Chapter 3
Geomorphic Diversity of Rivers in the Upper Yellow River Basin

Gary John Brierley, Guo-an Yu and Zhiwei Li

Abstract The Yellow River is the third longest river in Asia and the sixth longest river in the world. The Upper Yellow River lies at the margins of and atop the Qinghai–Tibet Plateau, the highest plateau in the world with an average elevation of 4000 m above sea level and an area of about 2.6 million km^2. This area contributes about 56 % of the total run-off, but only 10 % of sediment load of the whole river basin. The river has a strong monsoon-driven seasonality in discharge, with around 60 % of annual run-off and 80 % of annual sediment discharge occurring during the flood season (June-September, especially July). Other than the impacts of a small (but increasing) number of dams along the trunk stream and tributaries close to the plateau margin, the flow regime of the Upper Yellow River is largely unregulated. Rivers of the Upper Yellow River Basin are globally significant examples of river response to tectonic uplift and incision. This chapter documents a 'journey along the Upper Yellow River', providing an account of river diversity and assessing controls upon the pattern of river types. Valley gradient and confinement are the primary controls on river diversity and evolution in this area. Adjacent to the Qinghai–Gansu border, tectonic uplift and climate changes have induced river

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bed incision via knickpoint retreat, cutting back through bedrock gorges and basin fills. An elevation (climate) induced gradient of riparian vegetation cover exerts a critical control upon the pattern of channel planform types along the river.

Keywords River diversity · Geomorphology · Alluvial river · Bedrock river · River pattern · River evolution · River management · Riparian vegetation

3.1 Introduction

> *Water, water, water … There is no shortage of water in the desert but exactly the right amount, a perfect ratio of water to rock.*
>
> Edward Abbey, *Wilderness Reader*

Rivers provide critical services for humans, including ready access to potable water, an easy means of transportation, fertile and replenished lands that are readily irrigated for agricultural use, a reliable source of renewable energy and food (fish), and many others. Beyond its importance in terms of drinking water, freshwater supports human well-being in many ways related to food and fibre production, hydration of other ecosystems used by humans, dilution and degradation of pollutants and cultural values. In many ways, rivers are the lifeblood of the land. As a consequence of their critical importance to human well-being, it is scarcely surprising that surface freshwaters—lakes, reservoirs and rivers—are among the most extensively altered ecosystems on Earth (Carpenter et al. 2011). In many instances, multiple stressors have transformed the morphology, hydrology, biogeochemistry, ecosystem metabolism and biodiversity of these systems (e.g. Dudgeon 2010). Flow regulation has fragmented almost all major river networks, impacting upon the transfer of mass and energy between continents and oceans. Few rivers retain their 'natural' riparian vegetation. Extensive sections of river have been channelized. Climate and land use changes have modified flow and sediment flux and altered the distribution and effectiveness of resistance elements upon valley floors. In many instances, rivers are adjusting to the legacy of past impacts. While these general assertions hold true for the middle and lower courses of the Yellow River, the Upper Yellow River is far less impacted. Given the pressure for the development in this area, for how long is this likely to be the case?

Management of water has exerted a critical influence upon economic and societal development in China. The emergence of hydraulic civilizations along river courses was closely tied to governance of water management that fashioned adequate supply of water of an appropriate amount and quality at the right time, meeting associated links for food production (Wittfogel 1956). All too often, however, historical efforts to meet societal needs have been addressed through a 'command and control' mindset with limited regard for ecosystem values (Holling and Meffe 1996). Security of supply and minimization of risk were the key challenges presented to engineers. Although these issues were addressed with considerable flair, undue emphasis upon short-term needs failed to address concerns for long-term sustainability which meets human needs while protecting environmental values. In simple terms, the quest for predictability and stability negates the inherent diversity and variability of natural systems. Requirements and commitments change as populations grow, climatic and environmental conditions change, and human needs/aspirations evolve. The quest for water of sufficient quantity and quality in the right place at the right time often conflicts with inherent variability and evolutionary traits. Social and economic collapse in response to environmental damage as a consequence of mismanagement is testimony to failed practices in the past (e.g. Diamond 2005; Wright 2005). In a sense, river health can be viewed as a barometer of the health of our society and our relationship to environmental systems, providing a measure of our commitment to sustainability.

Many challenges are faced in managing the shifting habitat mosaic of dynamic (living) rivers (Everard and Powell 2002). A harmonious approach to environmental management builds upon a solid understanding of the type of river under consideration, striving to work with its character, behaviour and evolutionary trajectory (Brierley and Fryirs 2005). Reach-scale understandings are framed in their catchment context, recognizing how adjustments to one section of river impact upon downstream or upstream reaches, thereby maintaining a ‘balance’ of flow and sediment fluxes. Balance does not equate to stability, or the spatial and temporal equivalence of erosional and depositional processes. Rather, it reflects the process regime for that section of river in its particular setting. Alterations to this process regime may have significant social, economic and environmental consequences. Indeed, history teaches us many lessons about the effectiveness and sustainability of river management practices and their impacts upon the flow-sediment regime of a river. For example, insightful management of the Min River at Dujiangyan in the upper Yangtze River Basin in Sichuan Province brought about practices that ‘work with nature’, such that this scheme has successfully provided flood protection and irrigated water supply for the area around the Chengdu plain for over 2000 years (Li and Xu 2006; Zhang et al. 2012). A quite different application and outcome has been achieved at the Sanmenxia Dam along the middle Yellow River, which was completed in 1960 (Wang et al. 2005, 2007). Untold damage has ensued.

