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Migration and cutoff of meanders in the hyperarid environment of the middle Tarim River, northwestern China

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ABSTRACT

A meandering channel has developed in the middle Tarim River, the longest inland river flowing through a hyperarid environment in northwestern China. Although the drainage basin of the Tarim River extends over 1 million km^2, flow in downstream reaches is largely restricted to summer months, and irrigation pressures have made the flood season increasingly short. The planform morphology, lateral migration rate, and cutoffs of 105 meanders were analysed using multiperiod remote sensing images and field survey analyses of channel bed and bank properties and of riparian vegetation cover. Results show that planform attributes of the meandering Tarim River are similar to those found in other environments. The ratio of the channel centreline length to the neck channel width of meanders ranges between 1.2 and 8.1, the bend curvature (ratio of bend radius to channel width) ranges between 0.30 and 2.8, and the average deflection angle of the bend apexes is 79.9°. Meander migration rates range from 1.4 to 96.7 m y^{-1}. From 2000 to 2013, 45 cutoffs occurred along the 400-km-long reach. As the riparian vegetation cover is sparse because of limited precipitation and because banks are comprised of dense roots, fine sand and silt materials, but lack clay, bank strength is limited and presents limited constraints upon bend movement.

1. Introduction

Although they are simply the product of differing combinations of flow and sediment interactions that are acting on valley floors of variable slope, width, and roughness attributes, alluvial channels demonstrate a remarkable diversity of forms (e.g., Church, 1992; Fryirs and Brierley, 2012). Despite this inherent variability, some morphological traits are ubiquitous in nature. For example, meanders demonstrate extraordinary adaptability across a wide range of environmental settings (Langbein and Leopold, 1966; Hickin, 1974) and are even found in nonterrestrial environments such as ice sheets, deep seas, and on Mars (Deptuck et al., 2007; Matsubara et al., 2015). Self-similar sinuous planforms of meanders are products of long-term lateral migration of meandering channels in laterally unconfined (alluvial) floodplain settings.

Many studies have used multiperiod remote sensing images to analyse the long-term, large-scale planform attributes of meandering rivers (e.g., Swamee et al., 2003; Nicoll and Hickin, 2010; Schwendel et al., 2015). If channel boundary conditions (i.e., bank material and riparian vegetation) are uniform and homogeneous, fractal geometry principles can be used to describe meanders as self-similar, self-replicating features (Hooke, 2007b). However, meander migration rate is affected by different controls in different environmental settings. For instance, geological structure and rock strength are critical controls upon the downstream translation of bends in partly confined valley settings (e.g., Nicoll and Hickin, 2010). Cohesive bank sediment banks and/or clay plugs of previously abandoned channel patterns may inhibit rates of meander migration (e.g., Fisk, 1944, 1947; Wolman and Leopold, 1957; Motta et al., 2012). Riparian vegetation cover and instream loadings of wood may exert a similar retarding effect (e.g., Brooks and Brierley, 2002; Brooks et al., 2003; Constantine et al., 2014; Yu et al., 2014). Nanson and Hickin (1983, 1986) proposed a quantitative relation between the migration rate and the radius of bend curvature (per unit channel width), wherein rates are highest when r_c/W is between 2 and 3. Building upon this principle, Constantine and Dunne (2008) established a relation between meander sinuosity and the formation rates and planform attributes of oxbow lakes. In contrast, Guneralp and Rhoads (2009, 2011) demonstrated a nonlinear relation between migration rate and sinuosity, highlighting that this relation changes with the morphological complexity of the meander. Furthermore, they developed a physically based model that shows how resistance induced by floodplain heterogeneity influences long-term meander evolution.

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These various papers indicate that lateral migration rate is not only determined by local flow-sediment interactions and bank boundary conditions but also by sinuosity and planform complexity of a given meander. In some instances, meandering patterns generate neck and chute cutoffs (e.g., Erskine et al., 1992; Hooke, 1995, 2004, 2007a; Camporeale et al., 2008).

Although arid zones cover 30% or more of the global land surface, the assertion by Tooth (2000) that research into dryland rivers remains in its infancy holds true today. Among many factors, this reflects difficulties such as field access and challenging field conditions, the lack of gauging and survey data (available records are neither persistent nor systematic), the infrequent nature of formative events (e.g., precipitation, runoff, flood), and problems establishing representative monitoring networks over large areas where rainfall and runoff are highly variable. The Tarim River is a green river corridor surrounded by the Taklamakan Desert in Xinjiang, northwestern China. This hyperarid environment hosts one of the largest sandy deserts in the world. During his exploratory travels, Sven Hedin (1903, p. 161) commented upon active bank erosion along the Tarim River, noting: 'Again and again we heard what sounded like the booming of heavy guns from some distant fortress; it was these clay avalanches (collapsing river banks) taking their final plunge into the torrent below' (our brackets; findings from this study indicate that clay deposits actually make up only a small proportion of bank deposits along the Tarim River). Unfortunately, no long-term flow and sediment data are available for this river. Although Wang et al. (2003) presented an initial description of meandering river pattern and hydraulic geometry relationships for the Tarim River and Yu et al. (2016) documented controls on river network evolution and recent river responses to human activities, no studies of long-term channel evolution have been conducted to date.

