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How important and different are tropical rivers? — An overview

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ABSTRACT

Tropical river systems, wherein much of the drainage basin experiences tropical climate are strongly influenced by the annual and inter-annual variations of the Inter-tropical Convergence Zone (ITCZ) and its derivative monsoonal winds. Rivers draining rainforests and those subjected to tropical monsoons typically demonstrate high runoff, but with notable exceptions. High rainfall intensities from burst weather events are common in the tropics. The release of rain-forming aerosols also appears to uniquely increase regional rainfall, but its geomorphic manifestation is hard to detect. Compared to other more temperate river systems, climate-driven tropical rivers do not appear to transport a disproportionate amount of particulate load to the world's oceans, and their warmer, less viscous waters are less competent. Tropical biogeochemical environments do appear to influence the sedimentary environment. Multiple-year hydrographs reveal that seasonality is a dominant feature of most tropical rivers, but the rivers of Papua New Guinea are somewhat unique being less seasonally modulated.

Modeled riverine suspended sediment flux through global catchments is used in conjunction with observational data for 35 tropical basins to highlight key basin scaling relationships. A 50 year, daily model simulation illuminates how precipitation, relief, lithology and drainage basin area affect sediment load, yield and concentration. Local sediment yield within the Amazon is highest near the Andes, but decreases towards the ocean as the river's discharge is diluted by water influxes from sediment-deprived rainforest tributaries. Bedload is strongly affected by the hydraulic gradient and discharge, and the interplay of these two parameters predicts foci of net bedload deposition or erosion. Rivers of the tropics have comparatively low inter-annual variation in sediment yield.

1. Introduction

Compared to mid- and high-latitude regions of the world, tropical land areas occupy only 19% of the land surface (Peel et al., 2007). On a continental basis, Peel et al. (2007) found that the South American land surface is most affected by tropical climate at 60.1%, followed by Africa (31%), Asia (16.3%), Australia (8.3%), and North America (5.9%), with Europe having no land experiencing tropical climate (Fig. 1). Because European and North American rivers (excluding Mexico and the Caribbean) are non-tropical, it is probable that inadequate attention has been paid in the literature to fluvial systems which may have been even more dominant in the geologic past (see Latrubesse et al., 2005). This disparity is now changing through growing international research connections, attempts to study and model the terrestrial system as a whole (Earth System Science), and the development of globally consistent databases, including those from remote sensing observations (Syvitski et al, 2012).

We employ here a narrow view of tropical rivers and base our analysis on those drainage basins whose boundaries are principally located within the tropical climate zone as defined by Peel et al. (2007), in their update to the Köppen–Geiger climate classification. Tropical zones have coldest months with temperatures greater than 18 °C and are strongly influenced by the Inter-tropical Convergence Zone (ITCZ). Three subzones are defined in terms of precipitation indices. 1) A rainforest subzone has for its driest month (P_d) >60 mm of precipitation (typically located within 5–10° of the equator; darkest color zone in Fig. 1). 2) A monsoon subzone is more seasonal, where the driest month P_d is <60 mm but equal or greater than 100 − (P_{avg} / 25), where P_{avg} is the average annual precipitation in mm (intermediate color zone in Fig. 1). The zone is influenced by significant seasonal wind, and seasonal precipitation variation can be very large. 3) A savannah subzone, defined as $P_d < 100 - (P_{avg} / 25)$, where there is a pronounced dry season (lightest color zone in Fig. 1). Note that other land areas in the geographic tropics (between +23.5° and −23.5° latitude) do not experience a tropical climate (Fig. 1).

Other studies define tropical river systems more broadly, such as: 1) if a river basin lies within the geographic tropics, or 2) if a river basin experiences warm temperatures with little intra-annual variability, or 3) if the floodplain or delta plain is located within the tropical climate belt. These definitions may include, for example, rivers that are influenced by snow or ice melt (e.g. the Indus), or have large portions of their drainage basin lying in more arid or temperate climates

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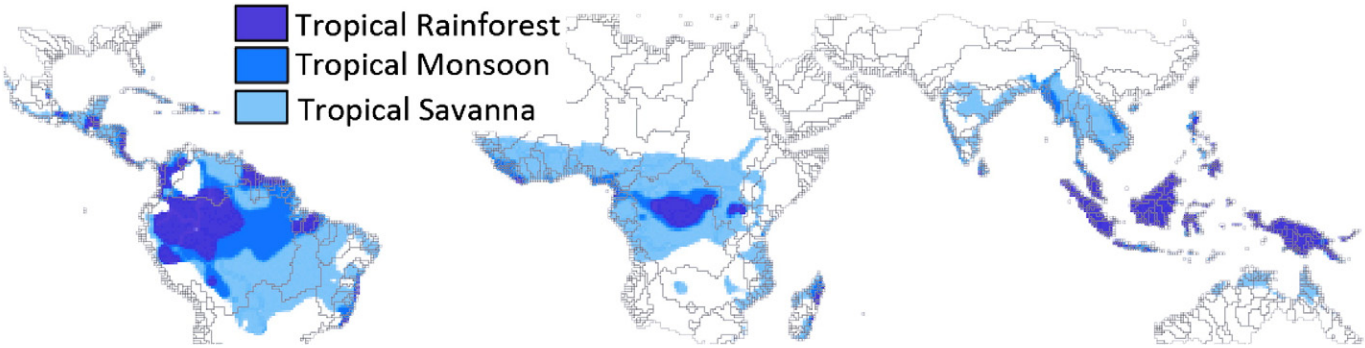


Fig. 1. Tropical regions of the world (after Peel et al., 2007) superimposed on drainage basins — see text for details.

(the Ganges, Brahmaputra, Parana) (e.g. Latrubesse et al. 2005). By restricting our study to the definition of river basins dominated by tropical climate, sensu stricto, we can examine the climate impacts such as the movement of the ITCZ across a drainage basin. This approach simplifies assessing the implications for tropical river systems in the geologic past. Our study still includes many important river systems: Magdalena, Orinoco, Amazon, and Sao Francisco in South America; Gambia, Volta, Niger, Congo, and Zambezi in Africa; many Indian rivers such as the Godavari, Krishna, and Mahanadi; the Irrawaddy, Mekong, and Chao Phraya in Southeast Asia; and rivers draining many islands — e.g. Madagascar, Sri Lanka, Malaysia, Indonesia, Philippines, Borneo, Papua New Guinea (PNG), Hainan, Cuba, Puerto Rico, and Hawaii. The movement of the ITCZ and its derivative monsoonal patterns also influences areas outside of the tropical belt, e.g. Mississippi, Yangtze, but these are not tropical regions and such rivers are not included here.

Modern tropical rivers have high geological relevance as they provide insight into the rock record during periods of generally warmer climate (e.g. Latrubesse et al. 2005). Tropical rivers may also carry a disproportionate amount of sediment load to the world's oceans, both in particulate and dissolved forms (Milliman and Farnsworth, 2011). The rate of biogeochemical weathering and rainfall intensity (convective, cyclonic, or orographic, Fig. 2) reaches its maximum in the tropical zone (Syvitski and Milliman, 2007). Bedrock materials susceptible to erosion by these rivers and streams may already be strongly weathered (deep profile saprolitic soils are common). Biochemical rather than physical weathering processes may play a much larger role in determining the particulate matter transported: dense vegetation cover and warm temperatures create conditions where organic chemistry provides runoff carrying high concentrations of humic and fulvic acids (the "black river" or Rio Negro is a classic example). In-river biochemistry is also different. For example, bacteria living in the Amazon River digest nearly all woody plant matter before it reaches the Atlantic Ocean, and the carbon is thereby released back to the atmosphere instead of being sequestered in the deep ocean: large amounts of CO_2 are "exhaled" (Ward et al., 2013). Lastly, the river basins are as geomorphologically variable as river basins located in temperate latitudes, reflecting the influences of tectonism and drainage network evolution. However, unlike the river basins to the north and south, tropical fluvial systems are little affected by cold seasons and warm season snowmelt, and by the very high physical weathering and uplift occurring in glacierized mountain belts.

Below we provide an overview on tropical rivers and focus on their characterization and uniqueness in light of the drivers of river hydrology — climate and weather systems, and rainfall. We first describe surface runoff at the river basin scale and with stream hydrographs, including the connection to weather events and flood frequency. Next we describe basic relationships between suspended loads and basin properties using observations from 35 tropical rivers, and simulation results from a global water balance-transport model, *WBMsed*. The bedload sediment transport in the presence of warm tropical water is defined and viewed along with other "unique" properties of tropical rivers within a global perspective.