This chapter provides an overview of the diversity, variability and evolutionary traits of river systems in the Upper Yellow River Basin. The rationale here is a simple one: we cannot manage rivers effectively until we can describe them in a meaningful way, interpret their behavioural regimes, and understand controls on where they are found and why, and explain how they are evolving. Much of the Upper Yellow River retains high ecological values (see Li et al. 2016b, Chap. 9). To protect and sustain these values into the future, the degradational or recovery trajectory of these systems must be understood before steps to improve (or maintain) their condition can be implemented.

The structure of this chapter is as follows. First, river diversity along the trunk stream is described through a ‘journey along the Upper Yellow River’. This is

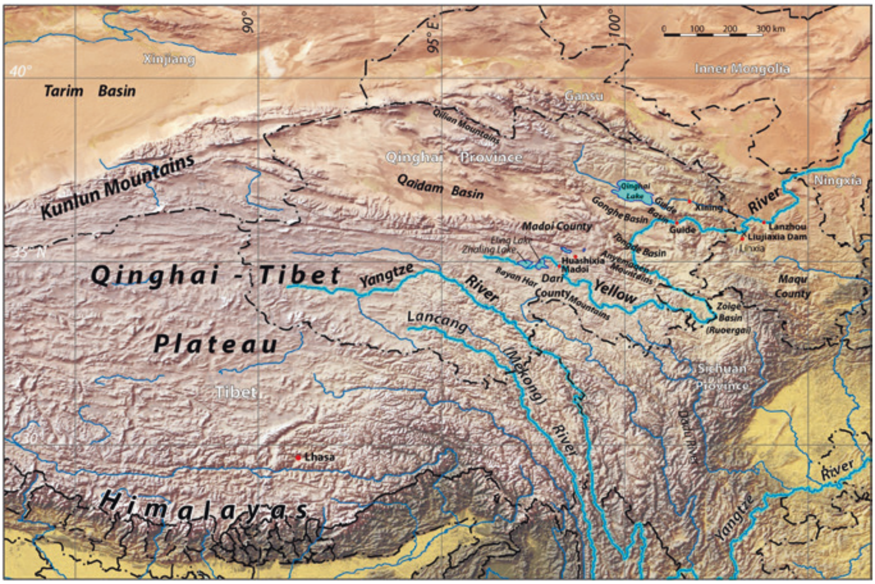

Fig. 3.1 Landscape setting of the Upper Yellow River atop the Qinghai–Tibet Plateau. Along with the headwaters of the Yangtze and Lancang (Mekong) rivers, this source zone is referred to as the Sanjiangyuan. The headwaters of the Yellow River are located upstream of the Zhaling and Eling lakes. The river flows initially in an east-south-east direction, before it takes a major turn to the north-west close to the margin of the Qinghai–Tibet Plateau at the First Great Bend (the Big Loop at Zoige (Ruoergai) Basin) in Sichuan Province. Downstream of this area, the river flows through a series of basin fills and gorges prior to descending from the plateau upstream of Lanzhou

followed by an assessment of controls upon the pattern of river types, including discussion of process relationships along the longitudinal profile of the river, tributary–trunk stream relationships and the imprint of evolutionary traits upon contemporary character and behaviour of the river. Finally, thoughts towards prospective river futures are briefly considered. For simplicity, the Upper Yellow River in this chapter is considered solely within Qinghai Province (Fig. 3.1). The drainage area of upper catchment of the Yellow River at Lanzhou is about 222,550 km^2.

3.2 A Journey Along the Upper Yellow River

The Yellow River flows across nine provinces and autonomous regions before emptying into the Yellow Sea north of the Shandong Peninsula. Based on the division used by the Yellow River Conservancy Commission, the upper reaches of the Yellow River extend from its source in the Bayan Har Mountains to Hekou Town in Inner Mongolia, just before the river makes a sharp turn to the south (see Fig. 3.1). This section of the river has a length of 3472 km, drains an area of 0.386×10^6 km^2 (51.4 % of the total basin area) and drops 3496 m (an average grade of 0.10 %).

From its source to Hekou Town, the Upper Yellow River has a length of 3471 km (63.5 % of the total river length; IRTCES, 2005). Along this section of the river, 43 tributaries drain an area >1000 km^2. The region encompasses a wide range of landscapes, from high-altitude broad plateaus underlain by permafrost, to broad deserts with high dunes, to steep mountain environments with cascading streams (Nicoll et al. 2013). The mean elevation above Lanzhou is around 3600 m. Along the course of the Upper Yellow River, several wide basins are separated by two major mountain ranges: the Bayan Har Mountain defines the southern edge of the Yellow River catchment, and the Anyemaqen Shan runs WNW-ESE through the middle of the upper catchment (Fig. 3.1). The north-west boundary is demarcated by the Chaka sub-basin, an internally drained basin considered part of the larger Qaidam Basin. The Qilian Mountain and the Huang Shui River, the largest tributary on the Upper Yellow River, mark the margin between the Qinghai–Tibet Plateau and the Inner Mongolia Plateau. To the south and west of the Yellow River watershed, tributaries to the Yangtze cut down through the plateau margin to the Sichuan Basin.

The Upper Yellow River contributes about 56 % of the total run-off and only 10 % of sediment load of the whole river basin (Xu et al. 2007; Wang et al. 2007). Steep rock hillslopes, low evaporation and high moisture retention atop the Qinghai–Tibet Plateau produce run-off coefficients that range from 30 to 50 %. There is a strong monsoon-driven seasonality in discharge (see Huang et al. 2016, Chap 4). Around 60 % of annual run-off and 80 % of annual sediment discharge occur during the flood season (June–September, especially July). Less than 1 % of the run-off in the Upper Yellow River Basin is generated from the glaciated area. Sediment discharge is highly correlated to run-off, with much more concentrated sediment load during summer months. Even then, the average suspended sediment concentration is less than 0.5 kg m^{-3}.

