Sedimentary Geology 267–268 (2012) 1–14

Contents lists available at SciVerse ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Invited Review

Floods, floodplains, delta plains — A satellite imaging approach

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ARTICLE INFO

Article history:
Received 4 October 2011
Received in revised form 4 April 2012
Accepted 23 May 2012
Available online 29 May 2012

Editor: G.J. Weltje

Keywords:
River sediments
Remote sensing
River basin depressions
Morphology

ABSTRACT

Thirty-three lowland floodplains and their associated delta plains are characterized with data from three remote sensing systems (AMSR-E, SRTM and MODIS). These data provide new quantitative information to characterize Late Quaternary floodplain landscapes and their penchant for flooding over the last decade. Daily proxy records for discharge since 2002 and for each of the 33 river systems can be derived with novel Advanced Microwave Scanning Radiometer (AMSR-E) methods. A descriptive framework based on analysis of Shuttle Radar Topography Mission (SRTM) data is used to capture the major landscape-scale floodplain elements or zones: 1) container valleys with their long and narrow pathways of largely sediment transit and bypass, 2) floodplain depressions that act as loci for frequent flooding and sediment storage, 3) zones of nodal avulsions common to many continental scale rivers, and often located seaward of container valleys, and 4) coastal floodplains and delta plains that offer both sediment bypass and storage but under the influence of marine processes. The SRTM data allow mapping of smaller-scale architectural elements in unprecedented systematic manner. Floodplain depressions were found to play a major role, which may largely be overlooked in conceptual floodplain models. Lastly, MODIS data (independently and combined with AMSR-E) allows the tracking of flood hydrographs and pathways and sedimentation patterns on a near-daily timescale worldwide. These remote-sensing data show that 85% of the studied major river systems experienced extensive flooding in the last decade. A new quantitative paradigm of floodplain processes, honoring the frequency and extent of floods, can be develop by careful analysis of these new remotely sensed data.

1. Introduction

Geologists have gained insight into the functioning of floodplains from the study of modern rivers and their associated Quaternary deposits (e.g. Schumm and Brakenridge, 1987; Schumm, 1991; Asselman and Middelkoop, 1995; Pizzuto, 1995; Blum and Törnqvist, 2000; Schumm et al., 2002). These insights have allowed for the development of floodplain facies models as an aid to interpret the rock record (Galloway, 1975; Postma, 1990; Galloway and Hobday, 1996; Miall, 1996; Bridge, 2003), and for other more conceptual models on the larger-scale response of floodplains to climate and sea level change (Blum and Törnqvist, 2000; Overeem, 2002; Vandenberghe, 2008).

Conceptual models define 'the floodplain' as the relatively flat area surrounding the active river channel that floods during high discharge events — every year to every few years (Fig. 1). Channel breaches and overflow are caused by: 1) overtopping due to floods, extraordinary tidal fluctuations, and wind-driven waves; or 2) mass failure of levee foundations as aided by subsidence, seepage, erosion, earthquake liquefaction and burrowing animals (Smith and Ward, 1998). The flooding of floodplains defines the complexity of ecosystems and water management, including riparian ecosystem dynamics, agriculture, and fisheries. Floodplain tie-channels link swamps and lakes with a river's water level (Rowland et al., 2009). Floodplain area varies with the height and duration (days to many weeks) of the flood wave, and depends on the surrounding topography in the case of a levee breach. Active floodplain size scales with the recurrence distribution of sometimes overlapping flooded areas — this patchwork of flooded areas becomes a statistical distribution over time with some areas being flooded infrequently even when the flood magnitude is small. Floodplains and their coastal deltas may also flood directly from intense rainfall (e.g. monsoons, tropical cyclones), generating both runoff and standing pools of water on their flat surfaces (Brakenridge et al., 1998; Brakenridge and Nghiem, 2004; Syvitski et al., 2009).

Any conceptual model must account for the dynamic nature of floodplains. Floodplain activity varies across historical and geological time, as influenced by sea level fluctuations, climate, tectonics, and human activity. Holocene floodplains may often be distinguished from their associated Pleistocene floodplain deposits (Blum and Törnqvist, 2000), and even deposits representing smaller climatic chronozones can often be distinguishable (Erkens, 2009; Hijma, 2009).