2. Tropical rainfall

Intense convective rainfall is the hallmark of the tropics (Fig. 3). The rainfall pattern responds to the position of the ITCZ, the major climate driver. ITCZ seasonal movement follows the solar nadir, although continental locations also influence the ITCZ position (Fig. 3). Through the convergence of the Hadley Cell Trade Winds, this atmospheric upwelling zone combines with equatorial moisture to expand the troposphere and develop the world's largest foci of thunderstorms (Fig. 2). Thunderstorm activity is regionally variable but sometimes exceeds 100 per year. The northern and southern margins of the ITCZ are zones of intense horizontal wind shear and low-level vorticity and thus the birthplace of tropical cyclones (Fig. 2) that often reach their maximum

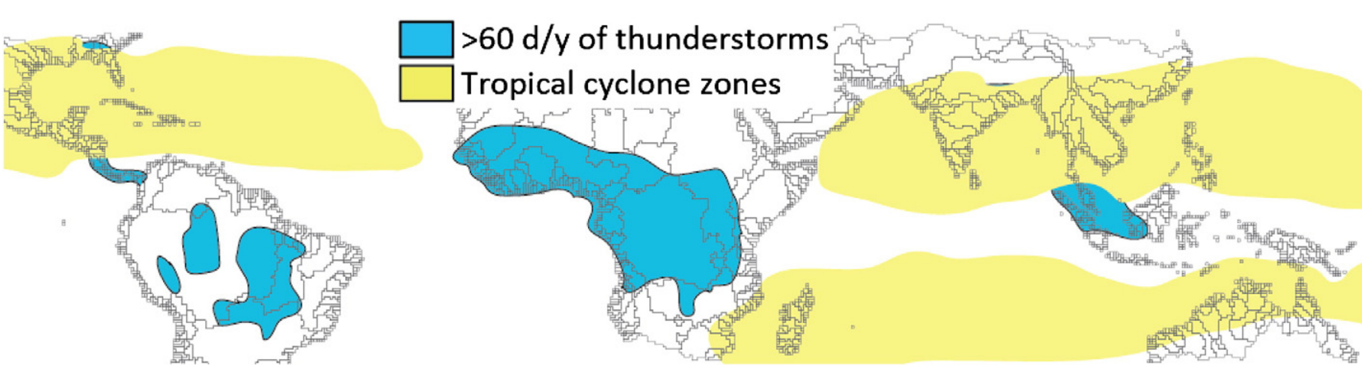


Fig. 2. Generalized tropical thunderstorm and tropical (hurricane, typhoon) cyclone zones (data NOAA, Unidata).

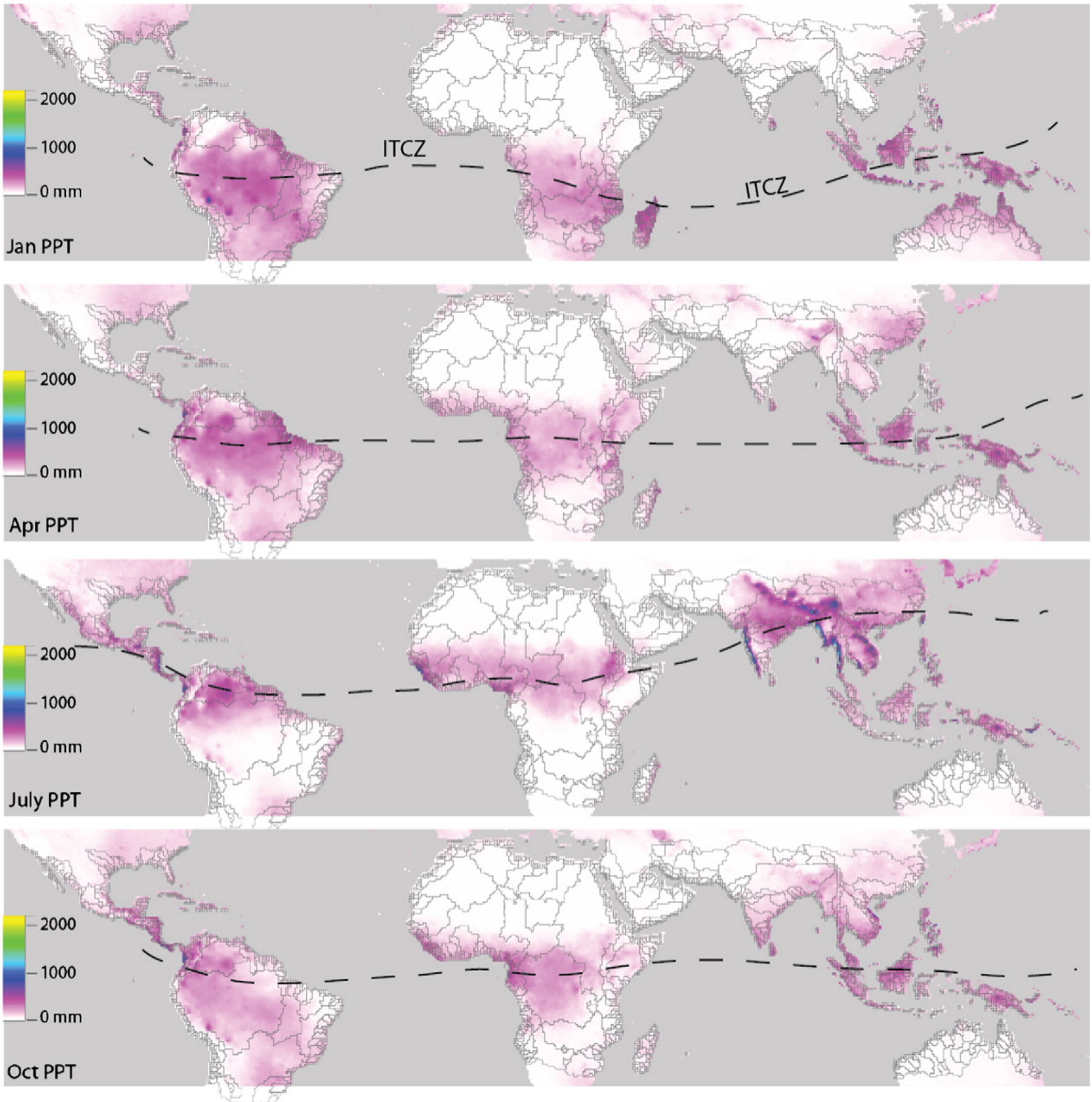


Fig. 3. Seasonal precipitation patterns (monthly averages in mm), NCDC-NCEP climate: www.cdc.noaa.gov/cdc/data.ncep.reanalysis.derived.html.

strength in the tropics (Syvitski et al., 2009). However, South America and West and Central Africa, and portions of Indonesia, PNG and Borneo do not experience tropical cyclones. Weak Coriolis rotation within 10° latitude precludes the formation of tropical cyclones. For South America, upwelling of cold ocean water on its Pacific Margin coupled with a much smaller spin-up zone in the South Atlantic limits cyclone formation.

Island topography provokes orographic precipitation from mountain clouds (i.e. in the cloud forest zone), fed by near continuous moisture sourced through latent heat transfer from adjacent tropical, surface ocean waters (e.g., watersheds in the islands off SE Asia, Central America, and elsewhere). Annual rainfall along the 800 m high mountain peaks of O'ahu, Hawaii can exceed 7 m in a year, yet much of the island area receives limited precipitation (<1 m/y). The highlands of PNG receive between 300 mm and 800 mm per month, yet the lowlands receive typically half of these levels. If an atmospheric river shed from the Pacific ITCZ were to intersect one of these island chains, they can also release large volumes of precipitation over mountains during events that can last for several days. An atmospheric river is a narrow atmospheric corridor of concentrated moisture that typically draws moisture away from the tropical regions as focused between zones of divergent surface airflow. Atmospheric rivers are the dominant meridional transport mechanism for moisture on planet earth.

The Tropical Rainfall Measuring Mission or TRMM, operated by the American and Japanese space agencies, was the world's first major effort focused on understanding the rain patterns of tropical regions (Adler et al., 2000; Huffman et al., 2007). The TRMM satellite, operating since 1998, carries: 1) a precipitation radar (PR), 2) a passive microwave radiometer (TMI), 3) a visible and infrared scanner (VIRS), 4) a radiant energy sensor (CERES) and 5) a lightning imaging sensor (LIS). These data are combined with a variety of other orbital data (e.g. the Special Sensor Microwave Imager (SSM/I) and other sensors), and operational data (TIROS operational vertical sounders), plus rain gauge data, and gridded to provide 0.25° × 0.25° precipitation every 3 h (e.g. Fig. 4). TRMM data offer a sustained, high temporal resolution view of the spatial patterns, timing, duration and intensity of tropical precipitation

