by area, population density in the smallest basins, those with areas under 10^3 km^2 and between 10^3 and 10^4 km^2, correlates with sediment yield ($r^2 = 0.37$, 0.33, and $p < 0.05$, 0.01, respectively). In contrast, intermediate-size basins (those 10^4–10^5 km^2) show no correlation with sediment yield ($p > 0.05$), but population density in the largest basins (those with upstream areas over 10^5 km^2) is strongly correlated with sediment yield ($r^2 = 0.83$, $p < 0.001$).

The fraction of land under cultivation by county (as reported by the provincial governments) ranges from 0 percent to nearly 15 percent in the region (Figure 3H). The highest proportion of land under cultivation is in the southern portions of the region and the lowest is in the Tibetan regions. Although several of the rapidly eroding areas are in counties more extensively cultivated, direct comparison of sediment yield and extent of agricultural land shows only a weak correlation when the entire data set is analyzed ($r^2 = 0.22$, $p < 0.001$; Figure 4H). When the basins are sorted by area and each group is analyzed individually, fraction of land under cultivation does not predict sediment yield ($p > 0.05$ in all cases).

The land cover for the study area consists primarily of grasses and forest (Figure 3I). On average, only about 10 percent of each of the basins for which we calculated sediment yield is cropland. The maximum percentage of cropland in a basin is as high as 86 percent (this value is for one intermediate reach) but sediment yield is low for basins with more than 40 percent agricultural land; the highest sediment yield among these basins is 1.41 kg/km^2/year. Sediment yield from the basins does not correlate with proportion of a basin under agricultural use defined by satellite data ($p > 0.5$; Figure 4I),