Valley gradient and confinement are the primary controls on the distribution of geomorphic process zones along rivers. The imprint of tectonic and incision histories varies markedly along the course of the Upper Yellow River. Adjacent to the Qinghai–Gansu border, tectonic uplift and climate changes have induced river bed incision, creating steep hillslopes and dissected landscapes. Very high erodibility and erosivity result in significant erosion and effective sediment delivery (i.e. these are highly connected landscapes). Incision processes via knickpoint retreat have extended upstream through bedrock gorges and basin fills. Beyond this area, low-relief plateau landscapes of former basin fills have highly disconnected process regimes (Nicoll et al. 2013). Hillslopes are disconnected from channel processes, with extensive sediment stores along valley floors. This gives considerable space for channels to adjust, creating a myriad of planform types. Fully self-adjusting alluvial reaches are separated by bedrock and/or terrace-confined valleys that constrain lateral and/or vertical channel adjustment. The channel bed along most of the Upper Yellow River is comprised of sand and fine-medium calibre gravels.

Significant transitions in valley width result in pronounced changes in river character and behaviour along the Upper Yellow River (see Figs. 3.2 and 3.3). In the sections that follow, river diversity is described for differing landscape compartments moving downstream from the river source.

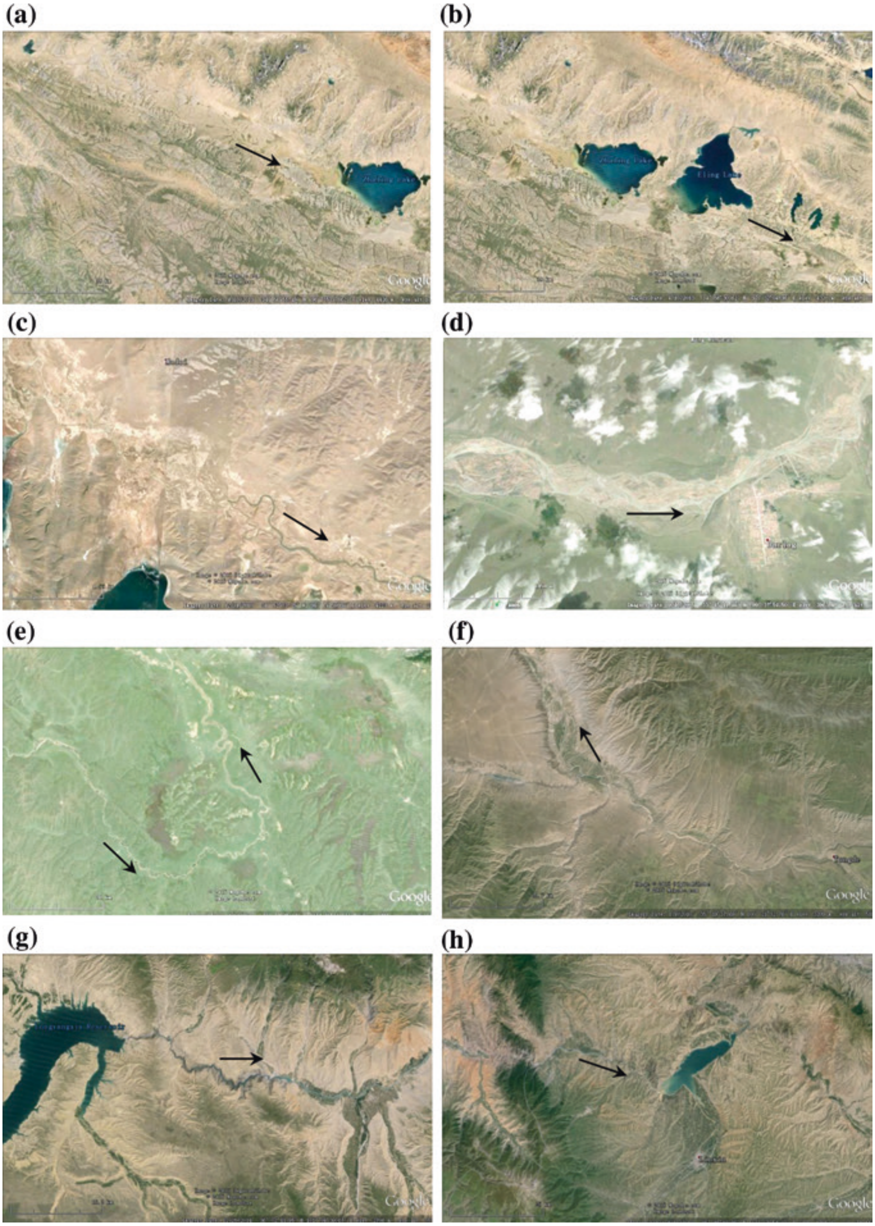

Fig. 3.2 Google Earth images of the river network of the Upper Yellow River. **a** Upstream of Zhaling Lake. **b** Zhaling/Eling lakes. **c**. Upper Yellow River near Madou. **d** Upper Yellow River near Dari. **e** Upper Yellow River at the Zoige Basin (Ruoergai). **f** Upper Yellow River in the Tongde Basin. **g** Upper Yellow River in the Guide Basin. **h** Upper Yellow River at Qingtong Gorge (Liujia)