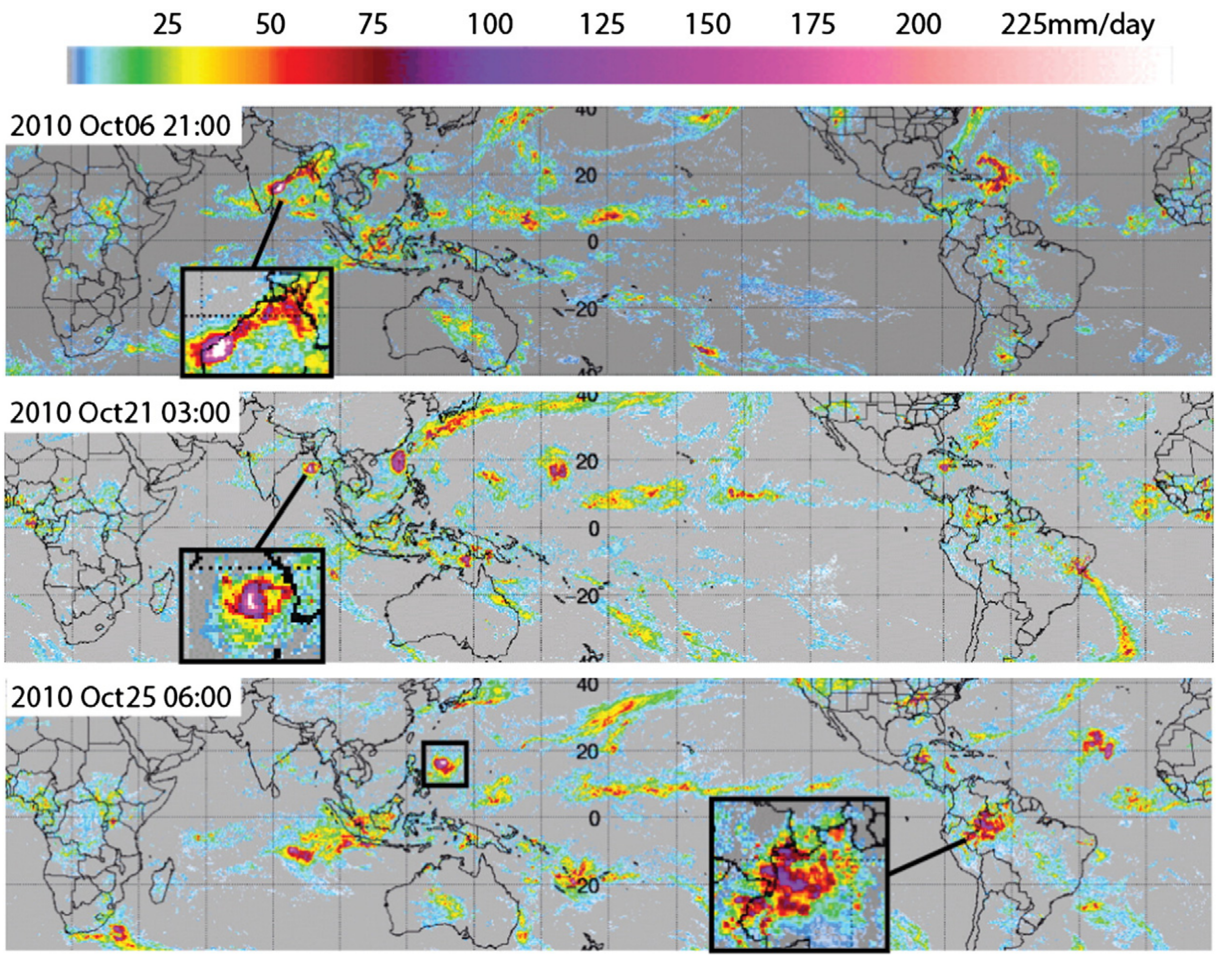


Fig. 4. TRMM data for three time slices during the Sept/Oct period of 2010. Rainfall events are often intense (>200 mm/d) and short lived. Oct 6 inset: Tropical Depression BOB2. Oct 21 inset: very severe cyclonic storm Giri. Oct 25 inset: heavy convective rainfall over the Amazon; small box: Typhoon #16.

over a 15 + y time span. Tropical rainfall events as observed from TRMM data are often from burst precipitation (hours to days) separated by dry periods (days to weeks). For example, the intense rainfall (>125 mm/d) over Amazonia on Oct 25, 2010 (Fig. 4) lasted only two days.

Convective rainfall systems over the tropics may carry a horizontal transport component, particularly over Africa, the Indian Subcontinent, and SE Asia mainland (e.g. Thailand) that are dominated by monsoonal winds and moisture. Much of the weather in the tropics develops over the ocean and moves landward, and this lateral translation of convective systems limits rainfall rates in these regions. Central Africa and South America, which have vast continental hydrology systems are exceptions. Large convective systems may also develop into rotating tropical depressions or waves over warm ocean water of the tropics and can evolve to cyclones where rainfall intensities can easily exceed 250 mm/d (Fig. 4). While cyclones can sometimes stall, they often travel rather quickly over ocean surfaces and dissipate over land. Such dissipation can lead to flooding rains in tropical catchments.

Tropical rainforests are themselves important contributors to their own rainfall (Supplemental Fig. 1), by mediating moisture, energy and aerosols (Niyogi et al., 2007; Pöschl et al., 2010). The aerosols released from the trees, convectively rise into the lower troposphere where cloud droplets attach as part of a process called cloud condensation nucleation. After air passes over extensive vegetation cover, at least twice as much rain may fall, a process that affects more than 60% of the tropical land surface (Spracklen et al., 2012). The ecosystem and the atmosphere are coupled in a feedback system where the cloud droplet number over a rainforest is limited by aerosols, and the quantity of aerosols depends on how much organic material is released by the ecosystem (Koren et al., 2012).

3. Tropical hydrology

Tropical river basins are among the highest runoff basins regardless of basin area. Small to medium size tropical rivers are characterized by high to very high runoff values. The Cilulung, Cimuntur, Citanduy, and Cojolang Rivers in Indonesia deliver 1.5–1.8 $m^3/m^2/y$ or m/y; the Purari and Fly Rivers of PNG, and the Porong River in Indonesia deliver 2.4–2.8 m/y; and the Kali Brantas and Solo Rivers in Indonesia deliver over 4 m/y. Truly impressive are the giant rivers that also show high basin-average runoff: Magdalena (0.94 m/y), Irrawaddy (1.04 m/y), Amazon and Orinoco (0.9–1.2 m/y). Typically, larger rivers have smaller runoff values as they often integrate a mixture of climate states (Syvitski and Milliman, 2007). Thus, the Amazon discharge is as large as it is not only because of the large drainage basin area, but its unusually high runoff/unit contributing area for a river its size. Rivers draining tropical savanna have much lower runoff values (e.g. Congo, Niger, Volta) due to the seasonality of rainfall in significant areas of these systems.

Multi-annual discharge curves (Fig. 5) from 12 representative tropical rivers from a selection of more than 60 rivers were examined to see how tropical climate is manifested through its integration by runoff hydrology. The 12 rivers represent a spectrum of basin size, from the World's largest, the 4.6 M km^2 Amazon River, to a small tropical island stream, the 116 km^2 Waikele, island of O'ahu, Hawaii (Table 1). These tropical rivers have much in common with other world rivers — basin

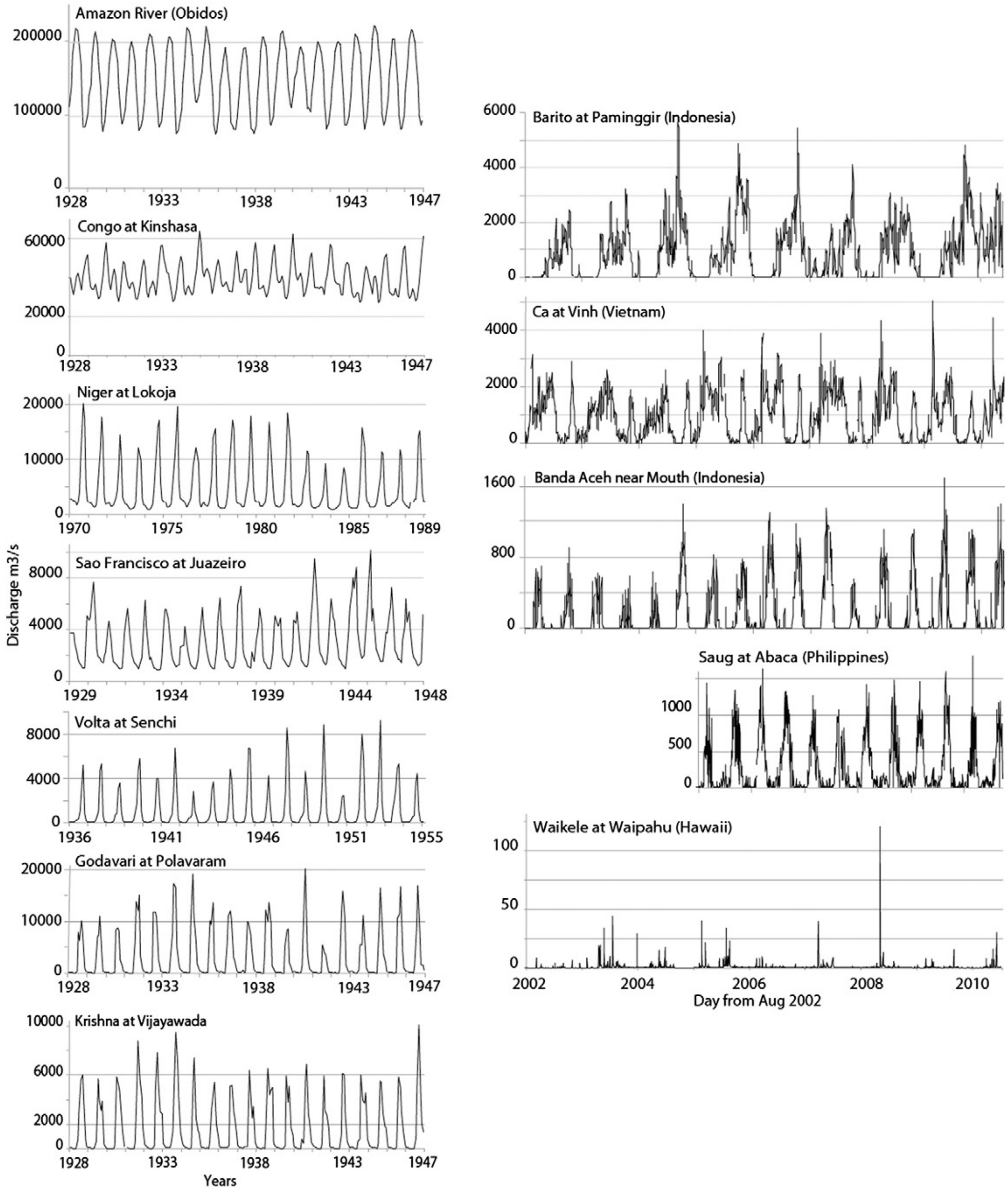


Fig. 5. Representative tropical river discharge curves, presented in order of drainage area (Table 1) from the largest at the top of the left column and ending at the lower right column. Left column is of *monthly* discharge data from calibrated stage height measurements (http://www.sage.wisc.edu/riverdata/) each covering a 19 year period and where possible the earliest measurement years before significant hydrological manipulation such as through dam operations. Right column is from *daily* remotely sensed microwave river width/area measurements (http://floodobservatory.colorado.edu/), except for the Waikele Stream, which represents gauged data, covering the period 2002–2010.5. The Right column continues the decreasing run-off trend (see text for details).

area and hinterland elevation often control the dynamics of surface runoff. Large rivers such as the Amazon and Congo have significant year round base flow and the inter-annual variability is small. Base flow used in this context is the sustained deep subsurface flow, mixed with any shallower subsurface flow, that pours into the river channel nearly continuously throughout the year. As basin area is reduced, base flow contribution as a percentage of the total decreases. Smaller rivers (Table 1) run dry during periods when the ITCZ is no longer above their drainage basins. In general, the coefficient of variation for discharge is very small for large rivers and increases for smaller ones. Exceptions occur, particularly when the dry season is either very short, such as for the Ca River in Vietnam, or very long, such as the Waikele Stream in Hawaii.