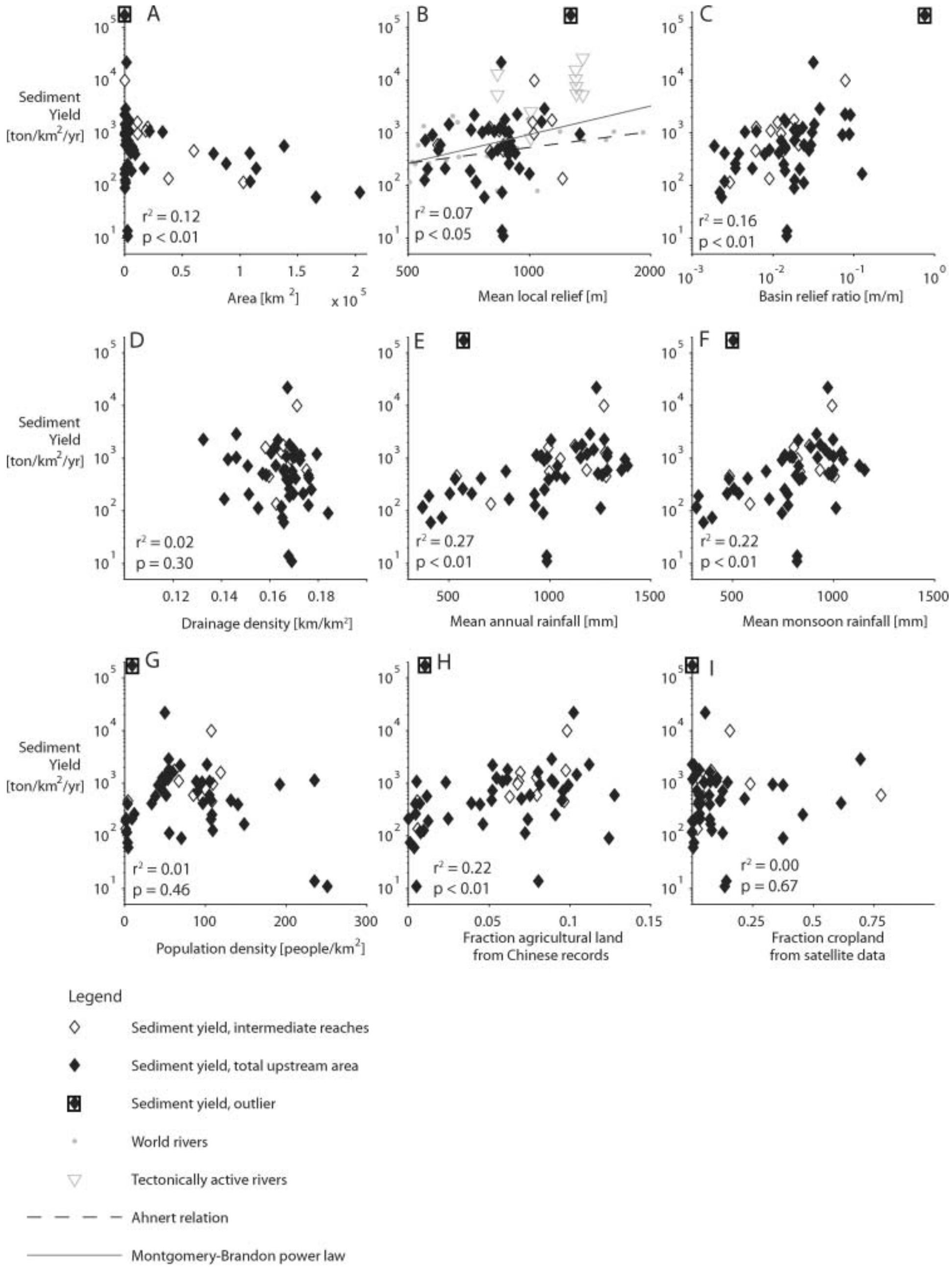

Figure 4. Scatter plots showing the relation between various geomorphic and anthropogenic metrics and sediment yield. Black diamonds indicate sediment yield for the entire upstream area and open diamonds indicate sediment yield for an intermediate reach between two stations. A box is around an outlier point that was left out of correlation analyses. (A) The sediment yield as a function of area. Note the decreasing variation in mean annual sediment yield with increasing basin area, suggesting that basins effectively buffer against sediment loading. (B) The sediment yield as a function of mean local relief. Global data from Montgomery and Brandon (2002) are shown in gray in the background as well as the Ahnert relation and the power law proposed by Montgomery and Brandon. Our sediment yield values approximately plot on top of world data for the same relief but with higher scatter. (C) The sediment yield as a function of total basin relief reveals a strong correlation with little predictive power. (D) Sediment yield is not correlated to drainage density. The outlier is missing from this plot because the basin is too small and dry to have any identified channels and thus does not have a calculated drainage density. (E) The sediment yield as a function of rainfall reveals a weak but robust correlation between the two. (F) Sediment yield is also weakly but robustly correlated with monsoon rainfall. (G) Sediment yield as a function of population density has no correlation. (H) Sediment yield is weakly correlated to fraction agricultural land (based on Chinese county-wide data). Note that on a county-by-county basis, rainfall is strongly correlated with agricultural land, suggesting that people farm more in places with more rain and making it impossible to unravel the two signals. (I) Sediment yield is not correlated to land use as classified with U.S. Geological Survey (USGS) classifications from satellite data.

Table 5. Geomorphic and climatic parameters for the intermediate reaches between two stations

Station number	Area (km^2)	Mean annual sediment yield ($ton/km^2/year$)	Mean local relief (m)	Basin relief ratio ($\times 10^{-2}$; m/m)	Drainage density (km/km^2)	Mean annual rainfall (mm/year)	Mean monsoon rainfall (mm/year)
104	72	−452	480	7.06	0.359	944	789
85	221	9,900	1,028	7.86	0.171	1,268	994
57	60,131	458	861	0.61	0.167	539	486
4	10,888	−747	1,505	1.11	0.164	844	681
43	174	−30	960	7.38	0.187	994	809
86	6,516	554	898	1.41	0.166	998	835
5	11,136	1,598	1,018	1.15	0.158	993	803
6	20,058	1,273	796	0.62	0.165	1,275	1,040
99	4,220	450	798	1.33	0.160	1,279	1,005
93	3,234	1,752	1,137	1.83	0.165	1,125	880
91	2,595	593	591	2.08	0.175	1,183	933
103	18,439	1,098	841	0.94	0.170	959	789
106	11,323	966	1,025	1.26	0.169	1,053	822
301	102,977	115	737	0.29	0.165	369	320
302	56,867	−66	843	1.31	0.168	487	423
305	38,066	135	1,209	0.90	0.163	708	586