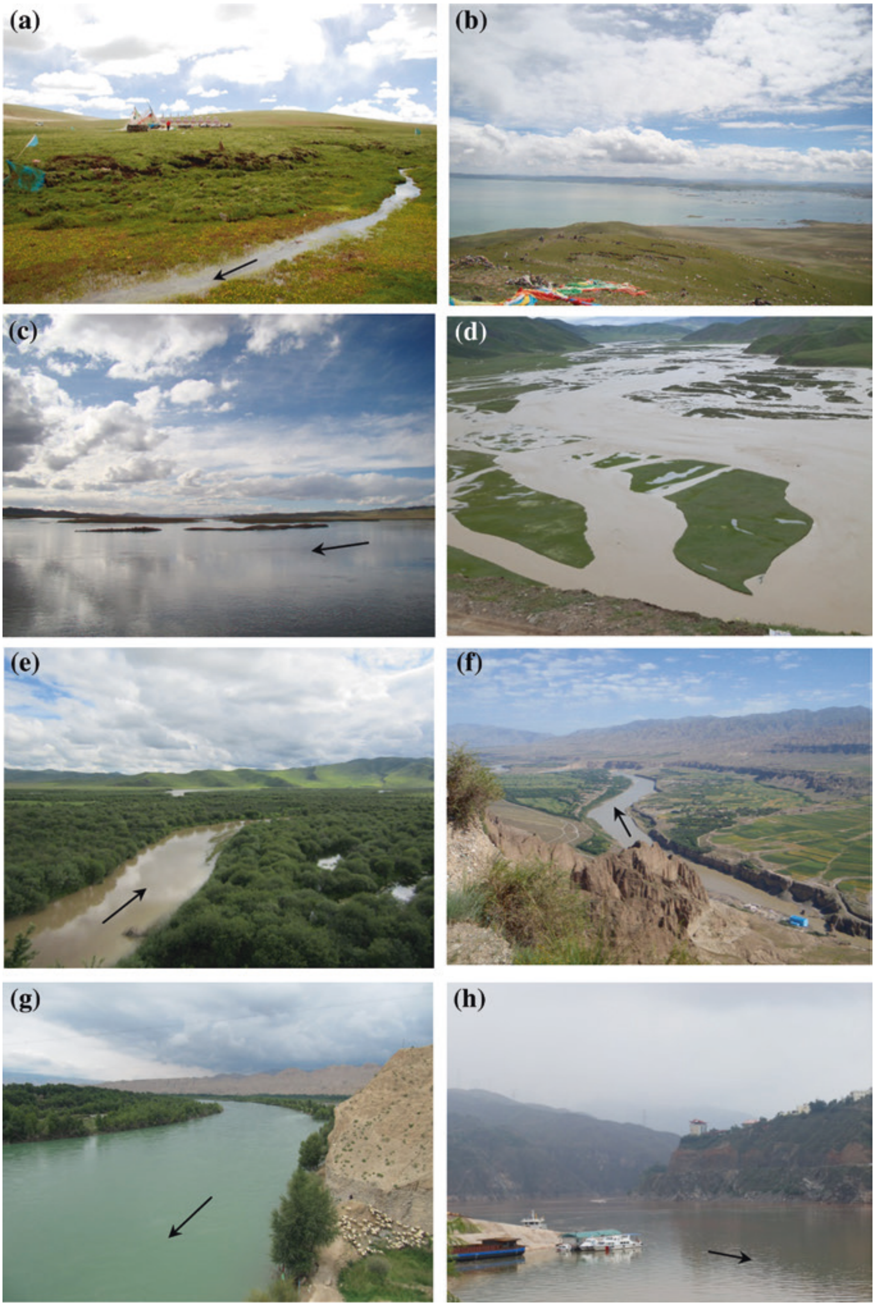

Fig. 3.3 Photographs of the Upper Yellow River. **a** The Yellow River rises from Yagradagzê (5214 m) upstream of Zhaling Lake (H. Tane). **b** Zhaling Lake. **c** Upper Yellow River near Madou (4200 m). **d** Upper Yellow River near Dari. **e** Upper Yellow River at the Zoige (Ruoergai) Basin. **f** Upper Yellow River in the Tongde Basin. **g** Upper Yellow River in the Guide Basin. **h** Upper Yellow River at Liujiaxia Gorge (Liujiaxia Reservoir)

3.2.1 *The Headwater Area: A Landscape of High-Elevation Lakes and Alluvial Plains*

The source of the Yellow River lies in the Bayan Har Mountains (maximum elevation 5266 m asl) which divide the Upper Yellow and Yangtze rivers. The river originates in the Yueguzonglie Basin at an elevation of 4600 m, around 200 km upstream of Maduo. The climate is very cold and dry. The town of Maduo (4272 m), which lies at the centre of the Mountain River Lakes ecographic district, has a mean annual temperature of around −4 °C and an annual precipitation of around 320 mm (of which 240 mm falls between June and September). The relatively subdued mountains and valleys of this area bear the imprint of glaciation, with various erosional and depositional landforms such as U-shaped valleys and large moraines (Stroeven et al. 2009). In general terms, hillslopes of these low-relief landscapes rise less than 200 m above the plateau surface (see Brierley et al. 2016a, Chap 1; Nicoll et al. 2013). An intricate tapestry of wetlands and waterways makes up the plateau landscapes of this area, with alluvial plains and lakes separated by low rounded mountains. Beyond their origins in springs, streams wind their way through a mosaic of tarns and morainal deposits, prior to flowing through fluvial outwash formations with anabranching, braided and meandering channel planforms (Figs. 3.2a and 3.3a).