Strong seasonality is a dominant feature of most tropical rivers. For example, rivers draining the Indian subcontinent can have maximum discharges in the tens of thousands of m^3/s, yet run dry that same year (e.g. Godavari River in 1907). Some rivers are influenced by both equatorial convective rainfall and monsoon-influenced rainfall, giving rise to two wet seasons and two very short dry seasons. Examples to varying degrees (Fig. 5) include the Congo, the Ca and some of the SE Asian island rivers (Saug, and Banda Aceh). Seasonality exceptions include the rivers of PNG with their rainfall dominated by orographic precipitation. There, the Sepik River, as measured at the Ambunti station (41,000 km^2 upstream area), has a monthly discharge ranging from 2800 m^3/s during its driest month (Sept) to 4600 m^3/s during its wettest month (Mar).

Table 1
Selected tropical river ordered on area upstream of gauging station. Elev is station elevation; longitude and latitude are of the gauging station, Q_{avg} is mean discharge, Q_{std} is discharge standard deviation, Q_{min} is minimum discharge, and Q_{max} is maximum discharge, Record Q is observed Q not part of data series, CV is discharge coefficient of variation, and Data is the number of years used to define these statistics.

River	Station	Country	Basin Area	Elev	Long	Lat	Q_{avg}	Q_{std}	Q_{min}	Q_{max}	Record Q	CV	Data
			km^2	m	Deg	Deg	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	–	Years
Amazon	Obidos	Brazil	4,618,746	37	−55.6	−1.9	155,430	12,857	71,000	250,000	370,000	0.08	29
Congo	Kinshasa	Congo	3,475,000	266	15.3	−4.3	40,223	4156	22,350	80,000	80,830	0.10	81
Niger	Lokoja	Nigeria	2,000,000	36	6.7	7.7	4976	4740	516	23,700	27,600	0.95	24
Sao Francisco	Juazeiro	Brazil	510,800	400	−40.5	−9.4	2818	1161	620	12,500	12,500	0.41	51
Volta	Senchi	Ghana	394,100	5	0.1	6.2	1212	574	9	15,000	15,000	0.47	28
Godavari	Polavaram	India	299,320	12	81.8	16.9	3157	5003	7	34,600	34,600	1.58	59
Krishna	Vijayawada	India	251,355	12	80.6	16.5	1783	2669	0	12,500	31,000	1.47	60
Barito	Paminggir	Indonesia	44,327	5	114.9	−2.5	915	1006	0	5655	?	1.01	9
Ca	Vinh	Vietnam	27,061	4	105.6	18.6	949	839	0	5026	?	0.88	9
Banda Aceh	Banda Aceh	Indonesia	1568	5	95.4	5.4	176	289	0	1700	?	1.64	9
Saug	Abaca	Philippines	1325	320	125.7	7.5	200	322	0	1800	?	1.61	9
Waikele	Waipahu	Hawaii, USA	116	6	158.0	21.2	1	2.6	0	120	120	0.43	60

For very large rivers there is little difference between daily discharge curves and monthly discharge curves; smaller rivers show greater disparity (e.g. Supplemental Fig. 2B, comparing daily and monthly records for the Niger River). Smaller river basins are more able to reflect the impact of individual rainstorms (Fig. 5), including tropical cyclones (e.g. Ca River in Vietnam). For many high relief islands (e.g. Indonesia, Hainan, Madagascar, Hawaii, Taiwan), flash floods are a signature response. For example, much of the orographic precipitation for Waikele Stream enters the porous and fractured volcanic bedrock and is transported to the coast as groundwater flow. When this groundwater system becomes overwhelmed, surface runoff can spike by several orders of magnitude (Fig. 5).

The Niger is an interesting example of a river that drains a 2 M km^2 tropical savanna climate zone, whereas its 100,000 km^2 greater delta region (downstream of the Lokoja gauging station) is exposed to a full tropical monsoon climate. The Niger Delta area (Fig. 6) receives 2.3 ± 0.26 m/y of rain (1998–2007). Actual evapotranspiration across the delta varies little, with a delta-averaged annual value of

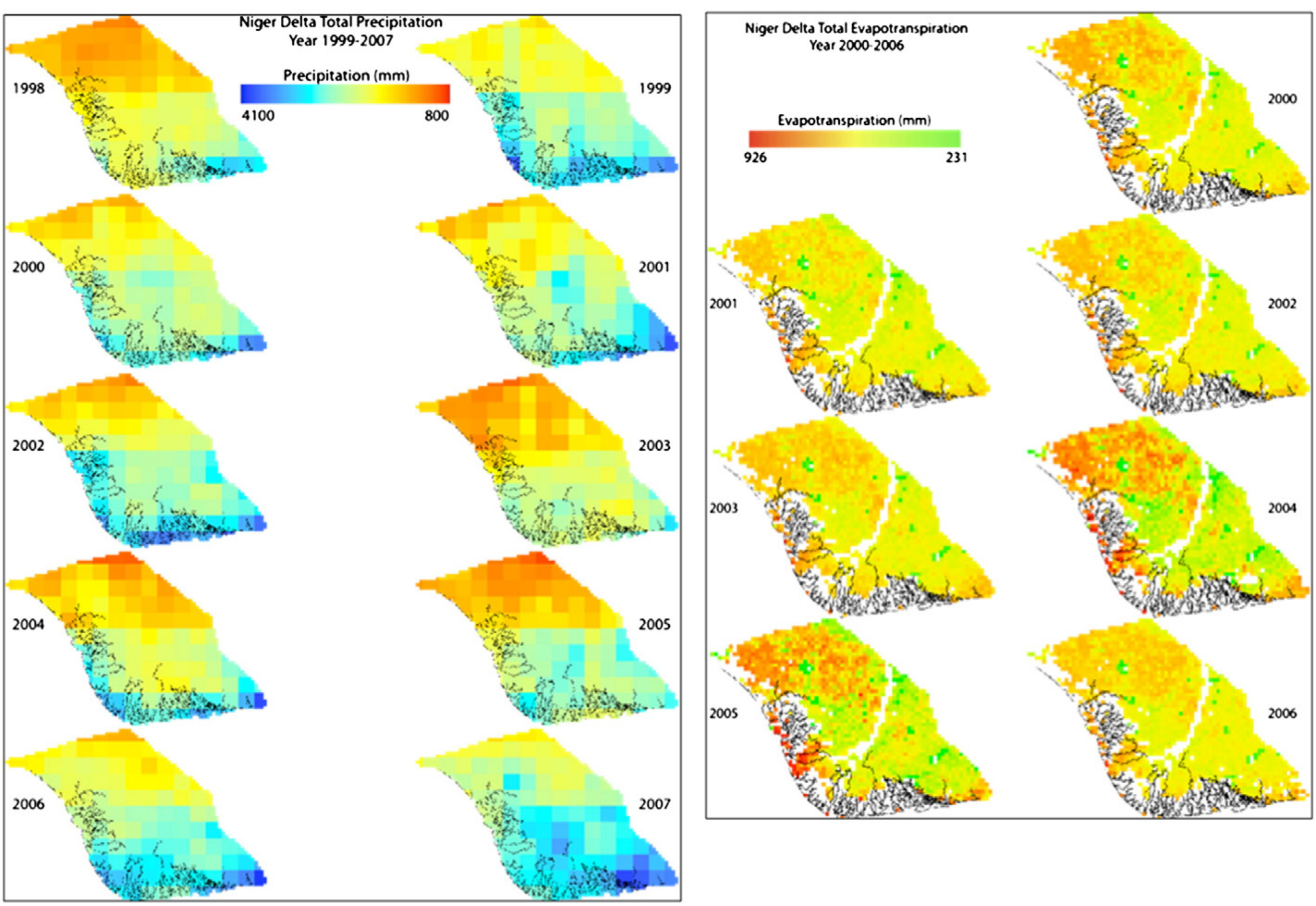


Fig. 6. Left: yearly averages (from 3 hourly data) of TRMM precipitation onto the Niger Delta (1998–2007). Right: yearly averages (from 8 day data) using the MOD16 Evapotranspiration product of the Niger Delta (2001–2006).

