Abstract
A climate-induced vegetation gradient induces marked variability in the character and behavior of anabranching reaches of the Upper Yellow River. Analysis of satellite imagery and field appraisal of biogeomorphic attributes shows that these reaches retain a good condition in geo-eco-hydrological terms. Degradational trends experienced in the late 20th century have been transformed into recovery pathways in recent decades. Changing land use practices, especially reduced stocking rates, and creation of various reserves have engendered environmental improvement. Recent climate change has supported improvements in geo-eco-hydrological conditions in the study reaches. A comprehensive suite of environmental protection programs of unprecedented scope and scale enhances the buffering capacity of landscapes and ecosystems in this region, supporting their ability to adapt to increasingly uncertain environmental futures.

KEYWORDS
climate change, conservation, environmental protection, land use change, Sanjiangyuan

1 | INTRODUCTION
Looking after good condition rivers before they become degraded is a critical component of proactive and precautionary management plans (Tickner et al., 2020; Tockner & Stanford, 2002). Remnant reaches are typically restricted to relatively small areas, especially for large river systems (Grill et al., 2019). Here we report upon conservation prospects for anabranching reaches of the Upper Yellow River on top of the Qinghai-Tibet Plateau (QTP) in western China. Although impacts of climate change are accentuated in such alpine areas, we show how recent evolutionary trajectories indicate that geo-ecological recovery and enhancement is underway in this region (sensu Fryirs & Brierley, 2016).

Managing at source is a foundation premise of river management. Contemporary approaches to land and water management in the headwaters of the Yellow River apply a coherent package of environmental protection measures of unprecedented scale and scope (Bryan et al., 2018; Cao, 2011; Jiang & Zhang, 2016). Proactive and precautionary
programs take on special meaning in efforts to look after the cradle of Chinese civilization; although highly valued, the river is sometimes referred to as “China’s Sorrow” because of disastrous consequences of frequent and devastating flooding in lowland reaches (Chen et al., 2012; Li et al., 2020; Yu, 2002). While middle and lower courses are amongst the most manipulated river systems in the world (Kong et al., 2016; Miao et al., 2010), headwater reaches remain in good condition in geo-eco-hydrological terms because of limited direct human impacts (primarily adjacent to towns, especially in lower elevation areas in the north-east part of the QTP), low population densities and low intensity land uses (primarily supporting of grazing-adapted ecosystems; Han & Brierley, 2021; Miehe et al., 2019). This article scopes prospective futures for management of this globally important river.

Once a characteristic feature of all large rivers, anabranching reaches are now increasingly rare and threatened (Gibling, 2021; Latrubesse, 2008). Significant diversity in the character and behavior of these multichanneled rivers reflects the range of processes that form and rework channel and floodplain compartments in differing environmental settings (e.g., Carling et al., 2014; Nanson & Knighton, 1996). Given their distinctive attributes, conservation and restoration of anabranching rivers is a priority concern in strategic approaches to environmental management (e.g., Brown et al., 2021; Harwood & Brown, 1993; Marcinkowski et al., 2017).

A pronounced climate-induced vegetation gradient generates marked variability in the geodiversity of anabranching reaches of the Upper Yellow River (Figure 1; Han & Brierley, 2020; Yu et al., 2014). Although various articles have appraised river flow responses to climate change in the Upper Yellow River region (e.g., Cuo et al., 2014; Meng et al., 2016; Zhang et al., 2017; Zheng et al., 2009, 2018), trajectories of river adjustment are yet to be related to assessment of river condition and recovery prospects in a comprehensive manner. This article appraises recent evolutionary trajectories of study reaches at Maduo (4185 m asl), Dari (3960 m asl), Maqu (3450 m asl), and Guide (2117 m asl). Building upon field and remote sensing analyses reported by Han and Brierley (2020, 2021) and Han et al. (2020), this study interprets recovery potential to scope “moving targets” that appraise prospective river futures in relation to climate and land use changes. Changes to river condition over time (i.e., degradation or recovery traits) are synthesized using the river recovery diagram (Brierley & Fryirs, 2005, 2016; Fryirs & Brierley, 2000, 2016). The article addresses three key questions:

1. How have geo-eco-hydrological interactions shaped the evolution of each reach in recent decades?
2. Does each reach presently sit on a degradation or a recovery pathway (i.e., is condition continuing to deteriorate, or is it improving)?
3. How can these findings inform management of river futures?