potentially reflecting inaccuracies in the land use classification rather than a lack of relationship between sediment yield and agricultural land. In all basins smaller than 10^5 km^2, $p > 0.2$ for correlations between cropland and sediment yield. For the largest basins cropland is a predictor of sediment yield ($r^2 = 0.76$, $p < 0.05$).

For the single regressions, it is interesting to note that the geomorphic, climatic, and anthropogenic parameters all have the best predictive powers for sediment yield in the largest basins. Because only seven basins have upstream areas greater than 10^5 km^2, however, the apparent strength of these relationships could be an artifact of the small sample size. In general the correlations between sediment yield and the parameters we examined are strongest for the entire data set rather than for the subgroups of basins segregated by drainage area. The only basin area group that is an exception to this generalization is basins with area $>10^5$ km^2. The sediment yields for these basins correlate with fraction of cropland from satellite data, population density, rainfall, and drainage density. Fraction of cropland from satellite data and drainage density only correlate with sediment yield for these large basins. The only predictive parameter that correlates better with sediment yield when basins are segregated by area is population density, which correlates with sediment yield for some groupings of basin area but not for the data set taken as a whole. In summary, area, rainfall, fraction of land under cultivation, and monsoon rainfall are significant predictors of sediment yield ($p < 0.01$ for all four parameters). Rainfall explains the most variation in sediment yield ($r^2 = 0.27$), followed by fraction of land under cultivation ($r^2 = 0.22$), monsoon rainfall ($r^2 = 0.22$), and basin area ($r^2 = 0.12$). However, rainfall is strongly correlated with both fraction of land under cultivation and monsoon rainfall, making it difficult to discriminate between the effects of rainfall and agriculture on sediment yield in these regions.

Table 6. Anthropogenic parameters for the intermediate reaches between two stations

Station number	Mean population density ($people/km^2$)	Fraction cropland (from satellite data)	Fraction agricultural land (from Chinese data)
104	126	0.14	0.08
85	108	0.16	0.10
57	4	0.03	0.01
4	69	0.07	0.04
75	235	0.14	0.08
43	480	0.04	0.08
86	95	0.05	0.06
5	119	0.04	0.07
6	48	0.02	0.08
99	108	0.03	0.10
93	62	0.08	0.10
91	85	0.78	0.08
103	67	0.10	0.07
106	109	0.24	0.07
301	3	0.00	0.01
302	8	0.01	0.01
305	1	0.02	0.01

Table 7. Summary of the single linear regressions for the entire data set and for the basins separated by area

	All basins		Basin area $< 10^3$ km^2		10^3 km^2 < Basin area $< 10^4$ km^2		10^4 km^2 < Basin area $< 10^5$ km^2		10^5 km^2 < Basin area	
	59		15		24		13		7	
N	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p
Relief (m)	0.07	<0.05	0.09	0.26	0.04	0.32	0.12	0.26	0.43	0.11
Basin relief ratio (m/m)	0.16	<0.01	0.07	0.33	0.10	0.14	0.15	0.19	0.02	0.75
Drainage density (m/m^2)	0.02	0.30	0.21	0.09	0.00	0.95	0.02	0.60	0.70	<0.05
Rainfall (mm/year)	0.27	<0.01	0.28	<0.05	0.11	0.10	0.30	0.05	0.79	<0.001
Monsoon rainfall (mm/year)	0.22	<0.01	0.22	0.08	0.09	0.16	0.30	0.06	0.54	0.06
Population density (people/km^2)	0.01	0.46	0.37	<0.05	0.33	<0.01	0.27	0.07	0.83	<0.001
Fraction cropland	0.00	0.67	0.03	0.57	0.02	0.52	0.12	0.24	0.76	<0.05
Fraction of land under cultivation	0.22	<0.01	0.05	0.41	0.13	0.08	0.26	0.07	0.22	0.29