≈0.6 ± 0.1 m/y. The Niger River discharge upon entering the delta region is approximately 4900 m^3/s on average (Fig. 5). Yet the mean discharge of water delivered to the coastal ocean, factoring in the delta precipitation, is ~19,000 m^3/s, many times more than the Niger River itself delivers to the delta. Peak discharges entering the ocean from all delta distributary channels may exceed 56,000 m^3/s, making the Niger Delta one of the most dynamic deltas worldwide. This "delta effect" (wherein large tropical deltas receive and deliver such significant amounts of freshwater to the coastal ocean) merits further investigation.

If we define flooding as the times and areas where the river channel no longer constrains the discharge, and unconfined flow over the landscape/floodplain ensues, then many areas of the tropics experience flooding on a regular basis (Fig. 7). However, the frequency and magnitude of flooding are often no more than in other global regions where rivers respond to other types of climate forcing and where humans have tried to constrain the flow between artificial stop-banks. Detailed maps (e.g. Supplemental Fig. 3) for the 21st century flooding are available at http://floodobservatory.colorado.edu/. Fig. 7 also suggests that tropical areas that are not influenced by either tropical cyclones or monsoons are less likely to experience significant flooding (cf. Fig. 7 with Fig. 2). Fig. 7 may contain bias, as it relies in part on news-media flood reporting prior to satellite mapping of flood inundation.

4. Tropical sediment loads

We use a series of equations to best explain how the tropical landscape yields sediment to a river network, including the impact on sediment storage (lakes, reservoirs, flood plains) or secondary erosion. The *BQART* formula (1) has an average uncertainty of 38% compared to the measured sediment loads of 488 global rivers that drain 63% of the global land surface (Syvitski and Milliman, 2007):

$$Q_s = w \cdot (1{-}T_E) \cdot E_h \cdot I \cdot L \cdot Q^{0.31} \cdot A^{0.5} \cdot R \cdot T \quad \text{for } T \geq 2^\circ\text{C} \tag{1}$$

where Q_s is the long-term (>30 years) suspended sediment load, w is 0.02 for units of kg/s, or 0.0006 for units of Mt/yr, Q is the discharge of water in km^3/yr, A is the upstream contributing area in km^2, R is the upstream relief in km, T is the upstream basin-averaged temperature in °C, I is a glacier erosion factor, L is a lithology factor, T_E is the trapping efficiency of lakes, reservoirs and floodplains, and E_h is a human-influenced soil erosion factor. *BQART* can be used to solve for the upstream yield of sediment, Y_s:

$$Q_s/A = Y_s = w \cdot (1{-}T_E) \cdot E_h \cdot I \cdot L \cdot Q^{0.31} A^{-0.5} R.T \tag{2}$$

or used to solve for suspended sediment concentration, C_s:

$$Q_s/Q = C_s = w \cdot (1{-}T_E) \cdot E_h \cdot I \cdot L \cdot Q^{-0.19} \cdot A^{0.5} \cdot R \cdot T. \tag{3}$$

The daily or instantaneous sediment load is defined using the PSI equation (Morehead et al., 2003):

$$\left(\frac{Q_{s,d}}{\overline{Q}_s}\right) = \Psi m \left(\frac{Q_d}{\overline{Q}}\right)^C \tag{4}$$

where $Q_{s\text{-bar}}$ (kg/s) is a long-term average from observations or Eq. (1); Q_{bar} (m^3/s) is the average discharge derived from either long-term observations or a water-balance model (Cohen et al., 2013); ψ is a log-normal dimensionless daily random variable used to define data scatter around a sediment-rating curve, where for small rivers ψ is large and for large rivers ψ is small (Morehead et al., 2003); $Q_{s,d}$ (kg/s) is daily discharge of suspended sediment; Q_d (m^3/s) is the daily discharge of water; C (−) is a sediment rating parameter, that varies on an annual time scale (Morehead et al., 2003); and m is a dimensionless constant of proportionality and conservation of mass term.

To examine the basic scaling relationships provided in Eqs. (1–3), we compare observational data from 35 Tropical River watersheds (see Supplemental Table 1). Across five orders of magnitude, mean discharge has a log-linear relationship with an upstream catchment area (Fig. 8A). Across similar orders, a river's long-term sediment load scales with mean discharge, albeit with more scatter (Fig. 8B) as the differences in basin relief, lithology, and human factors exert their influence. A river's mean suspended-sediment concentration also scales with it's sediment yield (Fig. 8C). Both are sensitive to relief and water dilution from downstream tributary rivers that are often less turbid.

We here employ *WBMsed*, a water balance/transport model to examine the role of climate on tropical discharge and sediment load (Cohen et al., 2013). *WBMsed* calculates the surface runoff based on grids of precipitation, evapotranspiration, infiltration, soil moisture, irrigation, reservoirs and diversions, and a fully distributed global suspended sediment flux model based on Eqs. (1–4) (Cohen et al., 2013). Sediment flux predictions (Eqs. 1–4) take into account relief, lithology, catchment area, discharge magnitude, temperature, reservoir trapping, and land use practices. The flow routing schema employs a cell-tree topology (e.g. HydroSHEDS) and a semi-implicit finite difference solution to the Muskingum–Cunge equation using a diffusive wave solution to the St. Venant equations such that acceleration terms in the momentum equation are ignored. Bankfull discharge is monitored for each pixel using a floodplain schema as described by Yamazaki et al. (2011) to simulate overbank flooding. Irrigation is set as a function of irrigated land within each computational grid cell, with irrigational water demand obtained from four sources: (1) small reservoirs, (2) shallow groundwater,

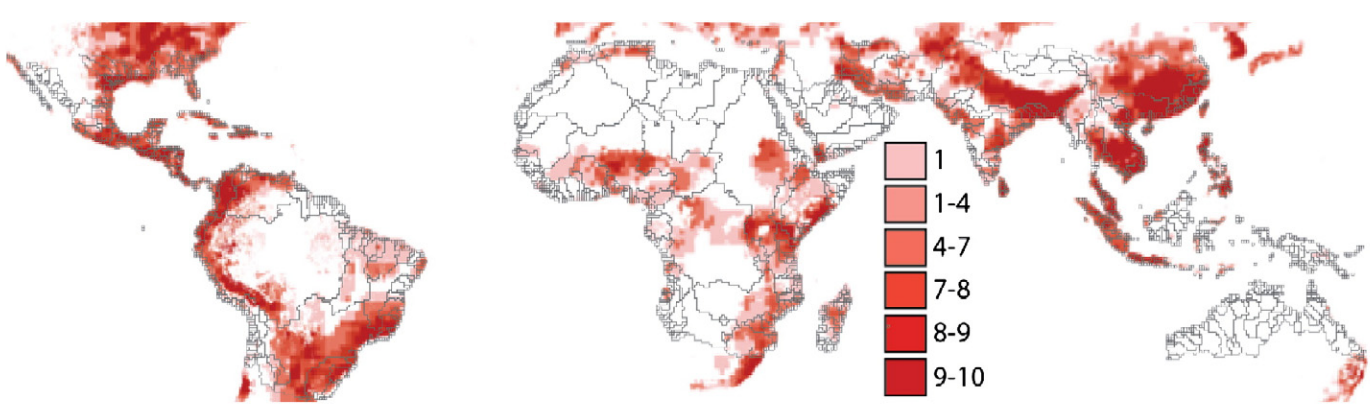


Fig. 7. Global flooding hazard frequency between 1985 and 2003 superimposed on drainage basin boundaries (data http://sedac.ciesin.columbia.edu/data/set/ndh-flood-hazard-frequency-distribution/data-download).

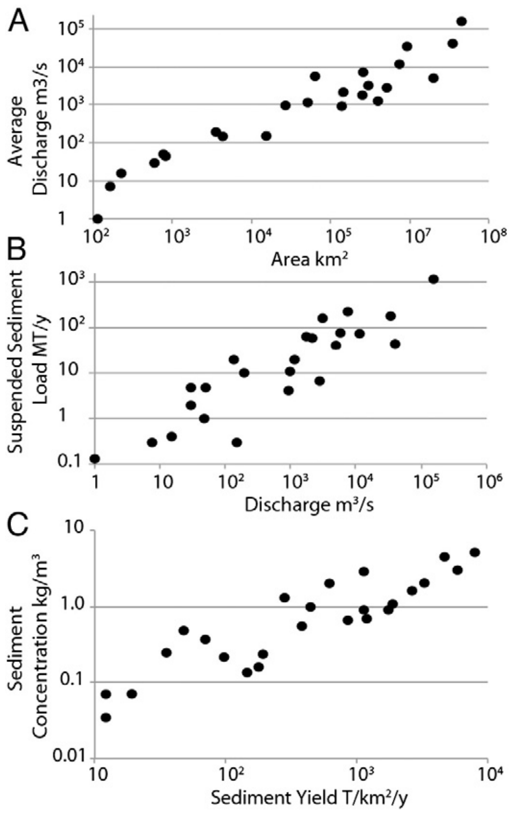


Fig. 8. Scatter plots of observational data collected from 35 Tropical river basins (see Supplemental Table 1 and text for details).

(3) nearby rivers, and (4) unsustained deep aquifers. Model implementation involves matching input resolution (time and space) with model resolution for global air temperature and precipitation (e.g. GPCC/NCEP), and appropriate boundary conditions (e.g. soil parameters, bedrock lithology, crop land, vegetation, reservoirs, irrigation parameters, ice cover, population).