2 | THE UPPER YELLOW RIVER

Rapid economic development in recent decades now supports aspirational calls for an ambitious blueprint of ecological civilization in China (Voltaire Network, 2018). Given its significance as the Mother River of China, protection of the Yellow River is important in biophysical, socio-cultural, and political terms, enhancing ecological and geopolitical security. Hailed as the roof of the world, the third pole and the water tower of Asia, the QTP is one of the least polluted areas on earth (Brierley et al., 2016).

Key shifts in Government priorities have underpinned major shifts in Yellow River management strategies over time, from an emphasis upon flood control and management to concerns for pollution and soil erosion management, and the contemporary focus upon ecosystem conservation and improvement (e.g., Jiang et al., 2016; Jiang et al., 2020). Building upon a comprehensive suite of interventions over the last 20 years, a new program entitled Ecological conservation and high-quality development of the Yellow River Basin issued by the Communist Party of China Central Committee and the State Council in October 2021 aims to further improve ecosystem quality and life conditions through sustainable use of water resources, co-ordinated management of degradation and protection of mountains, rivers, forests, farmlands, lakes, and grasslands (http://www.gov.cn/zhengce/2021-10/08/content_5641438.htm). Chapter 3 in the Outline of Ecological Protection and High-quality Development Planning in the Yellow River Basin focuses on Strengthening the Construction of Upstream Water Conservation Capacity, emphasizing initiatives that “Follow the laws of nature, focus on key areas, accelerate the containment of the trend of ecological degradation, restore important ecosystems, and strengthen the function of water conservation through natural restoration and implementation of major ecological protection and restoration projects” (https://baijiahao.baidu.com/s?id=1713084220403824204&wfr=spider&for=pc).
FIGURE 1 Location/topography map and representative photographs of the four study reaches. (a) The Sanjiangyuan National Park (source zone of the Yellow, Yangtze and Lancang [Mekong] Rivers) lies on top of the Qinghai-Tibet Plateau. (b) The Yellow River drains from Zhaling and Eling Lakes in headwater areas, flowing through an alternating sequence of gorges and anabranching reaches. (c) Anabranching reaches of the upper Yellow River demonstrate significant variability in geo-eco-hydrological terms, with prominent floodplain ponds and wetlands at Maduo, braided-anabranching characteristics at Dari, laterally stable vegetated islands at Maqu and elongate bar-island complexes in the regulated reach at Guide.
In recent years, the Chinese Government has established a suite of environmental protection initiatives in the Sanjiangyuan—the source zone of the Yellow, Yangtze, and Lancang (which joins the Mekong after it emerges from China) Rivers on top of the QTP (Figure 1; e.g., Li et al., 2012; Sun et al., 2018). Formally established in 2020 following a 20-year trial period, Sanjiangyuan National Park oversees a co-ordinated package of measures that ties management of conservation and biodiversity to climate change initiatives, energy policies, and land use policies (including ecological compensation mechanisms; Xiao & Zhao, 2017). These programs recognize the strategic importance of protecting China’s water security, while emphasizing concerns for local cultural and ecological values (Shao et al., 2016). They are supported by a river and lake chief system, which commenced in 2007 and was assigned into Law in 2017, striving to inspect, preserve, and protect assigned rivers/reaches, with a particular focus on pollution (water quality management) (Wu et al., 2020; Zhan, 2019). Monitoring and early-warning systems integrate air, land, and ecosystem networks supported by Earth observation science and technology and big Earth data applications (Guo et al., 2018).

