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River network evolution and fluvial process responses to human activity in a hyper-arid environment – Case of the Tarim River in Northwest China

Guo-An Yu [a,b,*], Markus Disse [b], He Qing Huang [a], Yang Yu [b], Zhiwei Li [c]

[a] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A Datun Road, Chaoyang District, Beijing 100101, China
[b] Technical University of Munich (TUM), Arcisstrasse 21, Munich 80333, Germany
[c] School of Hydraulic Engineering, Changsha University of Science & Technology, Changsha, 410114, China

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A B S T R A C T

The Tarim River, the longest dryland river in an extremely arid region of China, has undergone ever-increasing human impacts over recent centuries (particularly since the late 1950s during which time large-scale land reclamation in the basin has taken place). Historical literature/maps, gauged hydrological data and satellite images were analyzed to examine how the river network evolution in the basin and the fluvial morphology of the main stem of the Tarim River have responded to human influences. The results demonstrate that human activity (inhabitation, land reclamation and water resources development) in the basin have had significant impacts on the Tarim River, causing major changes in runoff and sediment transport, river network composition and river morphology (especially planform patterns). Gauged hydrological data from the past five decades presented an obvious reduction in runoff and sediment load in the Tarim River, even though the runoff from source tributaries exhibited a gentle increase. The annual occurrence of low flow events showed a significant increase, and the occurrence of moderate-high flow events followed a gentle decrease. The river network system has disintegrated from a historically '(quasi-) centripetal' system with nine tributaries into several isolated river systems, which have mainly developed since the 20th century. Currently, only four tributaries flow into the main stem river, which is dominated by braided channel patterns in the upper reaches and meandering (typically with distorted bends) patterns in the middle reaches. The braided reach was in aggradation and in high lateral mobility. The mean width and braiding intensity of the braided reach followed a gentle decrease mainly due to the reclamation of river flood plains to farmlands and embankments. The sinuosity index of the current Tarim River channel is distinctively lower than the indexes of the old channels that were abandoned decades or centuries ago, even though the sinuosity index of the meandering channel followed a gentle increase in recent decades due to the increased occurrence of low flow events. Human activity has changed the natural fluvial processes and morphology of the Tarim River and has reduced the diversity of the river network system.

1. Introduction

The arid zones on Earth cover 30% or more of the global land surface and support an ever-growing human population (Thomas, 2011). Rivers in these zones often play a central role in landscape change and exert a strong influence on the human use of these marginal environments (Tooth and Nanson, 2011). Therefore, the processes, forms and changes of these rivers are increasingly a focus of scientific and applied research. Among this research, many have investigated the hydrological regimes, sediment dynamics and fluvial processes of these rivers (e.g., Leopold and Miller, 1956; Leopold et al., 1964; Graf, 1988; Laronne and Reid, 1993; Thornes, 1994; Knighton and Nanson, 1994, 1997, 2001; Tooth and Nanson, 1999, 2004; Tooth, 2000b; Alexandrov et al., 2003; Achite and Ouillon, 2007; Reid and Frostick, 2011; Powell et al., 2012).

Human activity has had a substantial influence on fluvial processes and even on the modification of river networks; numerous studies have investigated human impacts, emphasizing rivers in temperate and humid regions (e.g., Brooks and Brierley, 1997; Surian and Rinaldi, 2003; Liébault et al., 2005; Gregory, 2006; Wohl, 2006; Hoffman et al., 2010; Rhoads et al., 2015). With the accelerated expansion of human activities from temperate and humid environments into arid environments, many dryland rivers have already been strongly influenced by, or are under significant threat from, various human interventions such as land reclamation and flow regulation, which often have more

* Corresponding author at: Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A Datun Road, Chaoyang District, Beijing 100101, China.
E-mail address: yuga@igsnrr.ac.cn (G.-A. Yu).

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significant potential to disturb hydrological (e.g., Jacobson et al., 1995; Schick, 1995; Tooth, 2000a; Mansur and Nurkamil, 2010; McDonald et al., 2013) and fluvial processes (e.g., Graf, 1978, 1979; Ortega et al., 2014). Related research has mainly been carried out in recent decades, for example, the changing channel patterns of the Gila River in Arizona, in the southwestern United States of America, resulting from flow regulation and the introduction of *Tamarix*, an exotic plant with more suitability than local vegetation (Graf, 1978, 1979, 1988); the flow regime and hydrologic change of the Murray and the Barwon-Darling Rivers (Maheshwari et al., 1995; Thoms and Sheldon, 2000); the adjusted channel morphology of ephemeral streams due to urbanization in southwest America (Chin and Gregory, 2001; Coleman et al., 2005); and changes in the dynamics and morphology of ephemeral rivers in Mediterranean regions (Hawley and Bledsoe, 2011, 2013). In general, most fluvial morphology-related studies were conducted on ephemeral rivers at relatively small spatial scales (dozens to hundreds of square kilometers) and basically belong to endogenic system in hydrologic feature. However, minimal attention has been paid to the evolution of river networks and fluvial processes of allogenic rivers in arid environments.

The Tarim River, the largest inland river in China, is a typical allogenic and perennial river flowing in a hyper-arid environment and has been massively modified in recent decades. Despite several studies that have examined human impacts on the environment, ecology and variation of the hydrologic regime in the basin (e.g., Han, 1980; Feng et al., 2005; Chen et al., 2010), investigation into the response of fluvial processes is weak and needs to be strengthened because this knowledge is important for understanding the changes in large dryland river systems, possibly shedding light on their potential evolution in the future and enhancing sustainable management strategies for river systems in arid environments.