The *WBMsed* model can also be used to demonstrate how tropical rivers behave under pristine conditions (i.e. subroutines for reservoir trapping or human-influenced soil erosion are turned off in the model run), but using modern (1960–2010) climatology defining the tropics. These "pristine" simulations clearly reflect a river basin's physical attributes (relief, area and lithology). They can be considered to represent pre-Anthropocene conditions of the Holocene. Maps of river networks display downstream changes in suspended sediment concentration (Fig. 9) and sediment yield (Fig. 10), demonstrating the impact of mountain chains and rainforest runoff. For example the tributary Rio Negro carries relatively low values of suspended sediment (Fig. 9). When it joins the main stem of the colder and more turbid Amazon River, the net effect is to lower the sediment concentration of downstream Amazon discharge through dilution (Fig. 9), which also lowers the effective sediment yield (Fig. 10C). Sediment yield reflects how much sediment has been produced and eroded from the upstream landscape and is available to be carried by the fluvial system. In contrast, the sediment concentration patterns reflect the sediment load but as diluted by the volume of water being carried, i.e. the dilution effect. In that respect it is interesting to compare Figs. 9 and 10C for the differences between sediment yield and sediment concentration of the streams and rivers that drain the Andes.

Under pristine Holocene conditions, the larger tropical rivers carry the largest sediment loads to the tropical coastal zone (Fig. 8B): Amazon, Orinoco, Irrawaddy, Mekong, and Congo. The most turbid

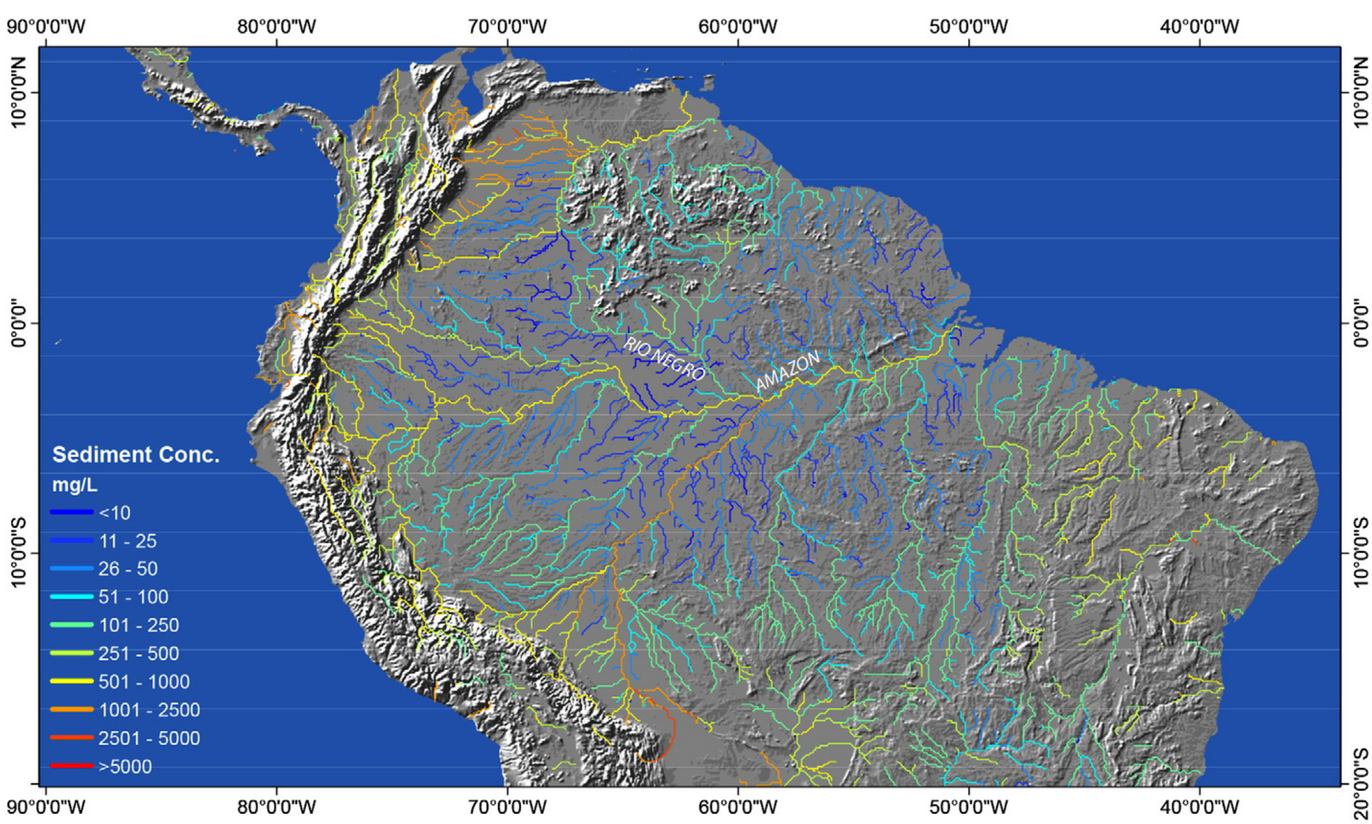


Fig. 9. WBMsed simulation of suspended sediment concentration (mg/L or kg/m^3) for the 1960–2010 observed climate but without the impact of human interference with the landscape employed in the simulation. Time step used is 1 day; grid space is 6 arc minutes (≈10 km). Map is simplified: only river basin units larger than 2000 km^2 and with a mean water discharge of >30 m^3/s are shown. Full tropical area map is provided as Supplemental Fig. 4.

tropical rivers, i.e. those with the highest sediment concentrations at their deltas (see Supplemental Table 1), include: e.g. Amazon, Orinoco, Magdalena, Toncantins in South America, the Niger, Volta, and Zambezi in Africa, the Godavari, Krishna, Mahanadi, and Brahmani in India, and the Irrawaddy, Mekong, Fly, other smaller island rivers and those draining the North Coast of Australia. The harder lithology and reduced relief across Africa contribute to its lower sediment yield and sediment concentrations compared with South America (Fig. 10B). The high relief across the island of Guinea (PNG) contributes to its incredible sediment yields compared to other islands of SE Asia (Fig. 10A).

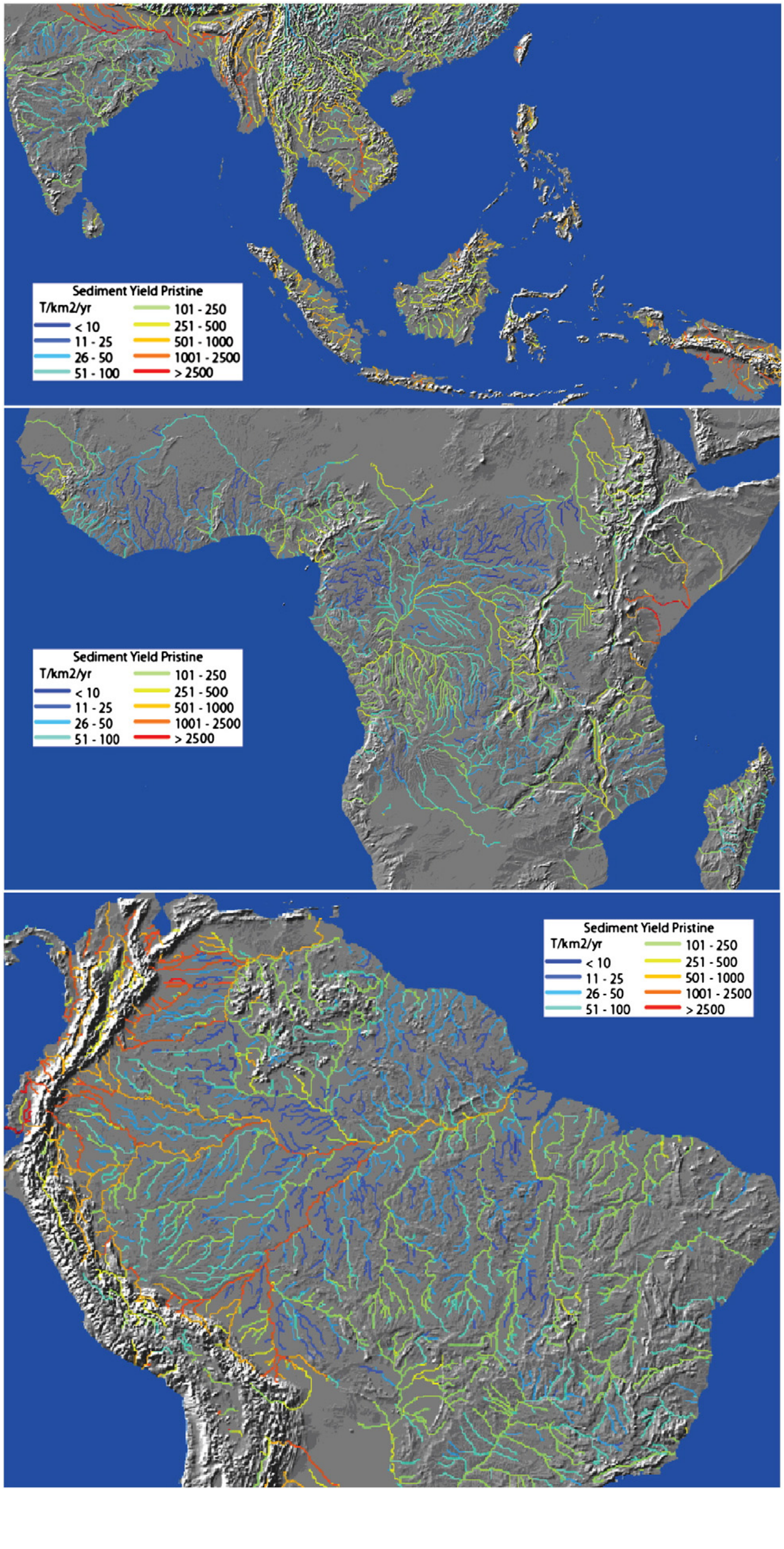
There is an inverse relationship between water viscosity and temperature (Kestin et al., 1978). This gives rise to a linear inverse relationship between particle settling and viscosity (Gibbs et al, 1971), as particle settling velocity is affected by kinematic viscosity. Thus the rate of particle settling increases linearly with water temperature. An average decrease of about 75% in bed-material discharge can occur for an increase of water temperature from 4 °C to 27 °C (Colby and Soott, 1965). These early findings are reaffirmed by Akalin (2002) who found that on average, a water temperature increase of 1 °C causes a ~3.1% decrease in the suspended sand transport. When individual sand size fractions are considered, there are about a 2.8, 3.4, 1.4 and 1.5% decreases in the suspended very fine, fine, medium and coarse sand transport, respectively. Although, on average, suspended sand concentration decreases by ~2%, suspended silt and clay concentration drops off by only 0.35% with a 1 °C increase in water temperature. Additionally, the flow velocity decreases by ~0.66% when the water temperature is increased by 1 °C, and there is ~2.2% rise in the von Karman parameter value in the main flow region as a result of the same range of water temperature increase (Akalin, 2002).