Uplift of the QTP and headward erosion of rivers have created various low relief basins that operate as a series of steps separated by gorges in the Source Zone of the Yellow River (SYR; Figure 1; Brierley et al., 2016; Nicoll et al., 2013). The region has an alpine continental climate with clear separation of dry and wet seasons, a small annual temperature range, large diurnal range, long sunshine hours (>2500 h/yr), and strong solar radiation. Between 75% and 90% of annual precipitation occurs from June to September associated with the South Asia summer monsoon and the East Asia summer monsoon (Zheng et al., 2009). At Maduo the climate is dry and cold semi-arid (around 460 mm a\(^{-1}\)), Dari and Maqu are humid and cold (around 700 and 520 mm a\(^{-1}\), respectively) and Guide is warm and very dry (around 300 mm a\(^{-1}\)) (Brierley et al., 2016). The growing season (mean daily temperature > 5\(^\circ\)C) is much shorter in Maduo (3 months), compared with 4 months in Dari, 5 months in Maqu, and 7 months in Guide. Despite the short growing period and low biomass production, these areas are rich in plant species, with up to 30 species per m\(^2\) (Chen et al., 2007). Climate change has extended the growing season in recent decades (Zhang et al., 2018). A temperature rise of 0.37°C–0.39°C 10 a\(^{-1}\) has been detected, with the most pronounced increase since 1997 (Wang et al., 2019). Rising temperatures since the 1960s, alongside earlier melt and later onset of permafrost, have resulted in falling groundwater tables, lower levels of lakes, drying of swamps and ponds, and transition of alpine wetland meadow to dry meadow in the SYR (Cheng & Jin, 2013; Cheng & Wu, 2007).

Although this area makes up only 15% of the whole Yellow River basin, it contributes over 35% of its water resources (Zheng et al., 2009). The region from Dari to Maqu accounts for 51% to the total flow of the SYR at Tangnaihai gauging station, while the areas upstream of Dari and downstream of Maqu contribute 21% and 28%, respectively (Figure 1). Flow and sediment flux is concentrated from June to September (about 70% and 85% of annual totals, respectively; Lv, 2017). Given the limited extent of glaciers in this region, rainfall runoff is by far the primary contributor to streamflow (Cuo et al., 2014). Major lakes control the peakedness and duration of flood events above Maduo. Notable decrease in streamflow and sediment discharge has been detected since 1989 (around 16%; Hou, 2020; Jiang et al., 2017; Wang et al., 2018). While streamflow in April, May, and June shows a slightly increasing trend in recent years, all other months show a decreased trend (Cuo et al., 2013). Reduced discharge since 1989 is a result of decreased precipitation (accounts for 70% of change) and slightly increased evapotranspiration (30%) (Jiang et al., 2017; Wang et al., 2018; Zheng et al., 2018). However, in the 2000s, precipitation only contributed for 3% of runoff reduction, while increased evapotranspiration accounted for 97% (Meng et al., 2016).

The QTP is the world’s largest pastoral ecosystem. Conversion from forest and the emergence of grazing adapted ecosystems commenced around 8000 years ago (Miehe et al., 2019). Over time, grazing practices have drained, degraded, and dehydrated many wetland areas, transforming them into terrestrial grassland habitats (Brierley et al., 2016). Livestock grazing, chiefly yak (Bos grunniens) and Tibetan sheep (Ovis aries), underpins the regional economy. The groundcover has low productivity and low forage height, ranging between 10 and 30 cm. Intertwined grass roots form a densely compacted but flexible mat-like turf layer. Soils are generally thin and relatively coarse, but have high organic content.

Changes to land use policies in the 1960s promoted population growth and increasing livestock numbers in the SYR (Qin, 2014; Ran et al., 2016). Grassland degradation, desertification, and salinization ensued from the 1970s to 1990s (Li et al., 2013, 2016, 2018; Zhou et al., 2005), but the relative influence of climate change and land use practices remains controversial (Harris, 2010). Today, grazing intensity is light at Maduo, but more intensive on floodplains and terraces at Dari and Maqu. Direct human impacts upon these upper reaches are limited to Huangheyuan Dam, a small facility above Maduo reach that was decommissioned in 2017 (Figure 1), and local channelization and gravel extraction activities. Guide town has a long history as a trading center. The warm climate and longer growing season in this area support horticultural activities on floodplains and terraces that have ready access to water. Expansion of horticultural
practices and creation of artificial wetlands have transformed floodplain areas since the closure of Longyangxia Dam in 1986 (Han et al., 2020).

Climate change on the QTP is happening particularly fast, with the rate of increase in air temperature twice the global average (Anslan et al., 2020). Net primary productivity (NPP) has increased in recent decades in response to climate change and human activities (land use policies, restoration programs, and creation of National Parks), with the relative impact of human activities upon vegetation recovery increasing since the introduction of a livestock reduction policy in 2001 (e.g., Cai et al., 2015; Chen et al., 2014; Liu et al., 2019; Pan et al., 2017; Yuan et al., 2021; Zhang et al., 2018). Alongside notable improvements in vegetation cover, conservation and restoration projects have enhanced the condition of wetlands and water bodies, increasing water storage and water supply capacity (Cao et al., 2020; Jiang & Zhang, 2016; Shao et al., 2017).