From the river source to Maduo, the river has a length of 370 km, drains an area of 20,930 km^2 and has three tributaries that drain an area >1000 km^2. This area is characterized by a chain of inter-montane basins that are linked west to east by the Upper Yellow River. The basins support extensive aquifers. This section of river flows through a series of swamps and grassland areas and traverses a series of major lakes. Zhaling and Eling lakes have capacities of 4.7 billion and 10.8 billion m^3, respectively (see Figs. 3.2b and 3.3b). Zhaling Lake (Gyaring Lake in Tibetan, meaning 'long grey lake') has an elevation of 4292 m. It covers an area of 526 km^2 (approximately 35 km × 15 km), drains an area of 8161 km^2 and has a mean depth of 8.9 m (maximum 13.1 m). Eling Lake (Ngorling Lake in Tibetan, meaning 'long blue lake') has an elevation of 4268 m. It covers an area of 611 km^2 (approximately 32 km × 19 km), drains an area of 18,188 km^2 and has a mean depth of 18.9 m (maximum 31.6 m). Indeed, Madou County is referred to as 'the county of thousand lakes', 15 of which are larger than 10 km^2. Valley floors of many rivers in this area are inset within deposits of formerly extensive lake networks. Extensive terraces are found beyond contemporary floodplain areas, with low-relief alluvial fans at valley margins. These features are comprised predominantly of coarse and silty sand with occasional gravel. Around Maduo, valleys are generally unconfined, with extensive floodplains, terraces and fans disconnecting sediment transfer from hillslopes to the stream network (Nicoll et al. 2013). The valley extends from 2 to 20 km wide. Given the average valley floor gradient of the upper Yellow River near Maduo of 0.0004, the channel has little energy to move sediment and deposits it midstream to create multiple channels. The channel adjusts laterally across shallow floodplains and is characterized by braided, anabranching and some meandering sections, with many floodplain wetlands (Figs. 3.2c and 3.3c).

As the average elevation of this area exceeds 4000 m, human activities are limited. Lush grassland pastures and vast expanses of open ground are found along river margins. However, due to the low temperatures and the location above the elevation-induced permafrost threshold, the growing season is very short. As a consequence, vegetation has little opportunity to stabilize channel bars, which are readily reworked to produce braided river morphologies (Yu et al. 2014).

3.2.2 Around Dari

From Maduo to Dari, the Upper Yellow River flows between the Bayan Har Mountains and the Anyemaqen Mountains. Beyond the low-relief upland area around Madou, the Yellow River enters the high relief topography of the Anyemaqen Mountains. Fluvial valleys begin to narrow, tributaries steepen, and hillslope processes begin to play a dominant role in the landscape. Numerous active fault complexes exert structural control upon the drainage network. The highest peak of the Upper Yellow River Basin, Maqinggangri (Maji Snow Mountain), extends to 6280 m, more than 2000 m above the adjacent valley floor. There are 57 glaciers within this range, covering an area of 126 km^2. Among these glaciers, Halong Glacier covers an area of 24 km^2. This is the largest and longest glacier in the Upper Yellow River drainage basin, extending over a vertical distance of 1800 m. Earlier phases of glaciation were much more substantive, extending hundreds of kilometres beyond contemporary glacial limits (see review in Nicoll et al. 2013). Extensive permafrost has created many periglacial landforms as products of frost heave, freeze–thaw and frost weathering. These features are more common in the humid east and south of the Upper Yellow River, but are relatively sparse in the arid north.

Dari (elevation 3968 m) is located at a strategic headland used for crossing the Yellow River. Local bedrock marks a constriction in valley width and a step along the course of the river, with a gorge (narrow, deep bedrock-controlled reach) downstream, and a shallow grade alluvial reach with wide and shallow channel cross sections upstream. A hilltop statue of King Gesar of Tibet who defeated the Tang Emperor's Army has a commanding view of the river at Dari County Town. Another statue on the floodplain shows the Tang Princess acknowledging her husband on the mountain top from the valley floor. Associated symbolism suggests that Tibetan shamanists rule the mountains, while Chinese animists rule the lowlands (Tane, personal communication, 2015).

Both mean annual temperature and precipitation at Dari are notably higher than upstream, at around 1 °C and 550 mm (of which around 400 mm falls between June and September). As Dari lies at an elevation close to the permafrost threshold, the growing season is slightly longer than in upstream (higher) areas. However, prevailing environmental conditions largely restrict human activities to animal husbandry in this area. Less severe climatic conditions relative to upstream areas play a significant role in supporting colonization of river bars by grasses and small shrubs during the summer months, despite higher flows at this time of year (Yu et al. 2013, 2014). This, in turn, promotes the development of an anabranching rather than a braided river. Multiple channels (including backchannels), bars and islands provide a wide array of hydraulic units, with some wetlands and ponds on floodplains (Figs. 3.2d and 3.3d). Valley width in this reach ranges from 500 to 2500 m with an average width of approximately 1000 m. The Upper Yellow River in this area has a slope of around 0.001. Aggradational floodplains have developed upstream of the bedrock constriction (pinch point) that has induced base level control at the knickpoint at Dari County Town (Yu et al. 2013, 2014).

3.2.3 Deep Valleys and Gorges Downstream of Dari

Downstream of Dari, the Upper Yellow River cuts through the rugged, finely dissected ranges of the Anyemaqen Mountains (elevation 3300–4500 m). Here, the river is characterized by deeply entrenched valleys and precipitous gorges. The valley is typically 15–300 m wide, with occasional or discontinuous floodplain pockets. There is limited space for sediment accumulations, even at tributary confluences, where relatively small alluvial fans are evident. Beyond Jiuzhi County Town, the river enters Sichuan Province at the First Great Bend (or the Big Loop), beyond which it turns sharply 180° to the north-west as it traverses the Anyemaqen Mountains, flowing through part of Gansu Province before returning to Qinghai Province (Li et al. 2013).