In the Jinsha and Yalong tributaries of the Yangtze River, Lu and Higgitt (1999) reported sediment yields ranging from 65 to 1,770 tons/km^2/year for thirteen watersheds. The sediment yields they reported correlate poorly with both population density and percent cropland (from the land cover data, $r^2 = 0.07$ and 0.09, $p > 0.2$, respectively); fraction of agricultural land is not available for Sichuan counties.

None of the eight stations with more than twenty years of records show systematic, temporal variation in sediment yield or sediment rating curve parameters (Figure 5). Most stations exhibit little variability in either sediment yield or rating curve parameters. Stations 4, 11, 103, and 106 exhibit temporal variability in sediment yield that is neither systematic nor related to the time periods of intense logging. Yang et al. (2007) conducted a similar sediment rating curve analysis on seven stations on the main stem of the Yangtze River and found that only two stations show a systematic variation in the slope and intercept of sediment rating curves. In both of these cases, slope increases with time and intercept decreases. Although Yang et al. interpreted these data to indicate an increase in droughts and floods over time in the Yangtze River basin, we argue that this trend simply implies that less sediment is carried at low flows and more is carried at high flows, and does not suggest a systematic increase over time in sediment transported in the river.

Discussion

Comparing regional sediment yields to indexes of development and geomorphic and climatic parameters reveals a weak correlation of sediment yield with both rainfall and fraction of land under cultivation ($r^2 =$ 0.27 and 0.21, $p < 0.001$, respectively; $r^2 = 0.29$, $p <$ 0.001 for the multiple regression with both variables) as well as with population density for smaller basins ($< 10^4$ km^2). The largest basins ($> 10^5$ km^2) have sediment yields that correlate with fraction of cropland from satellite data ($r^2 = 0.76$, $p < 0.05$), rainfall ($r^2 =$ 0.79, $p < 0.001$), population density ($r^2 = 0.83$, $p <$ 0.001), and drainage density ($r^2 = 0.70$, $p < 0.05$). Rainfall, fraction of land under cultivation, and population density are all correlated ($r^2 > 0.50$, $p < 0.05$ for all single and multiple regressions of these three variables), making it difficult to unravel the relative importance of each. Additionally, although the majority of precipitation falls during the monsoon, monsoon rainfall patterns are nearly identical to annual rainfall patterns and using monsoon rainfall instead of mean annual rainfall does not significantly change the analysis. These results suggest that the gradient in sediment yield across the IRYT is controlled by the rainfall gradient and that the net anthropogenic influence on sediment yield across this region is comparable to the variation in sediment yield that might be attributed to variation in rainfall. Because more agricultural land tends to be in areas that have higher rainfall, it is not surprising that the relationship between sediment yield and patterns of rainfall and agricultural land generally follow parallel trends. Additionally, the strong qualitative coincidence of high sediment yields and high population densities, high rainfall, and higher fractions of agricultural land suggest at least a weak anthropogenic control on sediment yield, the details of which are lost when comparing basin-wide averages.

Sediment yields and sediment rating parameters for stations with more than twenty years of data show no systematic temporal changes, and the standard error of the annual means is below 5 percent. For these stations the interannual variation in sediment yield and the