This paper outlines the human activities that have occurred in the Tarim River Basin in recent centuries (especially in the past five decades) and traces the evolution of the river network system back in history, going on to examine in detail how the fluvial morphology of the Tarim River has changed in recent decades in response to changes in hydrologic and sediment dynamics from ever-increasing human impacts.

2. Research area and methods

2.1. Research area

Located in the northern Qinghai-Tibetan Plateau, the Tarim Basin is the largest inland river basin in China, encompassing a total basin area of 1.02×10^6 km^2 (35°N-43°N, 74°E-90°E) (Fan et al., 2006) (Fig. 1). The basin, also called the Southern Xinjiang (or *Nanjiang* in Chinese Pinyin) Basin in Chinese geographical references, is surrounded by the high mountains of the Tianshan, Eastern Pamir, Kunlun, Karakorum and Aerhchin ranges, which results in orographic precipitation patterns. The current main stem of the Tarim River has a channel length of approximately 1321 km, starting from XJK (Xiaojiake, the confluence site of the Aksu, Yarkand and Hotan Rivers), basically flowing from the west to the east, then to the southeast, finally emptying into Taitema Lake. The natural ecosystem and human activities in this hyper-arid basin rely heavily on water resources, directly or indirectly, from the Tarim River.

The climate of the continental basin is extremely dry with very large temperature fluctuations; the highest and lowest recorded temperatures were 43.6 °C and −27.5 °C, respectively. Although annual precipitation in the mountainous headwater regions can reach approximately 200–500 mm, it is only 50–80 mm in the main stem area (and just 10 mm in the central desert area) (Chen et al., 2009), whereas the annual potential evaporation amounts to 2100–3000 mm or more (Feng and Cheng, 1998). The Tarim River can be regarded as an allogenic (exotic) river because its surface runoff is basically fed from snowmelt and

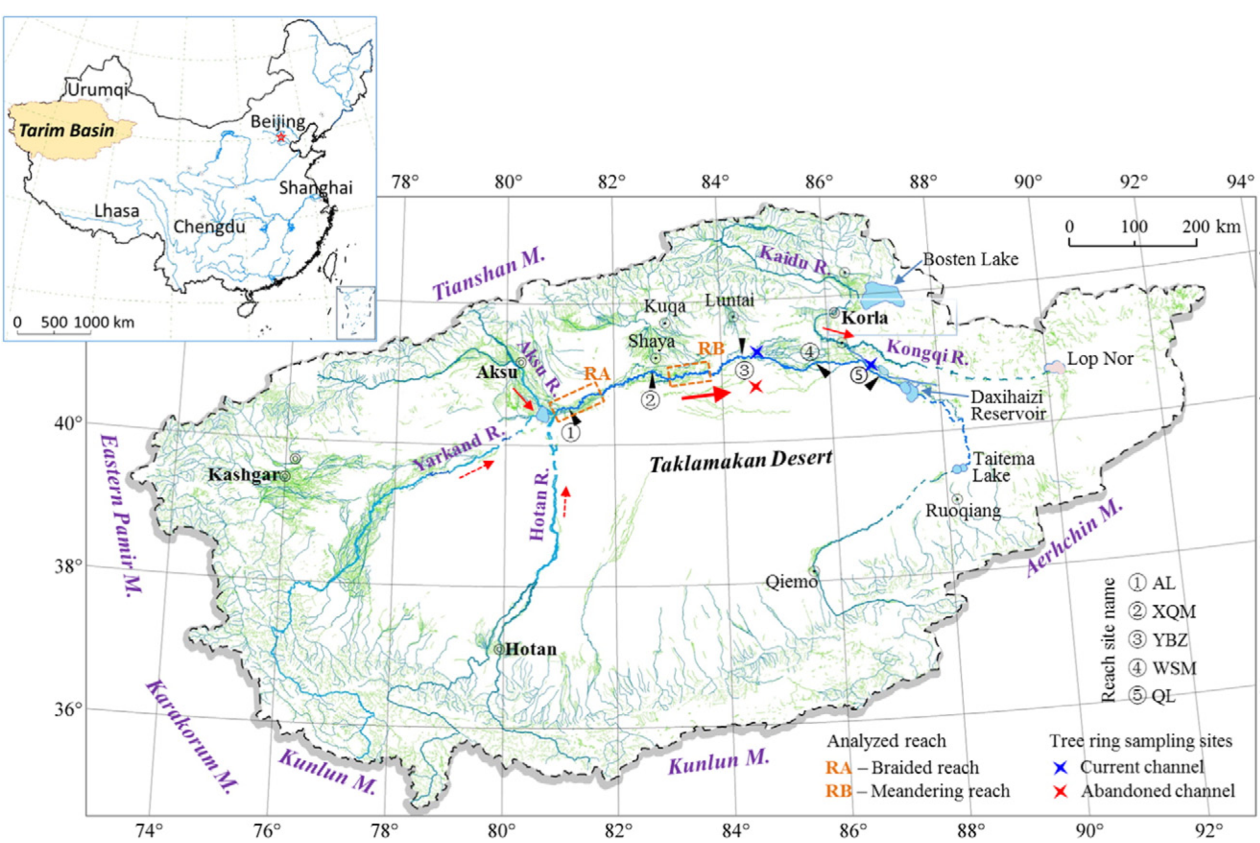

Fig. 1. Location of the Tarim River Basin and its current river network system.