Han and Brierley (2020) summarize relations between plant floristic groups and hydrogeomorphic processes for four anabranching reaches of the Upper Yellow River using the Fluvial Biogeomorphic Succession (FBS) model developed by Corenblit et al. (2007). Plant floristic groups categorize species in relation to shared functional attributes based upon criteria that reflect variability in plant life history strategies and interactions with prevailing environmental conditions (Merritt et al., 2010; Tabacchi et al., 2019). Primary vegetation patch categories for each reach were: dense grass at Maduo, dense grass and shrubs at Dari, dense shrubs at Maqu, and dense shrubs and trees at Guide. Other than Maduo reach, pioneer plant communities (grass and sedges) have decreased in recent decades, while the proportional area of post-pioneer vegetation (woody plants) has increased. Han et al. (2020) show how closure of Longyangxia Dam immediately upstream of Guide reach in 1986 resulted in a dramatic reduction in the width of the active channel zone and decreased channel multiplicity as mid-channel bars aggregated into larger compound features. Additional floodplain areas created by flow regulation have been used primarily for agricultural purposes but also to establish extensive wetland parks. Han and Brierley (2021) appraise the contemporary geo-eco-hydrological condition of the Upper Yellow River in Maduo, Dari, and Maqu reaches. Although contemporary conditions closely approximate expected reference conditions in hydro-geomorphic terms, land use pressures result in notable room for improvement in terms of vegetation interactions.

3 | PAST, PRESENT, AND FUTURE GEO-ECO-HYDROLOGY OF THE UPPER YELLOW RIVER

3.1 | Geo-eco-hydrological condition and recovery trajectory of the Upper Yellow River at Maduo

The Upper Yellow River at Maduo (4180 m asl) flows atop thick basin fill deposits in a low slope, wide valley setting (Figure 1; Nicoll et al., 2013). Huangheyan Dam, a small facility located 125 km upstream of the study site, commenced operations in December 2001 and was decommissioned in 2017. Previously, flood flows were already buffered by Zhaling and Eling Lake (Figure 1). Characteristic of suspended load floodplain systems with a fine gravel bed substrate (8–16 mm) and cohesive fine-grained banks (Nanson & Croke, 1992), this anabranching reach operates under low unit stream power conditions (<10 W m⁻²), other than during occasional flood events [pre-2017 data]; Figure 2a). Large, vegetated islands and compound bars make up the active channel zone, with small anastomosed channels in floodplain areas. Little change in channel size, alignment, and position was observed over the period of record, despite a series of floods from 2013 to 2017 (Figure 2b).

Maduo reach is dominated by the biogeomorphic phase of the FBS model. A high proportion of inactive geomorphic surfaces have a very low cover of post pioneer vegetation (alpine meadow wetland plants) and no established woody vegetation patches (Han & Brierley, 2020). The sedge and forb community and sparse forb community are interpreted to reflect degradation of the meadow structure. Grass (alpine meadow) and sparse vegetation (degraded alpine meadow) make up 23% and 39% of the active channel zone and 62% and 28% of floodplain areas, respectively.

