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One-dimensional modeling of a recent Ganga avulsion: Assessing the potential effect of tectonic subsidence on a large river

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ABSTRACT

River avulsion as studied in small-sized and medium-sized rivers is partly explained by the water surface gradient advantage of a new channel course over the old course, caused by spatial differences in aggradation and compaction. Recently, the effect of meandering upstream of the avulsion node, or bifurcation, was shown to have an equally large effect on avulsion duration as gradient advantage. These effects remain poorly understood for the largest rivers on Earth, where gradients are very small, subtle gradient advantages are affected by tectonics, and often several anabranches remain active simultaneously. Our objective was to assess the relative importance of these factors in the River Ganga in determining the pacing of an avulsion. We used a combination of historical data, remote sensing, and one-dimensional modeling. The course of the Ganga in historical times was through the present Ganga–Bhagirathi system but then there was either a gradual or sudden shift to the present Ganga–Padma system. Historical evidence and remnant paleochannels, as observed in satellite sensor data, corroborate the changing pattern of the Ganga River system, but the exact causes of the shifting and of the short avulsion duration remain unclear. Based on generalized data, using a one-dimensional model we ran idealized scenarios bracketing different tectonic subsidence estimates for long-term morphodynamic evolution of the upstream channel and the two downstream bifurcates. The model predicts flow and sediment partitioning at the bifurcation node, and includes the effect of migrating meanders at the bifurcation and width adjustment of the bifurcates. Our modeling demonstrates that the old and the new branches can remain 'open' and morphologically active for a long time because of the large backwater effect and the high mobility of the sediment. The bifurcation stabilizes at an asymmetrical flow and sediment division, which in smaller rivers (such as the River Rhine) would be followed by residual channel filling but in the much larger Ganges results in morphologically active anabranches. The model results reveal that neither a gradient advantage nor a bend upstream of the bifurcation leads to an avulsion within centuries as has been observed in some large rivers in tectonically inactive regions. On the other hand, a realistic tectonic uplift of the old branch or subsidence of the new branch may force an avulsion to take place quickly, and historical data show that the study area is seismically active. The combination of these factors leads to a realistic modeled avulsion duration of less than three centuries. Historical data indicate that these general conclusions might also apply to other large rivers in this region, e.g. the Brahmaputra and the Teesta. We conclude that large rivers may avulse quickly in response to tectonics but attain an anabranching pattern because of the large dimension of the residual channel and backwater effects.

1. Introduction

Some fluvial rivers are not single channels but bifurcate into two or multiple downstream branches. Such branches characterize anabranching and braided river systems (see Ashworth and Lewin, 2012; Kleinhans et al., 2013 for reviews). Avulsion is one of the processes through which anabranching river systems evolve (Latrubesse, 2008; Ashworth and Lewin, 2012). Avulsion can be defined as the process by which a river partially or fully relocates from its present main course to a new course or to an existing secondary course by natural means (Fisk, 1944; Leeder, 1978; Heller and Paola, 1996; Jones and Schumm, 1999; Slingerland and Smith, 2004). River avulsion, as studied in small-sized and medium-sized rivers, is partly explained by water surface gradient advantage of a new channel course over the old course, caused by spatial differences in aggradation and compaction.

In large river systems, the avulsion process remains poorly understood, as gradients are very small and several anabranches can remain active simultaneously with the major branch. In addition to low gradient, high discharge in large rivers may lead to much larger backwater effects than in smaller rivers, which may also lead to older branches

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remaining active simultaneously. Some fluvial geomorphologists consider avulsion to be a higher level process which depends, for example, on associated riparian vegetation and presence or absence of paleochannels (Heritage et al., 1999; Taylor, 1999). Besides the specific avulsion processes in large rivers, another surprising property is the variation in avulsion durations which can vary from as low as 28 years for the River Kosi, India, to 1400 years for the River Mississippi, USA (Slingerland and Smith, 2004). Ideally, avulsion duration is defined as the time between initiation of a new channel and complete abandonment of the previous channel (Stouthamer and Berendsen, 2001). However if avulsion is by the process of annexation (Slingerland and Smith, 2004) of an existing secondary channel and the older channel is not abandoned after the major discharge shifts to the secondary channel, then it becomes difficult to define the timeline of avulsion as no new channel is created and no old channel is abandoned. Where two channels exist simultaneously, the avulsion duration can be defined as the time taken for the original secondary channel to become dominant in discharge conveyance. In the present paper, this latter definition is used.

Avulsions can be gradual or abrupt depending on the rate at which a river aggrades over the existing floodplain. Besides differential aggradation and presence or absence of paleochannels, tectonic movement may also be responsible for avulsion (Coleman, 1969; Mike, 1975; McDougall, 1989; Blair and McPherson, 1994; Dumont, 1994; Harbor et al., 1994; Smith et al., 1997; Schumm et al., 2000). For example, in the Okavango River in Botswana, tectonic movement has been held responsible for major avulsions (Wilson, 1973; Hutchins et al., 1976; Cooke, 1980), although direct evidence is absent. Several studies in the South American rivers (e.g. R. Amazon, R. Rio Negro, Solimoes River, Upper Parana and Araguaia River) have also shown the effect of tectonics on channel morphology resulting in avulsion (Mertes et al., 1996; Latrubesse et.al, 2000; Latrubesse and Rancy, 2000; Latrubesse and Franzinelli, 2005; Valente and Latrubesse, 2012). In contrast in most rivers, however, avulsions are often explained without recourse to tectonic effects (Speight, 1965; Smith and Smith, 1980; Smith, 1983; Wells and Dorr, 1987; Schumann, 1989; Smith et al., 1989; Brizga and Finlayson, 1990; McCarthy et al., 1992; Li and Finlayson, 1993; Richards et al., 1993; Blum, 1994; Törnqvist, 1994). In the Indian subcontinent, earthquake-induced faulting in the River Indus at two locations (apex of two fans) resulted in repeated avulsions (Schumm et al., 2000). Similarly, in the eighteenth century the River Brahmaputra avulsed 80 to 100 km to the west due to tilting induced by a major earthquake (Morgan and McIntire, 1959; Johnson and Alam, 1991).