3.2.4 Around Maqu: Grasslands and Wetlands

Entry into the first major sedimentary basin marks an abrupt change in the landscape, from a region marked by strong structural control and steep, narrow valleys to the low-relief, poorly drained area of the Zoige Basin. The course of the Yellow River changes nearly 180° within this basin, likely reflecting deformation around the tip of the Kunlun fault complex (Harkins et al. 2007). Fluvial landscapes in this area are relatively unconfined, with wide valleys giving space for low-gradient, alluvial systems to develop. Many tributaries are disconnected from the main stem, ending in shallow lakes and swamps.

The Yellow River enters into Ruoergai grassland/wetland of the Zoige Basin at an altitude of ~3500 m, flowing across the broad and flat alluvial plain before finally moving into valleys near Maqu County at an altitude of ~3400 m. The Ruoergai Basin is largely comprised of grassland, low mountains, wide valleys and swamps. Quaternary sediments on the valley floor attain a thickness of around 200 m near Tangke Town in Zoige County. Mean annual temperature at Maqu (elevation 3471 m) is around 1.6 °C, while mean annual precipitation totals around 600 mm (of which 430 mm falls between June and September).

The Upper Yellow River near Maqu is predominantly a meandering–anabranching–anastomosing river (Figs. 3.2e and 3.3e). The knickpoint downstream, which represents the upstream extent of a phase of historical incision, acts as a local base level control, behind which valley infilling has generated valley floor slopes of approximately 0.0002. The low-energy channels have relatively stable banks, with a high proportion of vegetated mid-channel bars/islands. Many abandoned meanders on floodplains and adjacent terraces attest to a long-term history of lateral migration, avulsion and incision, with indications that the channel has straightened its course in the relatively recent past (Li et al. 2013). Floodplains, extensive backswamps and tributary fans store large volumes of sediment, disconnecting the river from the valley margins. Many tributaries such as Bai, Hei, Zequ and Nanmucuoqu Rivers have developed highly sinuous, meandering channels upstream of their confluences with the Upper Yellow River. Interestingly, braided–meandering and meandering–braided transitions are coincident with variable flow inputs from tributary rivers (Bai and Hei rivers, respectively; Li et al. 2013).

3.2.5 Incised, Confined and Meandering Reaches Beyond the Zoige Basin

Beyond Maqu County, the Upper Yellow River has incised through basin-fill deposits and intervening bedrock steps (gorges) and has a confined (imposed) meandering alignment. Tectonic controls likely induced the shift in river course at the First Great Bend, as the river re-enters the Anyemaqen Mountains before emerging within the Tongde Basin approximately 250 km downstream. Incision of the Upper Yellow River has fashioned these landscapes, as trunk and tributary systems have cut down through the broad Tongde and Gonghe sedimentary basins. Alluvial fans and terrace sequences are prominent. The boundaries of both the Tongde and Gonghe basins are delineated by narrow bedrock ranges, with the Yellow River flowing through a narrow bedrock gap (Craddock et al. 2010). Aeolian reworking of deposits creates some major sand dune fields in this area, especially adjacent to lakes and alluvial valley floors. Prominent examples include the dune field atop the Santala (three terraces) near Gonghe and the largest continuous dune field in the Yellow River Source Region at Mugetan (30 km long from west to east, 15 km wide from north to south; see Li and Wang 2016, Chap. 8).

The Lajia Mountains district (3000–4500 m) is a historic south and west crossing place on the Upper Yellow River. At Tongde (elevation 3289 m), the mean annual temperature and precipitation are 0.7 °C and 425 mm (of which around 310 mm falls between June and September). Adjacent to Xinghai in the Tongde Basin, the Upper Yellow River is terrace- and valley-confined, with little room to move (Figs. 3.2f and 3.3f). Rigid banks form narrow gorges and entrenched

Fig. 3.4 Telescopic fan at Tongde Basin

channels. The valley floor has a slope of around 0.002. River morphology in this reach is largely a product of knickpoint retreat through the basin fill. The combination of a lack of space and relatively high flow energy generally prevents the formation of mid-channel bars and secondary channels. As a result, the channel is relatively homogenous, cut off from its historical floodplains, leaving it with little room to adjust or deposit sediment. Sediment entering the channel from upstream or local tributaries is efficiently flushed through this reach because of the relatively steep gradient, lack of storage space and high stream power. Near Xinghai, a significant tributary drains from the north through a prominent inter-montane basin. However, tributaries are unable to exert a significant influence upon the Upper Yellow River trunk stream in this area, because valley confinement induces constraints on the capacity for lateral adjustment along the incised river. In some instances, however, telescopic alluvial fans have developed where there is sufficient space for differing phases of fan growth to be preserved (Fig. 3.4). In general terms, steep hills and dissected mountain blocks separate valley basins in this area, with deeply dissected rugged hills and mountains at elevations of up to 4400 m and broad valley basins at an elevation of around 3000 m. Majestic terraces record the long-term accumulation of lacustrine and alluvial deposits within the Gonghe Basin. Valley fills are up to 1 km deep, with terraces [locally referred to as the Santala (three levels)] extending over tens of kilometres wide.

Overall, the section of the Upper Yellow River from Madou to Longyangxia has a length of 1418 km, drains an area of 110,490 km^2 (cumulative area 131,420 km^2) and has 22 tributaries that drain an area >1000 km^2.