Although geomorphic adjustments have been negligible since 1986, notable changes to the riparian wetlands/lakes/ponds, plant community composition, and biogeomorphic interactions have occurred over this period. The extent of floodplain ponds and wetlands decreased, especially from 2001 to 2017. Although temporary recovery is evident immediately following large flood events, loss of aquatic hydric plants associated with exposure of dry lake and pond beds has been accompanied by drainage of surrounding meadow wetlands. This has induced a transition from wet meadow to dry meadow species. By 2017, 74% of the active channel zone and 34% of floodplain wetland meadow systems were
Evolutionary adjustments of the Upper Yellow River at Maduo. (a) Trend in unit stream power from 1986 to 2017. Total stream power ($\Omega$, W m$^{-1}$) is calculated as $\Omega = \gamma Q_s$ and unit stream power ($\omega$, W m$^{-2}$) as $\omega = \Omega/W$ where $\gamma$ is the specific weight of water (9800 m$^{-3}$), $Q$ (m$^3$ s$^{-1}$) is the average discharge (daily data), $s$ is the friction slope of the flow (estimated bed slope of the study reach), and $W$ is estimated bankfull channel width (in m). Bed slope is measured along the thalweg (primary channel) using 30 m Shuttle Radar Topography Mission data. Reach-scale assessment of bankfull width uses stable channel banks and vegetation patterns to interpret flow inundation of floodplain surfaces. (b) Satellite imagery from 1986, 2001, and 2017 show limited geomorphic adjustments but changes to ground cover and wetland area are evident. (c) Recovery diagram for Maduo reach. The river recovery diagram first assesses whether recovery is underway or the reach remains on a degradation trajectory. If a transition from degradation to recovery is underway, this may reflect reversible change to a restoration state or irreversible change to a creation state, recognizing that both states reflect an improvement in geo-eco-hydrological condition. While local areas may adjust along a particular trajectory, assessment is made for the condition and trajectory of the reach as a whole (i.e., whether it retains its integrity and functionality and if geo-eco-hydrological condition is improving or not). (d) Schematic images that accompany the recovery diagram showing geo-eco-hydrological adjustment from state I (initial) to state T (turning point), with likelihood that this reach will transition to a recovery state (B) rather than a further degraded state (A) (see text for details).
degraded to either sparse vegetation or bare patches (Han & Brierley, 2021). Wetland degradation is likely related to altered groundwater levels associated with changes to permafrost thaw conditions and decreased recharge from floods, as accentuated drought conditions endanger prospects for succession of hydric plants in the following growing season (Sawyer et al., 2009). To date, there is no indication that transition from a “wet” hydro-mesic meadow community to a “dry” meso-xeric meadow community has altered root strength and decreased the erodibility of surface materials, as accentuated bank erosion and reworking of floodplain materials has not taken place (cf., Micheli & Kirchner, 2002).

The geomorphic condition of the Upper Yellow River at Maduo is good in terms of the integrity of the geomorphic unit assemblages and hydrological connectivity between the active channel zone and the floodplain (Han & Brierley, 2021). However, as reported by Han and Brierley (2021), ecological conditions are moderate-poor, marked by loss of alpine meadow wetlands from 1986 to 2017. Although adjustment away from an initial state (I on Figure 2c,d) reflects overall deterioration in condition, there is no indication that either a biotic or an abiotic threshold has been exceeded. The reach is considered to be at a tipping point (T) on the river recovery diagram (Figure 2c,d). Despite their limited prominence today, likely responses to reduced land use disturbance pressure and global warming indicate significant prospect for recovery toward a restoration condition (B on Figure 2c,d). However, further reduction in the areas of floodplain wetland, accompanied by a transition to dry meso-xeric meadow communities, would reflect deterioration in geo-eco-hydrological conditions (A on Figure 2c,d). Under the latter circumstance, larger areas of bare ground patches could increase opportunities for rodent impacts, further degrading geoecological conditions and reducing recovery prospects (Li et al., 2016, 2018).

Recent field observations (Summer, 2019) indicate that enhanced flow conditions, alongside reduced stocking rates (Shao et al., 2016) have improved floodplain connectivity and facilitated wetland recovery since 2017. Removal of Huangheyan Dam commenced in late 2017 and was completed in 2019. Coincident with high rainfall in 2018 and 2019, increased water supply has recharged groundwater and transfer of surface water to floodplains, assisting wetland recovery.

### 3.2 Geo-eco-hydrological condition and recovery trajectory of the upper Yellow River at Dari

The Upper Yellow River at Dari has a braided-anabranching configuration with high geomorphic complexity comprising active, inactive, and vegetated bars/islands and floodplain surfaces (Figure 1). This is the most geomorphologically active site of the four study reaches. Bars are comprised of medium (8–16 mm) or very coarse (32–64 mm) gravel, while very fine sand is dominant on floodplains (Han & Brierley, 2020). Valley width pinches in and out with a “beads on a string” configuration (Wohl et al., 2018). Local bedrock confinement and tributary fans act as base level controls, as evident at Dari township (Yu et al., 2014). As the river has a steeper slope than at Maduo, unit stream power during annual flood events is much higher, ranging from 50 to 300 W m$^{-2}$, but there is no indication of systematic changes to stream power over the period of record (Figure 3a).

