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Invited review

Morphodynamics of rivers strongly affected by monsoon precipitation: Review of depositional style and forcing factors

Piret Plink-Björklund

Department of Geology and Geological Engineering, Colorado School of Mines, USA

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ABSTRACT

Rivers that receive significant amounts of their surface water supply from monsoon precipitation characteristically experience seasonal floods, and display seasonally highly variable discharge, controlled by the monsoon trough passage and its related cyclones. The intense summer rainfall causes high-magnitude floods, whereas rivers only transmit a low base flow during the dry winters. For many rivers in the sub-humid to arid subtropics, bordering the monsoon domain, the monsoon rain is also the main source of surface water recharge. However, such rivers may receive monsoon rain and transmit discharge only during abnormal or strengthened monsoon seasons. This annual discharge variability or range, as compared to the mean annual discharge, distinguishes the monsoonal and subtropical rivers from the rivers in equatorial tropics and temperate perennial precipitation zones, where the annual range is relatively small compared to the annual mean discharge.

This review explores the effects of this seasonal and yearly variable rainfall, and the resultant highly peaked discharge pattern on river morphodynamics, and presents a comparison of modern and ancient monsoonal and subtropical river deposits. The field datasets and literature analyses discussed herein provide recognition criteria for monsoon-controlled river deposits, by documenting the diversity of the sedimentary facies, macroforms (bar forms), and architectural elements common in ancient and modern monsoon-controlled rivers. The review demonstrates that seasonal and inter-annual precipitation range is a key control on river morphodynamics, and resultant sedimentary facies characteristics, rather than the specific climate zone or average annual precipitation.

1. Introduction

The global monsoon defines essential features of the Earth's climate, and monsoon rainfall directly affects more than 70% of the world's population. The monsoon rainfall is the key parameter in global hydrological cycle and is most influential on human sustenance and society (Wang and Ding, 2008). The Asian monsoon alone directly affects the livelihood of 60% of the world population. The monsoon regions reside on either side of the equatorial perennial rainfall region and occupy about 19.4% of the total area of Earth's surface (Fig. 1a, b). However, the monsoon rainfall accounts for 30.8% of the total precipitation on the globe, and thus the monsoon regions are the most concentrated rainfall-regions in the world (Wang and Ding, 2008). Of all the atmospheric circulation systems, monsoons exhibit the most significant seasonal variations (Zhisheng et al., 2015). Monsoon means "season" (Zhisheng et al., 2015), and is defined by the high seasonal precipitation variability and an annual reversal of the low-level winds, as a function of the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ; e.g., Wang and Ding, 2008) (Fig. 1a, b). More than 80–90% of annual precipitation in this region falls during the summer monsoon. This annual precipitation variability or range, as compared to the mean annual precipitation, distinguishes the monsoon domain (encircled by black line in Fig. 1a) and its bordering sub-humid to arid subtropics (green shades outside the black line in Fig. 1a), from the perennial rainfall regime in equatorial tropics and temperate zones, where the annual precipitation range is relatively small compared to its annual mean (Wang and Ding, 2008) (Fig. 1a).

Monsoon rain is the main surface water supply to many of the world's rivers whose catchments fall within the tropical or subtropical monsoon domain (green shades in Fig. 1a). Such rivers characteristically experience seasonally highly variable discharge, controlled by the intense monsoon precipitation during the passage of the monsoon and its related cyclones (see also Latrubesse et al.(2005); Syvitski et al.(2014)) (Fig. 1c–i). The intense summer rainfall causes high-magnitude floods, whereas these rivers only transmit a relatively low base flow during the dry winters (Fig. 1f). Some monsoonal rivers, such as the rivers in the Gangetic plains in India, can have discharges 40–50 times greater during the summer monsoon compared to the dry winter (Sinha and Friend, 1994; Sinha and Jain, 1998; Latrubesse et al., 2005). For example, the Ganges River delivers 80% of water discharge and 95% of its sediment load during the summer monsoon season (Goodbred, 2003), as only the monsoon flood discharge is geomorphically effective and able to transport sediment. This large discharge range, as compared to its annual mean is an inherent property

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of monsoonal rivers, as it characterizes monsoonal and sub-tropical rivers with a variety of drainage basin sizes, including those >10,000 km^2, and in a variety of geomorphologic–geologic settings (Latrubesse et al., 2005). Thus, this paper invokes that this large seasonal discharge variability or range, as compared to its annual mean, sets these rivers (Fig. 1f) apart from the perennial rainfall regime experienced by rivers in equatorial tropics and temperate zones (Fig. 1g).

Monsoon anomalies may cause droughts, catastrophic floods, and other extreme weather or climate events (Seneviratne et al., 2012; IPCC, 2014; Zhisheng et al., 2015). Monsoonal rivers are especially prone to catastrophic terrestrial flooding events (Sinha, 2009; Brakenridge, 2012; Syvitski and Brakenridge, 2013). Thus, the monsoon inter-annual variability, the consequent flood hazards, as well as the impact of anthropogenic climate change on monsoonal systems worldwide are topics of extensive research (e.g., www.wcrp-climate.org; IPCC, 2014). Yet, key questions remain unanswered about this most significant component of the global hydrological cycle, such as extracting long-term trends from high-frequency inter-annual variability, or climate forcing from human activity-induced changes (e.g., Seneviratne et al., 2012; IPCC, 2014). For instance, increased frequency and magnitude of terrestrial flooding have been suggested to result from the intensification of extreme monsoon precipitation due to anthropogenic global warming (e.g., Seneviratne et al., 2012; IPCC, 2014). Yet, similar effects can also occur due to human activity within the catchment, such as pasture and intensive agriculture that increase sediment supply and channel bed aggradation rates, which can cause