3.2.6 Moving Through the Margins of the Qinghai–Tibet Plateau: A Riverscape of Gorges, Terraces and Fans

The section of the Upper Yellow River from Longyangxia to Xiaheyan (Qingtongxia) has a length of 794 km, drains an area of 122,722 km^2 (cumulative area 254,142 km^2) and has eight tributaries that drain an area >1000 km^2. This section of river flows swiftly through multiple long gorges that alternate with 17 sections of wider valley. Bedrock confinement in narrow gorges creates opportunities for the development of hydroelectric plants. Beyond the Longyangxia Reservoir (storage capacity of 24.7 billion m^3, construction completed in 1992), the Upper Yellow River enters the Guide Basin, where basin-fill deposits create a major suite of terraces. Given the longer period since incision worked its way through this reach, the valley floor is much wider than upstream, with significant drapes of reworked alluvial and hillslope materials making up extensive fans at valley margins. These topographic considerations, along with more ameliorative climate conditions, present greatly enhanced prospects for agricultural and horticultural exploits. Indeed, local irrigation practices extract water from this anabranching section of river. Immediately, downstream of Guide Township, a left-bank tributary, cuts through a dissected sandstone (Danxia) landscape, creating a stunning backdrop to the river (Figs. 3.2g and 3.3g).

Liujiaxia Dam lies just downstream (construction completed in 1974). The section of river before the border with Gansu Province is characterized predominantly by the striking Liujia Gorge, with several major landslide scars indicating phases of hillslope collapse, temporarily damming the Upper Yellow River (Figs. 3.2h and 3.3h). Loess deposits form a dominant drape over much of this landscape.

3.3 Controls on the Patterns of River Types Along the Upper Yellow River

The topography of the Upper Yellow River Basin is dominated by the subdued relief of the plateau, which is made up of two components—the geologically controlled flatlands of headwater areas and large basin fills at Zoige, Tongde, Gonghe and Guide. Adjacent mountain ranges and ridge lands have more pronounced relief, with glacial features restricted to elevated parts of the Bayan Har Mountains. The accentuated relief at the plateau margin presents a stark contrast. A pronounced step on the longitudinal profile of the Upper Yellow River upstream of Lanzhou demacrates the transition from the Qinghai–Tibet Plateau to the Loess Plateau (Fig. 3.5). Upstream extension via knickpoint retreat has triggered dramatic incision through a series of bedrock steps (gorges), interspersed with terrace landscapes of incised basin fills. Tributary streams have adjusted to changing base level conditions, creating majestic alluvial fans at confluence zones (Fig. 3.4). Incision has limited the space over which channel adjustments can take place in these reaches.

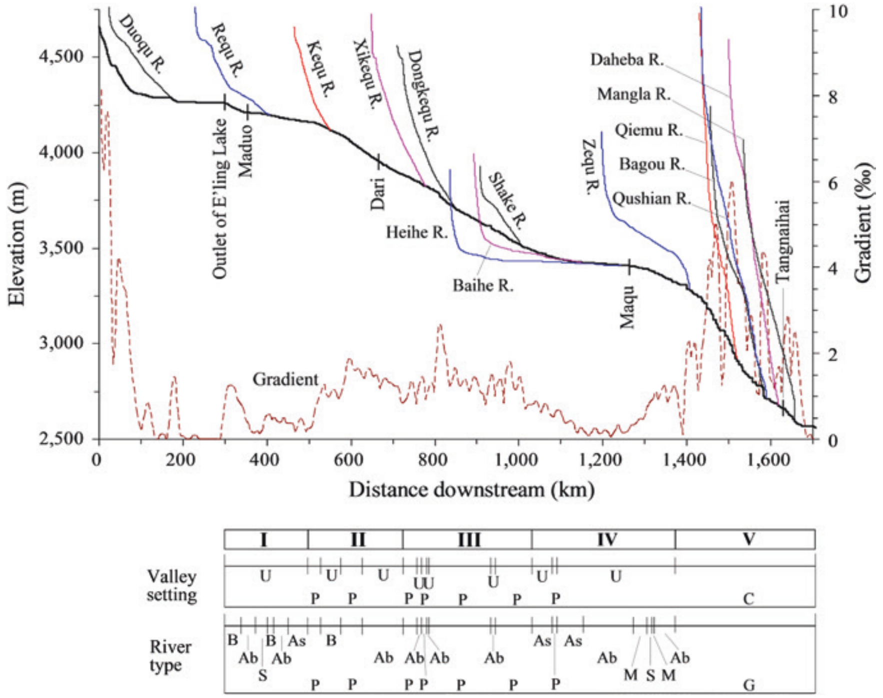

Fig. 3.5 Longitudinal profiles of the Upper Yellow River and key tributaries (modified from Yu et al. 2014). In terms of valley settings, a refers to unconfined, p to partly-confined, c to confined. In terms of river type, B refers to braided, Ab to anabranching, S to straight, As to anastomosing, P to partly-confined river, M to meandering, and G to gorge

Uplift of the plateau is thought to have begun about 50 million years ago, but the majority of its altitude has been formed since about 10 ± 8 million years ago (An et al. 2001; Harrison et al. 1992; Molnar et al. 1993) or more recently (e.g. Li et al. 1996). Spatially differentiated uplift rates ranged from 1 to 10 mm per annum, increasing from the north to the south of the plateau (Li et al. 1997; Zhang et al. 1991). Major east–west strike–slip faults and associated active normal faults developed in response to uplift; current slip rates on these faults average 1–20 mm per annum (Yin and Harrison 2000; Tapponnier et al. 2001). Regional metamorphism and igneous activity have accompanied these tectonic movements (Liu et al. 1980; Yin and Harrison 2000).