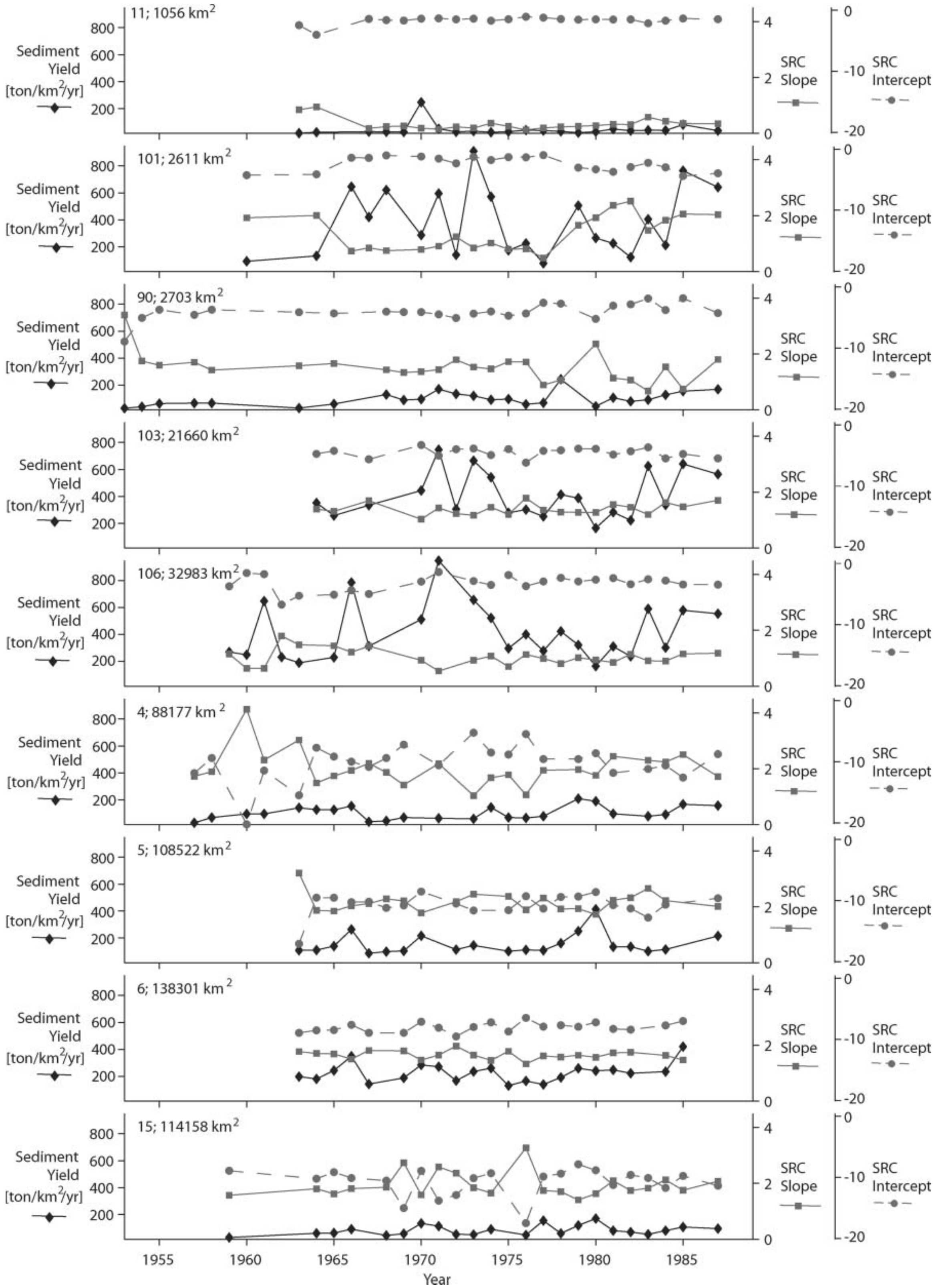

Figure 5. Sediment yield as a function of time (black line with diamonds) and sediment rating curve parameters as a function of time (gray dashed line with circles shows the *y*-intercept and gray solid line with squares shows the slope). Each plot has the station number (for reference to Table 1) and upstream area of the station noted. These sediment yield values are for the entire upstream area, not for any intermediate reaches. Details for how we obtained these values are shown in Figure 2. An interesting trend in the sediment rating curve figures is that the intercept and slope are inversely correlated to one another. None of the parameters show major trends during the period of record for any station.

slope and intercept of sediment rating curves systematically decrease with increasing basin area (Figure 4A). The most likely explanations for the lack of change in sediment yield and sediment rating curve parameters through time are (1) that deforestation and development activities are not profound enough to overshadow natural variability in sediment yield in the IRYT or (2) that any anthropogenic influence on patterns of sediment yield is a result of long-term agricultural activity that predates the establishment of the hydrology stations from which our data were collected.