From 1986 to 2017 the active channel area in the study reach decreased from 36.3 to 30.4 km$^2$ (Figure 3b; Han & Brierley, 2020). The reach operated as a bedload-dominated braided reach from 1986 to 2006, with multiple bars subject to recurrent shifting and reworking. Since 2007, channels and islands became better defined and less active, and the reach adopted the characteristics of a mixed load river. While the proportional area of inactive geomorphic units remained relatively stable at around 33 km$^2$ since 2007, the area with well-developed riparian vegetation cover increased from 10.8 to 20.5 km$^2$.

Riparian vegetation now exerts a growing influence upon geomorphic process relationships in Dari reach (71% of floodplain areas and 43% of bar and island areas are vegetated; Han & Brierley, 2020). Of this, grass cover makes up 7% and 44%, respectively. Shrub patches (short shrub) are slightly more prominent in the active channel zone (8%) than on floodplains (6%), while large parts of the inactive channel zone (28%) have a sparse vegetation cover indicative of initial stages of colonization. Sedge/Graminoid grasslands are considered to represent the post pioneer (mature) community on floodplains in this area. Biogeomorphic interactions are inferred to have facilitated a shift in river trajectory in Dari reach. An increase in the cover of short shrub patches within the active channel zone has accompanied reduced rates of planform change since 2007. Germination or sprouting on large woody debris at an early stage of biogeomorphic succession has enhanced shrub development, increasing instream resistance, stabilizing channel boundaries, and accentuating the formation of pioneer islands (Abbe & Montgomery, 1996; Gurnell et al., 2009; Tal et al., 2013). At present, this
reach is dominated by the pioneer phase of the FBS model, with a higher proportion of active bars and pioneer landforms than inactive geomorphic features (Han & Brierley, 2020).

The contemporary hydrogeomorphic condition of Dari reach is good in terms of the integrity of the assemblage of geomorphic units and connectivity relationships (Han & Brierley, 2021). The eco-condition is moderate within the
active channel zone (where 20% of vegetated bars or islands have degraded to a bare soil surface) and poor on the floodplain (where 45% of surfaces are degraded to sparse vegetation or bare land). Besides the expected seral stages in a reference condition, large areas of graminoid and forb mixed groups, mixed forb dominated degraded sparse vegetation communities, fragmented meadows, and degraded bare landforms indicate disrupted ecological integrity (Han & Brierley, 2021). Excessive grazing and trampling by stock have depleted vegetation cover and increased the area of exposed soil, especially adjacent to readily accessible channels. Fragmentation of sedge meadows has increased opportunities for rodent (pika) invasion, especially in distal parts of floodplains, increasing the extent of bare patches that are vulnerable to erosion (Li et al., 2013, 2016). Alongside this, channelization to protect infrastructure (primarily roads) has locally disrupted river morphodynamics in this reach.

The river recovery diagram interprets deterioration in geo-eco-hydrological condition in Dari reach from an initial state (I, 1987) to a turning point (T) in 2017 (Figure 3c,d). Subsequent adjustments indicate recovery toward a restored state (B) associated with a transition from pioneer to biogeomorphic FBS phase adjustments. The system is now more resilient to flood disturbance while retaining a diverse array of habitats. At this early stage of adjustment, large areas of pioneer landforms are covered by fine-grained non-cohesive sediments that support only limited pioneer vegetation (both herbaceous and short shrubs). Maintenance and/or further enhancement of this condition increases prospect that inactive geomorphic landforms will act as seed banks that allow short shrub vegetation to expand faster than previously (Ziliani & Surian, 2016). Increasing woody vegetation not only increases resistance and promotes sediment retention, but also it maintains rich habitat diversity for fauna and flora and supports enhanced water quality. Alongside impacts of a milder climate, reduction in stock grazing can further improve geo-eco-hydrological condition (Song et al., 2018). Designation of the Dari River Wetland Park conservation project along a major tributary of the Upper Yellow River in 2017 supports such initiatives, reducing land use pressures, allowing the river to self-adjust and enhancing prospects for shrub development (Guo et al., 2019).