Rivers avulse across wide floodplains: 700 km wide in the case of the Holocene Yellow River. Historical maps help locate these paleo courses: over the last 4000 y for the Yellow River (Fig. 5L), 2000 y for the Nile (Fig. 5D), 1000 y for the Po (Fig. 5U), and the last 200 to 500 y for many other world rivers (Syvitski et al., 2009). Channel avulsions on floodplains and delta plains (e.g. Figs. 8 and 9) are still hotly debated (as summarized in Slingerland and Smith, 2004), with studies documenting the influence

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doi:10.1016/j.sedgeo.2012.05.014

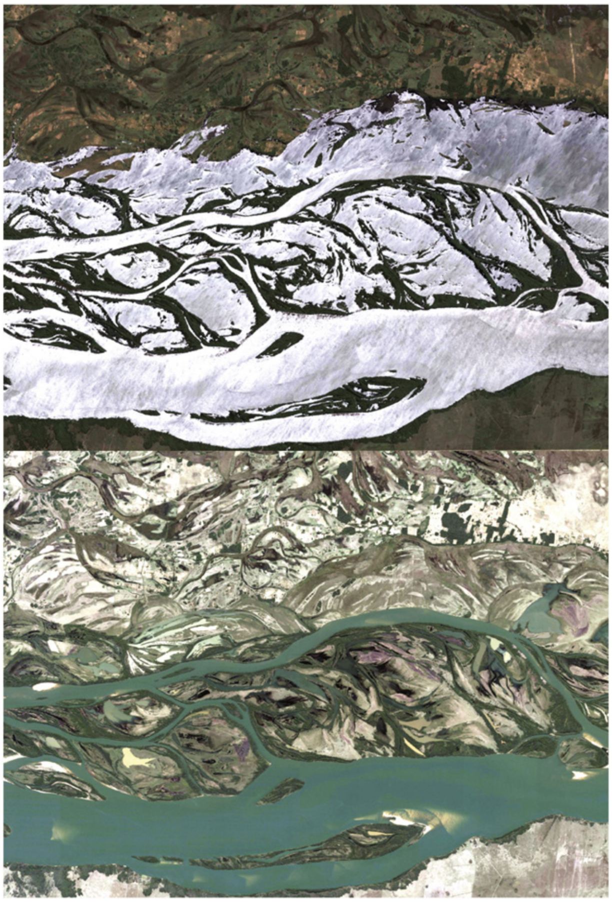

Fig. 1. Parana River orbital images taken at the border between Argentina and Paraguay, SE of the town of Pilar (width of each image is ~10 km). Upper Panel: High discharge, Oct. 22, 2009 ©GeoEye. Lower panel: low discharge, Sept 25, 2005 ©Digital Globe. The low discharge image illustrates the patchwork of amalgamated bars, suggesting continuous evolution; however, most of the bars are completely inundated at high water. Abandoned meandering channels just outside of the flood margin suggest even larger floods occur occasionally.

of human activity (Syvitski et al., 2005), tectonics, earthquakes (Bilham et al., 2007; Bilham and Lodi, 2010) and gradient capture (Stouthamer and Berendsen, 2007; Edmonds et al., 2009; Hood, 2010). From a geological perspective, floodplains encompass the entirety of these interleaved and overlapping floodplains deposits (Bridge, 2003).

Worldwide mapping of floodplain landscape elements and dynamics is now possible using high-resolution remote sensing data (e.g. LANDSAT, SRTM for morphology and MODIS for changes in water levels and sediment loads: Fig. 2). Morphological data allow distinction between bars, levees, splay deposits, and the more featureless flood-cover zones (Figs. 3 and 4). Some floodplain features are not necessarily tied to overbank flooding (Fenneman, 1906), but rather involve the reworking of sediment via within — channel dynamics at high flows, e.g. pointbars or river braids.