Although it is possible that these sediment yields reflect agricultural practices, the erosion rates for most basins are lower than longer term rates calculated from ^{10}Be in modern river sand (Figure 6; Henck et al. 2007). This suggests that if sediment yields have increased because of agricultural activity, it is either buffered in the system and not visible in short-term records or is not large enough to exceed longer term erosion rates. In contrast, two basins with extremely high modern sediment yields (basins upstream of stations 32 and 311) suggest erosion rates of 8 mm/year and 65 mm/year, respectively, which far exceed the longer term rates (0.05–0.38 mm/year). Basin 311 is a small watershed in Tibet and sediment yield was only monitored in the watershed for five years. GoogleEarth images show extensive terracing and landslide scars in that basin. Erosion rates of 65 mm/year are not sustainable over any significant period of time; therefore, we hypothesize that a major disturbance (such as a landslide, fire, logging, or mining) occurred in the watershed immediately prior to the time sediment yield measurements began. Heavy logging and agricultural land use apparent on GoogleEarth suggest that sediment yield data from these catchments reflect a transient response to disturbances.

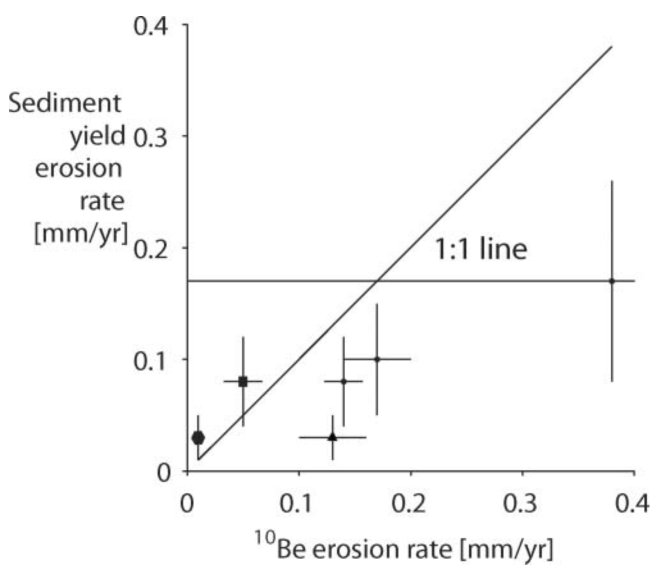

Figure 6. Erosion rate calculated from sediment yield as a function of erosion rate measured over millennial time scales from ^{10}Be data. Salween data are shown with a square, Mekong data with circles, Yangtze data with a hexagon, and Tsangpo data with a triangle. The modern erosion rates are generally lower than would be expected from the longer term data, with the notable exceptions of the point on the Yangtze River where sediment yield erosion rates are higher than ^{10}Be erosion rates and the point on the Salween River where sediment yield erosion rates are slightly higher than ^{10}Be erosion rates but within the error of the sediment yield data. We use reported errors for ^{10}Be data and estimate 50 percent errors on sediment yield data. Unfortunately, the areas of data do not overlap for a large area. Salween, Mekong, and Yangtze River ^{10}Be data are from Henck et al. (2007), Tsangpo River ^{10}Be data are from Finnegan et al. (2008), and Yangtze River sediment yield erosion rates are calculated from Higgitt and Lu (1996).