Alternative scenarios envisage accentuated degradational impacts of human activities into the future (A1 and A2 on Figure 3c,d). Presently, direct human disturbance along the 65 km Dari reach is restricted to around 1 km of river length near Dari town, alongside local gravel extraction activities. To date, these impacts have not compromised the geo-eco-hydrological integrity of the river as a whole. However, further construction of artificial levees (stopbanks) would threaten the geo-ecological integrity of this reach. Local demands for such measures have increased since 2015 (A1 on Figure 3c,d). Alternatively, overgrazing and/or more intensive land use on floodplain areas would result in further deterioration in river condition in Dari reach (A2 on Figure 3c,d). For example, grassland degradation and fragmentation would increase soil erosion and potentially induce permanent (irreversible) loss of wetlands (Herbst et al., 2012).

3.3 | Geo-eco-hydrological condition and recovery trajectory of the Upper Yellow River at Maqu

Maqu reach lies atop thick basin fill deposits (Nicoll et al., 2013). A multithread anabranching reach with fully vegetated islands is inset within significant terraces that retain the imprint of former meandering channels of both trunk and tributary systems (Yu et al., 2014). Of the four study reaches, this area has the widest floodplains, the broadest range of geomorphic units (active bars, benches, compound bars, islands, sand/gravel sheets, suspended load floodplains, secondary channels, cut-offs, and oxbow lakes) and the highest proportion of dense riparian shrubs and trees. The $D_{50}$ of coarse sediment on active bars is 22 mm (coarse gravel), while islands are comprised primarily of very fine and fine sand (Han & Brierley, 2020). Although this reach experiences moderate-high unit stream power events (typically 200–500 W m$^{-2}$; Figure 4a), significant instream resistance limits the ability of flows to rework channel geometry or planform (Figure 4b). The active channel area decreased notably from 1986–2007. Increase in established vegetation cover since 2007 has limited subsequent channel adjustments. Limited variability in stream power conditions over the period of record indicate that this sequence of adjustments is not directly related to the flood history (Figure 4a).

Maqu reach has a low proportion of active bars, with 76.5% of the inactive geomorphic surfaces in the active channel zone covered by established vegetation (shrubs and short trees). Compound bars and islands are comprised of 43% shrubs (including shrubs and short trees), but this makes up just 0.8% of floodplains. Around 98% of floodplains are grass covered. This reach is dominated by the ecological phase of the FBS model (Han & Brierley, 2020). Conversion of pioneer communities to post pioneer communities has been the primary biogeomorphic change since 1986. Since 2003, the proportion of woody vegetation has continuously increased. Initially, this cover was restricted to seasonal and chute
channels—areas subject to less disturbance with a higher ground water level and greater nutrient availability. Over time, merging of small instream geomorphic units into larger features, especially around woody vegetation patches (Tal et al., 2013), has created marked elevation differences across the valley floor.

**FIGURE 4**  Evolutionary adjustments of the Upper Yellow River at Maqu. (a) Stream power trend (and associated flood history) from 1986 to 2017 (see Figure 2 caption for details). (b) Satellite imagery from 1986 and 2017 shows the limited extent of geomorphic river adjustment in the study period, with local (non-systematic) alterations to channel multiplicity. (c) Recovery diagram for Maqu reach (see Figure 2 caption for details). (d) Schematic images that accompany the recovery diagram show progressive improvement in geo-eco-hydrological river condition from the initial state (I) to states B1 (around 2007) and B2 (2017). However, unless effective management practices are maintained, deterioration in condition to state a could occur (see text for details)
The geo-eco-hydrological condition of Maqu reach is good (Han & Brierley, 2021). Light grazing has not jeopardized the geomorphic structure of this reach. Floodplains retain 100% grassland cover, without signs of degradation in species composition. However, significant shrinkage of floodplain/terrace wetlands adjacent to White and Black River confluences may reflect incision of tributary systems and lowering of the groundwater table, alongside impacts of overgrazing and construction of artificial ditches (Li et al., 2015; Niu et al., 2012; Qi & Li, 2007).