What makes these temperature influences so interesting for tropical rivers is that there is so little air temperature variation throughout the year (Syvitski et al., 2003). Thus tropical river-water temperature is generally very warm except for the influence of the tropical atmospheric lapse rate of about 7 °C/1000 m of elevation change (Syvitski et al., 2003). Some tropical rivers are influenced by a minor amount of glacier and snowmelt. Reflecting its higher elevation sourcing, the Amazon is a few degrees cooler than the Rio Negro at their confluence. However both rivers are very warm (20 °C to 30 °C) from their travel across the Amazon jungle. Tropical rivers are known for their very high proportion of fines (clays). While the abundance of fines in transport might reflect the accelerated biochemical weathering of source rocks and soils (White and Blum, 1995; Deepthy and Balakrishnan, 2005), intensified downstream fining might also reflect the decreasing transport competency associated with increased water temperature and reduced kinematic viscosity. Further research on this topic is needed.

A river's bedload ranges from between <1% and 20% of the total sediment load for locations near river mouths, with a global average of 6.6% (Syvitski and Saito, 2007). The bedload is strongly affected by a river's hydraulic gradient, velocity, bottom shear stress, and discharge. Two parameters (gradient and discharge) compete with one another along a river's reach. Discharge (and velocity) is almost always increasing downstream, whereas channel gradient is generally decreasing downstream with notable exceptions. If both parameters are increasing in value downstream, then the bedload will also increase, as long as there is sufficient bed/channel material to move. If a river's slope decreases as, for example, when a meandering planform is adopted along relatively flat bottomland topography reaches, then the bedload will be deposited. Eventually the river reach will reach an equilibrium state where an appropriate bedload rate is achieved to reflect this new hydraulic gradient. If a large tributary river joins the main stem, for example such as the Rio Negro joining the Amazon (Fig. 9), the increased discharge will increase the bottom shear stress, and the confluent channel will transport both the original upstream main-stem bedload and the bedload contributed from the joining tributary. Fig. 11 shows this competition between discharge and river gradient as they influence the bedload carried by the Magdalena River in Columbia. River reaches alternate between the bedload deposition (negative values) and bedload erosion (positive values). As the river flows through an 800-km^2 flat floodplain zone known as the "Mompox" tectonic depression and characterized by numerous lakes, 12.4% of the bedload in transit is deposited (Hannon, 2011; Syvitski et al., 2012). Many other tropical rivers flow across similar sags or depressions, developing deposition foci: e.g. Sylhet–Megna, Phichit–Chao Phraya, Strickland-Fly depression, Tonle-Sap depression–Mekong, Niger–Idah depression, Mahakam intermontane depression.

5. How different are tropical rivers?

1) Solar-induced forces shape the tropical climate and its manifestation through hydrology and sediment transport. Given the shape and position of our present continental plates, these tropical influences affect north and central South America, middle Africa and the eastern Indian sub-continent, and SE Asian rivers and many tropical islands.
2) The atmospheric forces derived from the movement of the ITCZ and its derivative monsoonal patterns provide globally unique levels of rainfall intensities whether convective or cyclonic, and even influence tropical orographic rainfall levels, which exceed most other rainforest coasts (e.g. Western Canada and Alaska). These intensities may be diagnostic of tropical climate intersecting with orography.
3) Significant portions of the tropics do not experience tropical cyclones (South America, West and Central Africa, portions of Indonesia, PNG and Borneo). Many regions of the world outside of the tropics do, however: rendering cyclonic impacts as not diagnostic of tropical regions.
4) Large tropical rainforests are intimately linked to their rainfall patterns and intensities, through the release of aerosols. These forest-released aerosols join with cloud droplets as nuclei allowing water moisture to reach critical mass and initiate condensation. This may be unique to this terrestrial environment.
5) Tropical rivers often exhibit high runoff values regardless of basin area (and despite high evapotranspiration). However, the relationship between discharge and area for Fig. 8A is $Q = 0.11A^{0.84}$ $R^2 = 0.91$, which is nearly identical to the global pattern ($Q = 0.075A^{0.8}$ $R^2 = 0.71$). High runoff is also not always the case (e.g. drier tropical regions of Africa and India).
6) Strong seasonality is often considered a dominant feature of tropical climate, but temperate and sub-polar regions are equally seasonal, even if the forces at play are different (e.g. pattern and intensity of cold fronts, freshet snow-melt release in the spring). There are important rivers in the tropics that are not seasonal (e.g. rivers of Papua New Guinea).
7) The delta effect where large tropical deltas receive and deliver significant amounts of freshwater to the coastal ocean appears to be diagnostic and worthy of further study.
8) A subset of areas not influenced by either tropical cyclones or tropical monsoons does not appear to experience significant or unusual flooding (Fig. 7) — this is unique, but only to these sub-regions, and not diagnostic of tropical systems.
9) The tropics experience a unique biogeochemical environment, developing thick saprolitic soils, high river concentrations of humic and fulvic acids, and bacterial consumption of woody plant matter. In the warmer tropical rivers, dissolved oxygen should also be less. Further global studies need to reflect on how such uniqueness manifests itself in fluvial environments and their deposits. Other great forest regions, for example the giant boreal forests, are also high producers of humic and fulvic acids (Rashid, 1985). There remains competing hypothesis for the high proportion of clays delivered to the ocean by tropical rivers (i.e. warm water effects — see below).
10) Tropical rivers may carry a disproportionately high sediment load to the world's oceans. Yet this statement is dependent on how


Sediment Yield Pristine
T/km2/yr
< 10
11 - 25
26 - 50
51 - 100
101 - 250
251 - 500
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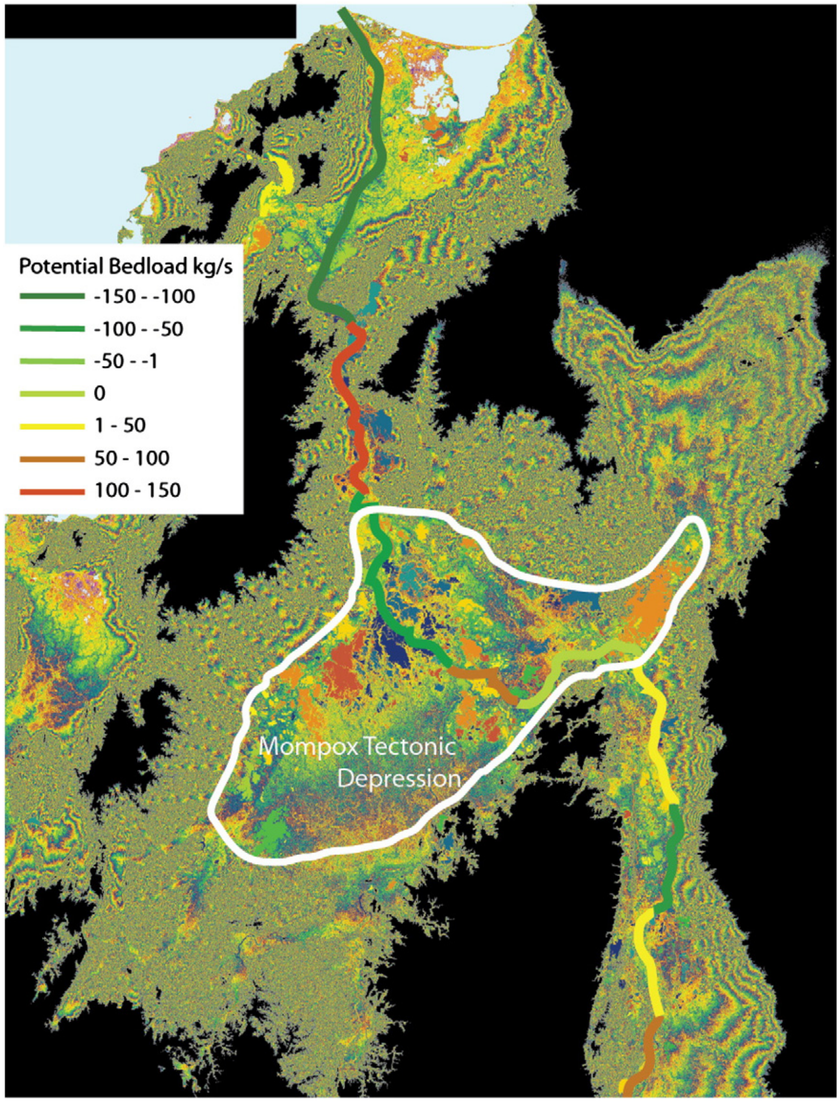

Fig. 11. Changes in potential bedload along the main stem of the Magdalena River calculated using the Bagnold formulae (Bagnold, 1966), with river gradient determined from the Surface Water Boundary Dataset (SWBD) — a composite of Landsat and Space Shuttle Radar Topography (SRTM) information — and discharge observations from country gauging stations (J. Restrepo pers. comm. 2009). River gradients are averaged along 5-meander reaches (data from Hannon, 2011). Negative values indicate net sediment deposition rates; positive values indicate net bed erosion rates. Background SRTM image is of a C-band InSAR model of elevation (Feb. 2000) — colors change every 1 m of vertical elevation, and cycle every 10 m; black elevations are >100 m.

one defines the tropical regions. If climate is the defining factor, as emphasized in this paper, this excessive load might not be real, as many other high load rivers (e.g. Indus, Ganges-Brahmaputra, Salaween, Red, Pearl, much of Taiwan) are excluded when restricted to tropical climate divisions. In addition the harder lithology and reduced relief across Africa negate the higher loads carried by the high-yield rivers of South America.