Here we study one particular avulsion of the Ganga river that may have been affected by tectonics. Nineteenth century literature associates the avulsion from the Ganga–Bhagirathi system with a major earthquake in the region in the early sixteenth century. Captain Sherwill, who was assigned in 1857 by the Government of India to ascertain the condition in the Hooghly, was of the view that the Ganga previously flowed on the present bed of the Bhagirathi–Hooghly (Parua, 2009). The present course along the Ganga–Padma was described as of recent origin, formed by the opening out of the left bank of the Ganga near Malda. This process was described as the result of a catastrophe that he attributed to a sudden failure of the left bank which was composed of loose yellow sand. Hayden and Pascoe, 1910 of the Geological Survey of India were of the view that the conditions prevailing on the Indo-Gangetic plain from early Tertiary time were similar to those existing at present and that there was a gradual subsidence, leading to the accumulation of enormously thick alluvial deposits. This accretion resulted in the change of the Ganga course from the Bhagirathi–Hooghly to the present Ganga–Padma. In 1919, H.G. Reaks (River Surveyor of Calcutta Port), in his study on the river hydraulics of the Ganga delta region, ascertained from the existence of old beds and from the histories of noted towns that the main flow of the Ganga was originally through the present Bhagirathi–Hooghly system as it was the most natural and direct course to the sea. A fifteenth century map of the rivers of Bengal, reported by Professor Meghnad Saha, shows the absence of the SE flow of the River Padma (Parua, 2009). Prof. Saha also emphasized that all the major historic settlements of south Bengal were on the banks of the Bhagirathi–Hooghly, as noted by Reaks in 1919. Based on the above studies, it is widely accepted that the main course of the Ganga–Padma system originally was through the present Bhagirathi–Hooghly system and the river avulsed from the older course to the present after the fifteenth century.

The initiation and location of an avulsion is governed by the trigger mechanism and the physical characteristics of the location. The trigger mechanism is generally a flood but can be related to tectonics, logjams, bank failures and or bar migration blocking one of the channels (Jones and Schumm, 1999). However, the location where the avulsion will occur is determined by physical characteristics such as channel geometry, bank stability, and topography. Outer meander bends where flow velocities are high and weak areas of the channel bank represent the most likely location of avulsion (Chrzastowski et al., 1994; Smith et al., 1998). A river may also relocate during high discharge to an existing secondary channel.

Once an avulsion has been initiated, there exists a channel bifurcation of which the development determines the fate of the avulsion. Bifurcation plays a key role as the morphodynamics of the individual branches downstream of the bifurcation depend on the partitioning of water and sediment fluxes between the two bifurcations. The bifurcation can be stable or unstable based on the timespan during which the two branches coexist. During the avulsion process, the sediment coming from upstream is unlikely to be distributed equally between the two channels downstream of the bifurcation resulting in changes in discharge, slope, or cross-section and consequent changes in the carrying capacity of the channels. The change in the capacity results in growth of one of the branches and closure of the other branch due to aggradation, ultimately leading to the failure or completion of the avulsion process.

Physics-based numerical modeling of idealized bifurcation configurations has shown an interrelationship between bifurcation stability, avulsion duration, and channel patterns (Bolla Pittaluga et al., 2003; Kleinhans et al., 2008). Model simulations could suggest that very few bifurcate channels are abandoned entirely, especially in large rivers. Instead, they attain a configuration of highly asymmetrical equilibrium in which the major flow, along with the sediment from the upstream branch, goes through the new branch and a small percentage ($<5\%$) flows through the older branch (Kleinhans et al., 2008). In small rivers, minor channels transport no significant sediment load but gradually transform into floodplain through aggradation of suspended material and encroachment of riparian and aqueous vegetation. In large rivers, we hypothesize that such channels may still transport bed sediment and have sufficient velocity to prevent transformation to floodplain. This would imply an anabranching pattern with multiple morphologically active smaller channels in addition to one main channel rather than an avulsive system with one active channel and abandoned channels transitioning to floodplain (Kleinhans et al., 2012; Carling et al., 2013).

The duration over which avulsion takes place is partly dependent on the width–depth ratio, the gradient advantage of one bifurcate over another, the length of the bifurcates and the curvature of the channel at the bifurcation, which drives helical flow and transverse sediment transport. A varying combination of the above parameters can lead to sharp changes in the duration of the avulsion; although in general the time period of avulsion is directly proportional to the bifurcate length (Bolla Pittaluga et al., 2003).

Other factors like backwater effects due to tides, meander migration, bank erosion, and bed sediment sorting can also influence bifurcations and, thus, the avulsion threshold as well as the duration of avulsion. In the large rivers of the world, especially tropical rivers, complex anabranching systems are common (Latrubesse, 2008). The mechanism that produces such multiple channel systems in large rivers are avulsion-based or accretion-based processes (Nanson and Knighton,