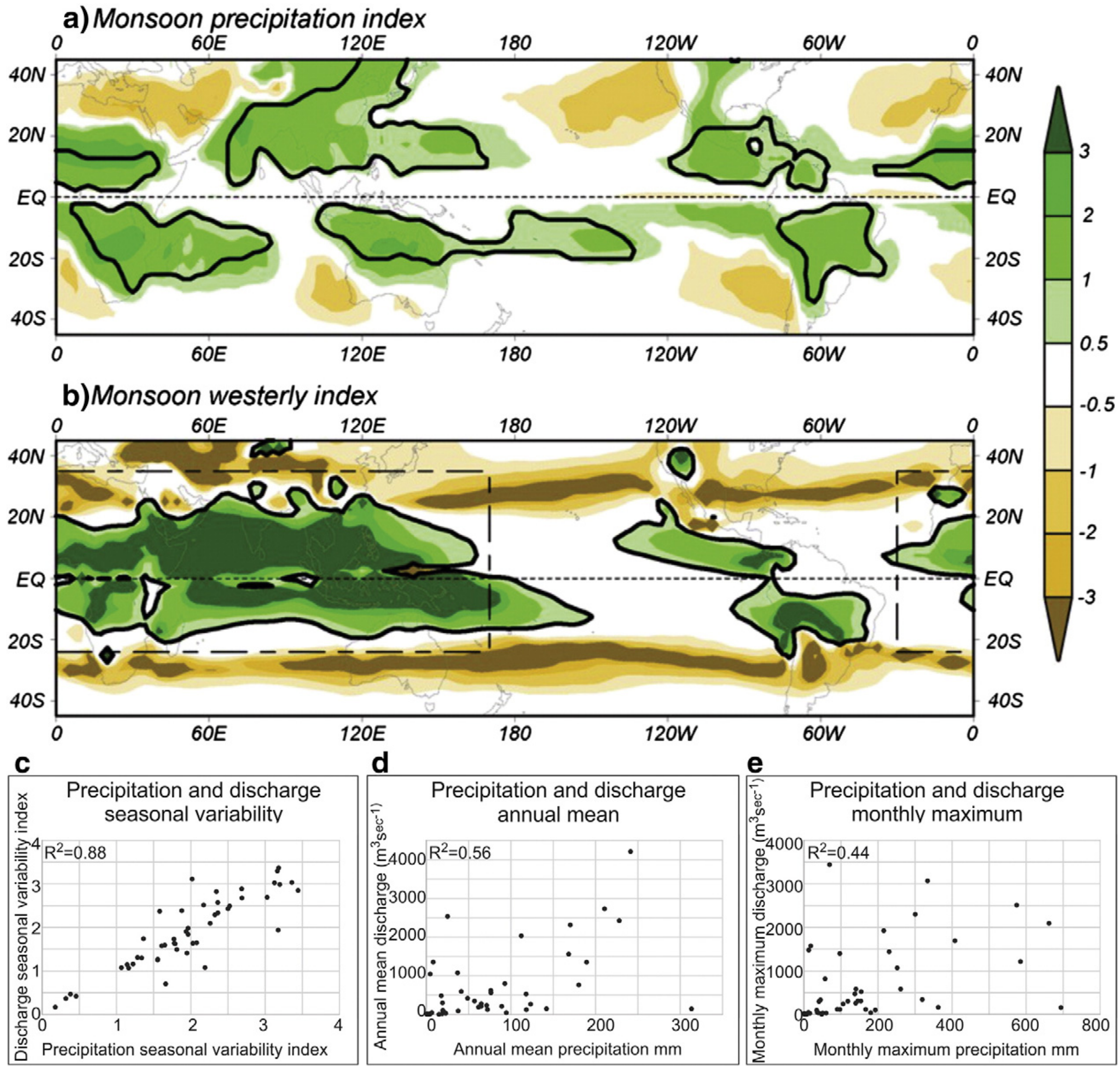

Fig. 1. Monsoonal domain (green colors encircled by black lines) is characterized by (a) a large annual precipitation range (summer minus winter precipitation) as compared to annual mean (monsoon precipitation index), and by (b) monsoon westerly wind index (from Wang and Ding(2008)). The bordering subtropical areas (green shades) also receive monsoon precipitation, but experience larger inter-annual variability. (c) The effect of this seasonal precipitation variability on river discharge is demonstrated by the robust correlation between the precipitation seasonality index and the discharge seasonality index. Both are here calculated as average of wettest month minus driest month divided by annual mean, and data for each river is averaged over ca 4–80 years (data from Leier et al.(2005)). In contrast, there is a low correlation between the annual means (d) or the annual monthly maxima (e). Examples of river discharge hydrographs (averaged over 6–63 years) for (f) rivers that receive large amount of surface water supply from monsoon rain and thus have a large annual discharge range as compared to annual mean (discharge seasonality index >2); compared to (g) rivers that receive surface water from temporal perennial precipitation and rainforest zone, and thus have a small annual discharge range compared to annual average (discharge seasonality index <2). (h) Characteristically, the positive deviation is proportionally larger in rivers with discharge seasonality index >2. (i) Comparison of discharge seasonality index, positive deviation, standard deviation and average flood discharge (average discharge of four consecutive month of highest discharge divided by annual mean). Discharge data in h–i from http://www.sage.wisc.edu/riverdata, except for Kosi and Naryani (http://icimod.org), Rhein (van Bokhoven, 2006), Kassala (Abdullatif, 1989). (j) Comparison of inter-annual variability between a monsoonal river (Ganges) and a subtropical river (Burdekin), over 8 years (data from http://www.sage.wisc.edu/riverdata).