11) Hot tropical river temperatures produce low viscosity rivers that carry less sediment per unit volume given comparatively similar bottom stresses. This feature is emphasized in the coarser bed material load, and may contribute to the downstream fining. However, many of the world's hot and dry climates (e.g. Australia, Sahara, Middle East, Pakistan) would have similar, if intermittent, low viscosity runoff.

12) Many tropical rivers flow across sags or depressions in the landscape, developing deposition foci. But this is not diagnostic (Syvitski et al., 2012).

13) Rivers of the tropics have low inter-annual variation in sediment yield (Fig. 12). While this is a defining characteristic, other regions outside of the tropics also have low inter-annual variability, for example broad swaths of Canada and Russia. In contrast, low runoff rivers globally dominate the pattern of high inter-annual variability (Fig. 12).

In summary there are many rivers of the tropics that appear unique, for example the giant high runoff Amazon River. When taken as a collection however, the many standard attributes assigned to rivers experiencing tropical climate do not hold for the tropical region as a whole. High

Fig. 10. WBMsed simulation of pristine sediment yield (T/km^2/yr) for the 1960–2010 observed climate, i.e. without the impact of human interference with the landscape employed in the simulation. Maps are not at the same scale. Time step used is 1 day; grid space is 6 arc minutes (≈10 km). Maps are simplified: only river basins larger than 2000 km^2 and with a mean water discharge >30 m^3/s are shown.

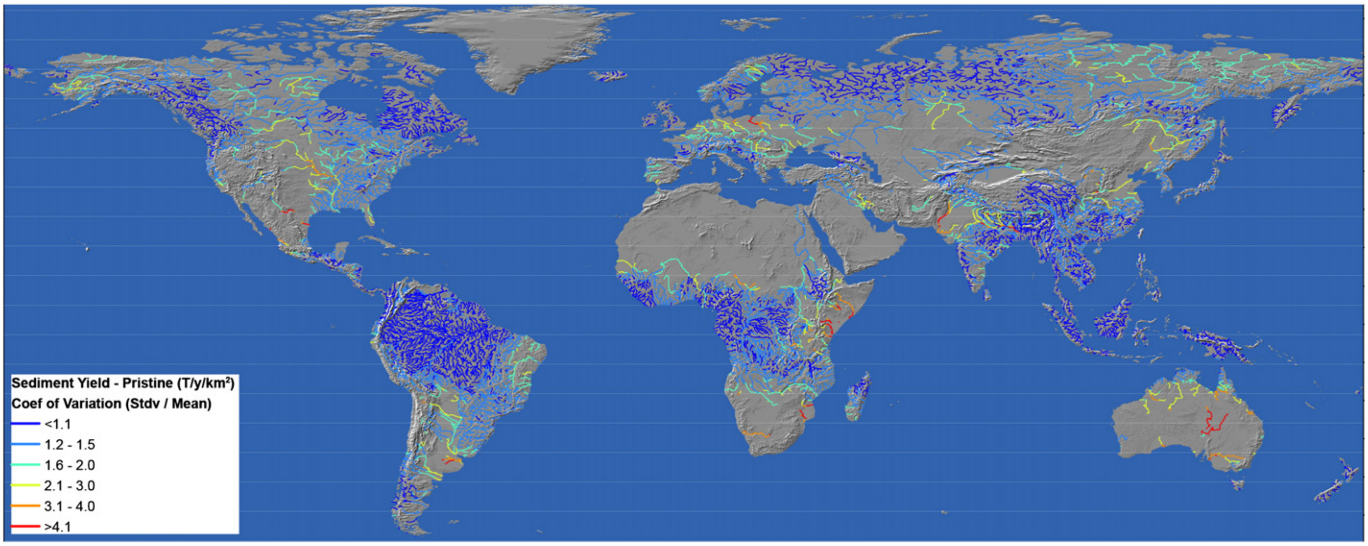

Fig. 12. The coefficient of variation (standard of deviation divided by mean) of sediment yield. High values reflect high sensitive areas to climate and are concentrated in areas that due to their dryness vary at time scales across decades (impact of ENSO, NAO, PDO, AO etc).

rainfall intensities are common in the tropics but more rarely occur in other climate regions. The release of rain-forming aerosols also appears unique, but its hydrological manifestation is hard to detect. The unique biogeochemical environment produces unique soil profiles, and the burial of significant woody debris in sediment is smaller than as found in other climatic zones. For example, trees that float down Siberian Rivers can travel nearly intact for 1000's of km, get sequestered on Canadian shores and fully exposed to the elements, can be sequestered on uplifting shores and survive for thousands of years. It remains for paleobotanists to determine the significance of low burial rates of tropical woody debris.

6. Summary

Following the narrow definition of the tropical climate zone by Peel et al. (2007), this paper presents an overview of how riverine fluxes of tropical river systems are influenced by the movement of the ITCZ and its derivative monsoonal patterns and by the tropical climate in general. The tropics are characterized by intense convective rainfall driven by the ITCZ; the region is the world's largest foci of thunderstorms and is the birthplace of tropical cyclones that often reach their maximum strength there as well. Although these three phenomena, which can be observed in TRMM data available since c. 1998, are spatially diverse, where occurring they significantly impact tropical river hydrographs. Many large drainage basins extend across tropical climate sub-zones, which significantly influence the hydrograph at different locations along the river. A striking example is the Niger River system. The Niger drains mostly a tropical savanna climate zone, yet the mean discharge quadruples at the delta due to the massive local precipitation received during the monsoon.

Compared to other river systems, tropical rivers may transport a disproportionate volume of sediment to the world's oceans, both in particulate and dissolved forms, even though their warmer waters somewhat reduce the effectiveness of some solid-load transport mechanisms. Rivers draining tropical Africa are an important exception. These tropical African rivers drain a relatively low relief continent, and where relief is present, it is often in the form of more resistant volcanic rock.

Many tropical rainforest river basins are strongly affected by seasonality with important exceptions for the rivers draining Papua New Guinea. Rainforest rivers have very high runoff values regardless of basin area. Analysis of multi-annual discharge curves of representative tropical rivers reveals that: a) base flow will decrease when drainage area is reduced, eventually running dry for the smaller rivers during periods when the ITCZ is not affecting the drainage basin, and b) typically the inter-annual variability will increase with decreasing basin area. Scaling relationships using observational data of 35 tropical rivers, indicate that average basin discharge increases with increasing basin area. Sediment concentration scales with sediment yield and both are comparatively low in large rivers.

Under pristine conditions, the largest tropical rivers carry the largest sediment loads to the ocean, even though warm water rivers can transport less particulate matter given the inverse relationship between water viscosity and temperature. About 75% less bed-material load will be carried downstream when freshwater temperature increases from 4 to 27 °C and typically 1.5–3.5% less suspended sediment load will be transported per degree Celsius, depending on the grain size.

To examine more closely the affects of climate on sediment load we employed the global water balance and transport model, WBMsed, excluding the impacts of human disturbances like reservoir trapping, and using 50 years of modern climatology. Simulations show the impact of mountain chains, reflected as high sediment yield and concentration, as well as rainforest runoff, diluting the sediment yield and concentration. High relief islands (e.g. PNG) of which topography generates orographic precipitation have significantly higher sediment yields than other islands of SE Asia. Of the total sediment flux, the bedload typically ranges from 1 to 20% and is strongly impacted by two parameters, the hydraulic gradient and the river's discharge, that compete with one another downstream, creating river reaches of net potential bedload erosion and deposition.

This paper is meant as an accessible overview on the characteristics of Tropical Rivers, and how precipitation dynamics combines with landscape attributes to define the flux of water and sediment delivery. While dispelling several myths and presumptions about tropical fluvial systems, the study uncovers other questions that warrant further investigation. 1) What are the geological impacts of bacterial and humic mediation on the sediment transport system? 2) Does river temperatures significantly contribute to the downstream fining of riverbed sediment? 3) What is the long-term geomorphic consequence of tropical rainforests directly impacting their own rainfall patterns? 4) Does the extraordinary amounts of rainfall falling directly on large tropical deltas impact their morphodynamics?

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geomorph.2014.02.029.

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