The decrease in variation of mean sediment yield and the interannual changes in sediment yield and sediment rating curve parameters with increasing basin area suggest a buffering effect of large basins, which might mask anthropogenic changes. This buffering is most likely to happen through small-scale storage of sediment as it leaves the altered subbasin and enters the larger river system. Large alluvial fans at the mouths of tributary valleys are common in the narrow reaches of the Salween and Mekong Rivers, providing evidence for active sediment storage along these rivers. In addition, the presence of two large intermediate reaches with apparently negative sediment yields provides further evidence of sediment storage (the areas upstream of stations 4 and 302, on the Mekong and Tsangpo Rivers, respectively). To show the magnitude of sediment storage in these two reaches, we plotted the total sediment yield as a function of basin area for the stations along the main stems of the Mekong and Tsangpo Rivers (Figure 7). Both of the reaches with negative sediment yields have numerous sand bars, small flood plains, and alluvial fans in which sediment is stored.

In light of a large body of literature showing that agriculture, development, and logging locally increase erosion rates (Syvitski 2003), we suggest that to the extent that these anthropogenic activities locally increase erosion, the sediment is stored locally and does not make it to the rivers in the larger basins. In addition, the correlation between sediment yield and rainfall, fraction of land under cultivation, and population density for basins smaller than 10^4 km^2 suggests that the variability we see in sediment yield is weakly controlled by these two factors, which are strongly correlated. Any additional variation from anthropogenic activities is almost

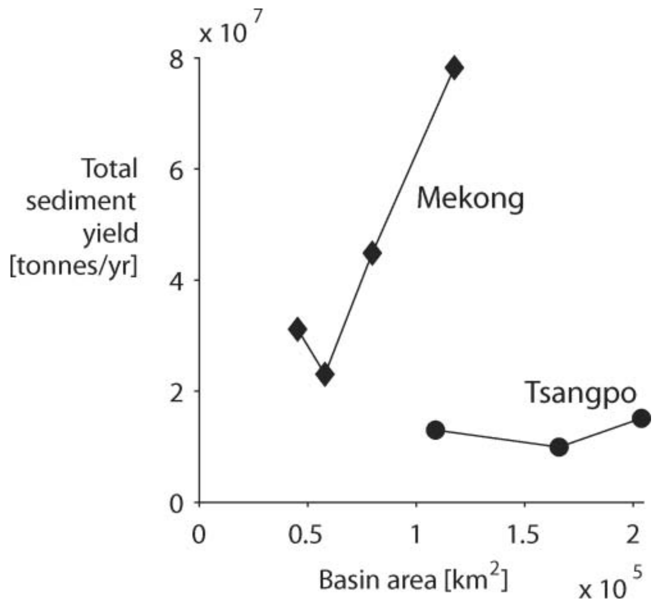

Figure 7. Cumulative sediment yield as a function of upstream area. The slope of the line is the erosion rate between two points. It is apparent from this figure that the upper Tsangpo River has a much lower overall erosion rate than the Mekong River.

certainly smaller than the magnitude of these controls, especially in larger rivers.

In contrast to suggestions that the Communist policies between the 1950s and 1980s have increased sediment yields, recent studies of modern sediment yields in China show a strong influence of dams on sediment yield following 1987 (X. Q. Chen et al. 2008). Although it is possible that significant amounts of sediment are stored behind dams in the basins we analyze, the data do not reflect any effect of dams being installed (such as a systematic decrease in sediment with increasing distance downstream). In addition, X. Q. Chen et al. (2008) found that the major effects of dams did not start until after 1987. Although dam locations are not freely available, Magee (2006, Map 1) showed only two completed dams on the Mekong River and none on the Salween River at the time of writing. The two completed dams on the Mekong are part of an ongoing project and thus have probably been built recently. Our data do not extend past 1987, so it is unlikely that we would see any effects from dams in the region. Major dam building efforts are currently underway in the watersheds we analyzed (Feng and He 2004; Magee 2006) and we expect that analysis of more modern data would clearly show these effects. In general, due to the apparent buffering effect that large river basins have on sediment yield, we suggest that future research on anthropogenic effects on sediment yield in this region focus on basins under 5,000 km^2 in size.