The question we pose is: *Do our conceptual models of floodplain processes and landscape development change in the era of global coverage of high-resolution remote-sensing data*? To explore this issue, we survey a selection of global floodplains using consistent orbital imagery and techniques to bridge the gap between modern process understanding and the interpretation of geological deposits. We limit findings to 33 medium- to large-scale floodplains restricted to areas between sea level and the 100 m elevation contour. These are the same river systems used in the recent analysis on global deltas (Syvitski et al., 2009). Even with this limitation, large terrestrial areas of the world are surveyed, as trunk-rivers can sometimes extend 1000's km inland from their river mouth position (Table 1). We concentrate on the surface morphology only of the active floodplains as imaged by the SRTM (Shuttle Radar Topography Mission) interferometric synthetic aperture radar (InSAR). We examine the propensity of these floodplains to flood, based on MODIS (Moderate-resolution Imaging Spectroradiometer) imagery acquired twice daily since 2000, and NASA/JAXA's Advanced Microwave Scanning Radiometer (AMSR-E) imagery acquired daily since mid-2002. Satellite tools such as MODIS and AMSR-E allow near-daily mapping of global rivers at peak flow and the associated flood areas and recurrences.

An important geological cautionary note is that these data are from the Anthropocene — the time when the human species have a major impact on the Earth's surface (see Crutzen and Stoermer, 2000; Zalasiewicz et al., 2008). Most studies that employ modern observations as an aid to interpreting the geological record are subject to this caveat. Although physics remain physics, humans have intervened against the force of gravity, decelerated and accelerated natural processes, focused energy, altered or destroyed ecosystems, and altered the earth's climatology. Using the present as a key to the past must proceed with this knowledge.

2. Methods

Floodplain topography is mapped with the global SRTM survey of February 2000, where an 11-day NASA/NGA Mission obtained a near

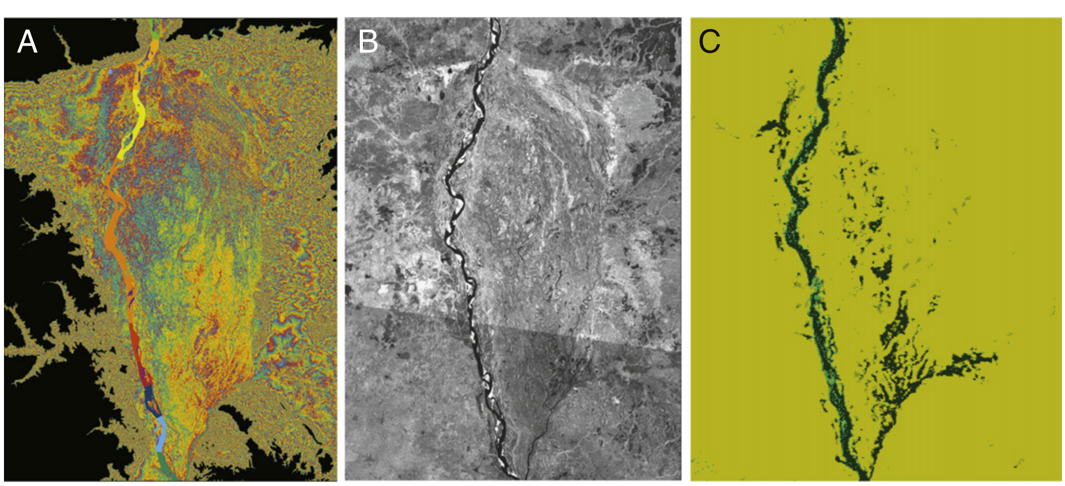

Fig. 2. Floodplain of the Niger River, near the town of Ajaokuta, Nigeria. The width of each image is ~100 km. A: 30 m pixel SRTM C-band InSAR model of elevation (Feb. 2000) — colors change every 1 m of vertical elevation, and cycle every 10 m; black elevations are >100 m. The river enters the top of the image at 25 m elevation above sea level and exits at 18 m asl. B: 30 m near-infrared LANDSAT image (day 109, 2001) taken at very low discharge. C: MODIS near-infrared 500 m pixel resolution imaging of the Niger R. during flood (day 288, 2006). Black represents clean water pooling from rainfall — greenish black represents river water with higher concentrations of suspended sediment.