This study uses findings from field surveys (2014–2016) and analysis of remote sensing images to assess the morphological characteristics, lateral migration, and cutoff evolution along the 750-km-long meandering channel in the middle reaches of the Tarim River. The objectives of this study are (i) to statistically analyse the meandering planform in the middle Tarim River; (ii) to assess the relation between migration rate and planform parameters from 2000 to 2014; and (iii) to interpret the number, pattern, and formation of meander cutoffs from 2000 to 2014.

2. Regional setting

The Tarim River is the longest inland river in China, with a channel length of 2179 km and a basin area of about 1.02×10^6 km^2 (Fan et al., 2006). The river flows from west to east along the northern edge of the Tarim Basin, prior to shifting to the southeast across the eastern part of the Taklamakan Desert, before it finally empties into Taitema Lake (Fig. 1). Three sides of the basin are surrounded by high mountains that generally extend above 4500 m, while the Tarim Basin ranges in elevation from 800 to 1300 m, with higher elevations in the west and lower elevations in the southeast. After the confluence of the Aksu, Yarkand, and Hotan rivers at Xiaojiake, the main downstream channel is referred to as the Tarim River (see Fig. 1). The Tarim River extends over 1321 km from Xiaojiake to Taitema Lake.

Annual runoff of the Tarim River is derived primarily from glacier and snowmelt from three headwater tributaries, the Aksu, Yarkand, and Hotan rivers. The primary water source, the Aksu River, has an average discharge of 195 m^3 s^{-1} in the flood season. The mean annual runoff at the Alar station (1957–2011) was 4.59×10^9 m^3 y^{-1}, with an average sediment load of 21.84×10^6 t y^{-1}, and Fig. 2 shows that the relationship between runoff and sediment load is nearly linear. Seventy-six percent of the annual runoff and 95% of the sediment load occur from June to September. Historically nine major tributaries flowed into the Tarim River, but today surface flow from five of these tributaries no longer reaches the Tarim River because of climate change, water diversion, and other human activities (irrigation now consumes 75.5% of

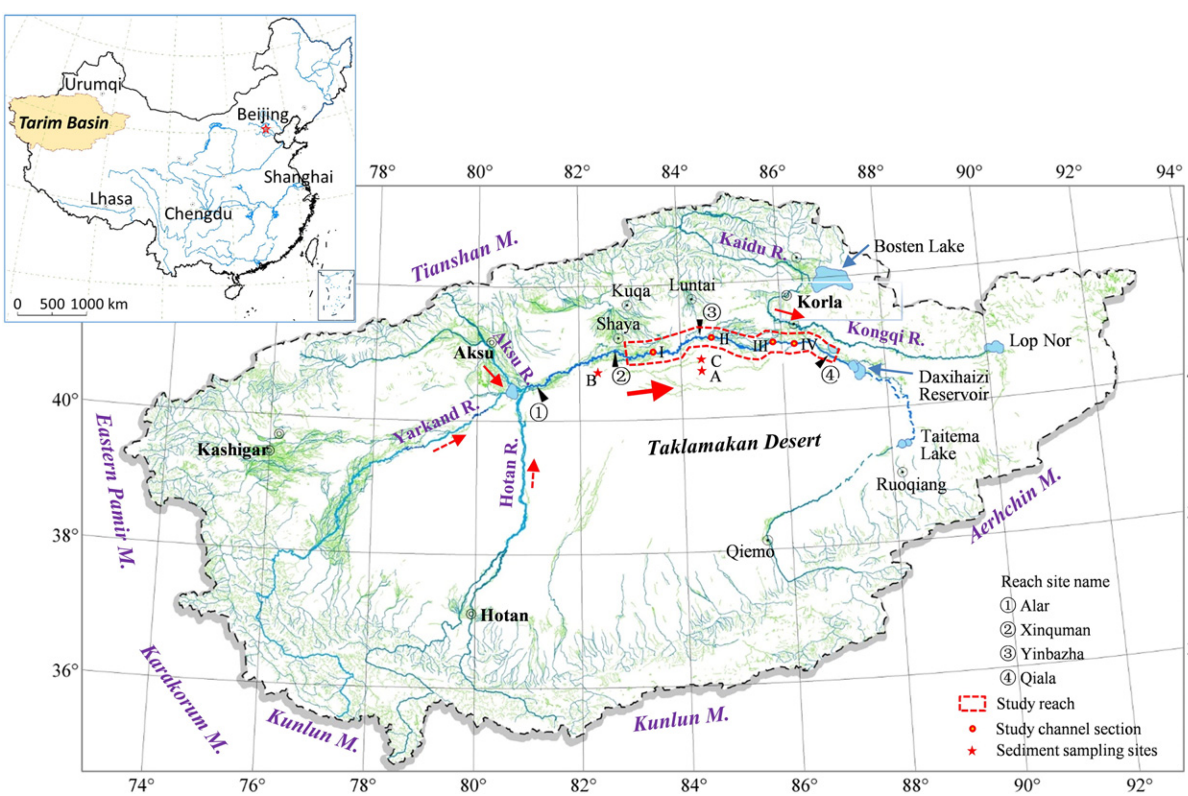

Fig. 1. Location of the Tarim River and meandering reaches.