Extending these results brings into focus the differences among the IRYT, the Yangtze River basin, and the Yellow River basin. Of the large body of literature on anthropogenic impacts to Yangtze River sediment yield, only three studies find that sediment yield increases with time. These either imply sediment yield from flood frequency data (Yin and Li 2001), imply changes in sediment yield based on land use data (G. J. Chen 2000), or present figures and tables that do not support the conclusion that sediment yield increased with time (Yi 2003). None of these studies used the methods presented here or those used in other studies in this region. Other studies find that sediment yield decreased or remained steady through time, primarily by using data from stations downstream on the Yangtze River rather than smaller tributaries (Lu and Higgitt 1998, 1999; Higgitt and Lu 1999; Z. Chen et al. 2001; Lu, Ashmore, and Wang 2003a, 2003b; Xu 2005; Z. Y. Wang, Huang, and Li 2007). Higgitt and Lu (1996) suggested that erosion rates in the Yangtze River do not currently reflect increased hillslope erosion due to human activities, a hypothesis supported by ^{137}Cs measurements (Lu and Higgitt 2000).

The Yellow River has an extremely long history of human disturbance and, in modern times, an acute water supply deficit. The longer history of disturbance in the Yellow River basin means that conservation efforts were started in the early 1900s and, thus far, appear to be successful in curbing sediment loss (Hassan et al. 2008), although the lack of water in the river as many as 220 days a year (S. J. Wang, Hassan, and Xie 2006) now means that it is impossible to know what the basin-wide sediment yields would be if the river flowed year-round. Obviously a large amount of sediment is stored in the basin because no water is available to transport the sediment out of the basin. The decrease in sediment yield in the Yellow River basin due to sediment storage is parallel to our results for the IRYT in that sediment yield is not necessarily commensurate with increasing local erosion or development.

Conclusions

Our data extend the complicated story of China's relationship with the environment and the effects of modern policies on erosion rates throughout the country, but we are unable to draw any strong conclusions about how much modern Chinese policies affected sediment yield from large watersheds. Despite reported environmental devastation to the countryside and accelerated erosion, we present a substantial data set on sediment yield that reveals only a weak correlation between modern sediment yield and fraction of land under cultivation and with population density in basins smaller than 10^4 km^2. The largest basins ($> 10^5$ km^2) have sediment yields that correlate with fraction of cropland from satellite data, population density, rainfall, and drainage density. We find no correlation of sediment yield with other geomorphic and human activity metrics and instead find remarkable temporal stability in sediment yield over several decades. These results do not, however, show that development activities and logging do not mobilize large amounts of sediment. Rather, we consider it more likely that they indicate that such sediment is being stored in higher order, ungauged channels, floodplains, or alluvial fans and is not being transported out of the study basins by the rivers. This is particularly likely to be true for larger basins, as they show less variability in annual sediment yield. If our interpretation is correct, the data indicate that larger basins are effectively buffered against rapid and extreme variations in sediment yield, suggesting that smaller basins are more likely to show the expected changes due to anthropogenic activity. Hence, particular caution is needed in relating regional sediment fluxes in and degradation of rivers to agriculture, logging, and construction. Although these activities might have large local effects, in southwest China they have comparable effects to regional patterns in rainfall in controlling basin-wide sediment yield. Smaller scale studies over a wide region are required to improve understanding of the processes related to producing, transporting, and storing sediment in this region. Such small-scale studies could provide a means to quantify the apparent qualitative correlation between sediment yield and both agricultural land and population density that is apparent on visual inspection of the data but is not reflected in basin-scale averaging and regressions.

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Notes

1. The epigraph to this article is drawn from J. Shapiro, *Mao's war against nature: Politics and the environment in revolutionary China*. (Cambridge: Cambridge University Press, 2001). In this book there is a note indicating that this text was "quoted in *Rand-McNally Illustrated Atlas of China* (New York: Rand-McNally, 1972), frontispiece. No other bibliographic information available."
2. Zangdian Guoji Heliu in Chinese.
3. Yalong Zangbo Jiang, Nu Jiang, Lancang Jiang, and Yuan Jiang, respectively.
4. The Three Rivers Region is where the Salween, Mekong, and Yangtze Rivers flow parallel to one another in Eastern Tibet. This area is not the Three Gorges; that is much further downstream on the Yangtze River.

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