The upwardly convex longitudinal profiles of all the major rivers draining the eastern margin of the Qinghai–Tibet Plateau indicate that despite their extreme erosion rates, rates of channel incision are outpaced by tectonic forcing (i.e. incision is unable to match continued uplift; Aiken and Brierley 2013; Harkins et al. 2007). The Upper Yellow River established its present course in the Late

Overview of the Danxia landscapes at the mouth of the Garang River, a tributary of the Yellow River (in the foreground) near Guide

Dissected badland landscapes of the lower Garang Valley, a tributary that joins the Upper Yellow River just downstream of Guide

Fig. 3.6 Photographs from Garang Valley, a left-bank tributary of the Upper Yellow River immediately downstream of Guide

Pliocene–Early Pleistocene. Previously, inland-draining (endorheic) basins that had developed very thick fills of sediment from combinations of river and lake deposits, with some aeolian units, were incised by headward migration of a fluvial knickpoint that integrated these basins to create the modern course of the river (Craddock et al. 2010; Fang et al. 2003; Li et al. 1997; Nicoll et al. 2013; Perrineau et al. 2011). The longitudinal profile of the Upper Yellow River has at least four major knickpoints related to the history of basin excavation and drainage integration during the Quaternary (Fig. 3.5; Craddock et al. 2010). The discrete base levels observed along the longitudinal profile reflect waves of incision, with oversteepened reaches separating the basin fills (Fig. 3.5; Craddock et al. 2010). Changes to base level created highly connected landscapes with very high drainage densities along some tributary systems (e.g. Garang Valley immediately downstream of Guide; Nicoll and Brierley 2016; Fig. 3.6). Major landslide events have dammed the river in confined valley sections at the plateau margin (e.g. Guo et al. 2014; Ouimet et al. 2007). Breaching of these landslide-induced dams and their associated barrier lakes creates significant flood events.

A significant gradient of riparian vegetation cover is evident in the source region of the Yellow River (Yu et al. 2014). Downstream of Eling Lake at Maduo, vegetation cover on mid-channel bars, floodplains and hillslopes is restricted to grass and occasional low shrubs with an average height of less than 20 cm. Further downstream at Dari, conditions are much more amenable to vegetation growth, with significant shrub establishment on mid-channel bars. Maduo has only two months per year with a mean minimum temperature above freezing, whereas Dari and Maqu have 4–5 months per year above freezing. Around the First Great Bend of the Yellow River, mid-channel bars have an almost 100 % cover of *Salix Atopantha schneid*, with significant shrub and grass communities beneath the *salix* trees. The influence of riparian vegetation upon flow resistance characteristics and bank strength affects channel morphodynamics. In the absence of riparian vegetation and/or cohesive materials to stabilize the banks, variable, unconstrained flow over a non-cohesive bed generates laterally unstable multi-channelled rivers. Hence, braiding is the default channel planform morphology around Maduo. Although the high width-to-depth ratios and low topographic relief of braided channels make these areas susceptible to vegetative encroachment during low-flow conditions when large areas of the bed are exposed, the likelihood of vigorous vegetation growth is limited because ambient environmental conditions do not persist for a sufficient length of time to support vegetative establishment and reproduction. As these conditions are met further downstream, vegetation exerts a more substantive influence upon channel planform type, favouring the development of anabranching and meandering rivers (Yu et al. 2014).

In summary, while much of the Upper Yellow River has a forced morphology that has been induced by the geological history of the region, localized areas are truly alluvial with fully deformable boundaries. In the latter areas, the contemporary channel flows within older basin-fill deposits, with significant flights of terraces and fans at valley margins. Vegetation relations to channel morphodynamics fashion a distinct gradient of channel planform types in these alluvial reaches. This physical template fashions the nature and extent of human impacts upon the river, and resulting biophysical responses.

3.4 Human Impacts upon the Upper Yellow River

In global terms, the landscapes of the Upper Yellow River are sparsely populated and have been subjected to limited development pressures. This remains a relatively remote, high-elevation region with limited prospects for many human activities. However, the human history of the region spans many millennia (Han et al. 2016, Chap 12), and terrestrial systems have been transformed by vegetation clearance and overgrazing (Li et al. 2016a, Chap. 7; Tane et al. 2016, Chap. 13). Other than local impacts induced by dams adjacent to the plateau margin, human modification of flow and sediment regimes in the study area is limited. Channelization is restricted to very short sections of river adjacent to towns. Indeed, it could be contended that the physical template of the river (i.e. its geomorphic structure and diversity of physical habitat) has not been subjected to severe pressure or impacts. Having said this, there are not many channel banks that have not been trampled by yak (Tane et al. 2016, Chap 13). Although land use changes may have induced some changes to biogeochemical relationships and water quality, there is a lack of industrial pollutants in the area, and use of fertilizers and herbicides is extremely limited (agricultural practices are largely organic). In general terms, the aquatic ecosystems of the Upper Yellow River are much less impacted than other parts of the system. To date, however, we have limited understandings of human impacts upon species biodiversity and abundance along the Upper Yellow River (Pan et al. 2013; Qi 2016, Chap. 11).

3.5 Concluding Comment: Prospective River Futures for the Upper Yellow River

Rivers of the Upper Yellow River Basin are globally significant examples of river response to tectonic uplift and incision, with majestic gorges and deeply etched tributaries within extensive basin-fill deposits. Long-term geologic histories of river capture remain as elusive scientific debates that will likely be resolved through detailed field and remotely sensed analyses and chronological appraisals in coming years. Although we have good appreciation of river diversity and patterns in the region, our understandings of evolutionary traits and ecological relationships are limited. In terms of human impacts, rivers in the region are generally quite resilient to change, and they remain in good geomorphic condition, with reasonable prospects for recovery. Other than local hydropower developments, human activities have exerted a relatively small impact on river geodiversity. However, future hydropower developments may alter flow and sediment regimes, modifying patterns and rates of fluvial erosion and deposition, thereby affecting channel morphology and habitat relationships. Also, long-term impacts of climate change on vegetation cover and run-off relationships may induce changes to fluvial processes in alluvial reaches. The future of the river will depend largely upon efforts to protect and enhance the high-quality environmental values of the river (see Brierley et al. 2016b, Chap. 15).

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