Figure 4c,d present a summary interpretation of the trajectory of adjustment to the geo-eco-hydrological condition for Maqu reach. In 1986, the active channel zone was wider, bars were more dynamic, and woody vegetation cover was much less than today (state I on Figure 4c,d). Islands and compound bars were mainly covered by herbaceous and shrub vegetation and floodplains were covered by grassland. Dynamic landform changes reflect an early stage of succession at the biogeomorphic phase of the FBS model (Corenblit et al., 2007; Han & Brierley, 2020). Subsequent improvement in geo-eco-hydrological condition occurred through to 2017 (states B1 and B2 on Figure 4c,d). In part this reflects reduced external pressure associated with the implementation of a Wetland Park in the 1990s, such that this mature anabranching river supports a diverse range of habitats for birds and animals with high biodiversity (Cai et al., 2015; Cuo et al., 2013; Jiang et al., 2015). Emergence of patches of shrubs and low trees since 2003 created better-defined main channels (Bertoldi et al., 2015). Over time, older parts of islands became separated from regular flood disturbance, with groundwater levels sustaining mature vegetation ecosystems (Merritt et al., 2010; Sawyer et al., 2009; Stromberg et al., 1996). As noted at Dari, direct human disturbance threatens the geo-ecological integrity of local sections of the Upper Yellow River at Maqu (state A on Figure 4c,d). Further stopbank construction, gravel extraction, drainage of wetlands and overgrazing would disrupt the prevailing balance of processes that sustain the good geo-eco-hydrological condition of this reach. Increasing erosion and/or bed incision would deplete habitat and threaten the viability of the riparian vegetation cover.

3.4 | Geo-eco-hydrological condition and recovery trajectory of the Upper Yellow River at Guide

Progressive reworking of vast volumes of sediments from terrace sequences at Guide reflects long-term incision as the Yellow River has cut through up to 800 m of basin fill deposits (Nicoll & Brierley, 2018). In stark contrast to the three upstream sites, direct anthropogenic activities exert a profound impact on this reach (Han et al., 2020). Prior to flow regulation, the Upper Yellow River at Guide was an anabranching river with dynamically adjusting channels and patchy vegetation cover made up of a mix of communities on bars, islands and floodplains. Closure of Longyangxia Dam in 1986 (alongside smaller structures at Laxiwa and Nina which were closed in 2010 and 2003, respectively) eliminated all high flow events over 1000 m$^3$ s$^{-1}$ and extreme low flow events under 300 m$^3$ s$^{-1}$ (Han et al., 2020). This decreased the range of unit stream power from 10–160 W m$^{-2}$ to 20–120 W m$^{-2}$ (Figure 5a). The reduced frequency of formative flows transformed Guide reach into a passive anabranching river (sensu Fryirs & Brierley, 2013; Figure 5b; Han et al., 2020). Many seasonally active channels disappeared. A wide range of small features became incorporated into much larger, more stable compound bars. The width of the active channel zone rapidly shrank by 40%.

Elimination of destructive floods and increased base flow supported the rapid establishment of woody plants (Gordon & Meentemeyer, 2006). This accelerated the coalescence of bars and increased the development of woody vegetation on larger islands (del Tánago et al., 2015; Sankey et al., 2015; Skalak et al., 2013). Reduced availability of fine-grained sediments has inhibited opportunities for herbaceous plants, while woody plants with strong root systems are able to colonize coarse gravel surfaces with shallower groundwater conditions (Polvi et al., 2014; Stromberg, 2013). Vegetation density is higher along channel margins, declining toward the center of islands (Han et al., 2020). Enhanced resistance induced by well-established woody vegetation restricts erosion of compound bars and islands. Today, there are virtually no pioneer surfaces. Guide reach now operates at the ecological phase of the FBS model (Han & Brierley, 2020), with a high proportion of inactive geomorphic features and a high cover of established woody vegetation patches.

Human activities have artificially blocked secondary channels to support more intensive land use on floodplains since 1990. Stopbanks and riprap restrict channel width. Much of the lower reach has been irreversibly reworked into a fixed, low sinuosity configuration. Water abstraction feeds both agricultural practices and recently constructed wetland parks on floodplain areas (Liu et al., 2008; Nicoll & Brierley, 2017; Zhang et al., 2011).

Following procedures outlined by Fryirs (2015), analysis of geo-eco-hydrological river condition at Guide is framed in relation to what is realistically achievable under prevailing boundary conditions. Irreversible change following flow
regulation in 1986 has transformed the behavioral regime of the river, moving it away from its pre-existing trajectory (Figure 5c,d). Immediately following dam closure the reach started to re-equilibrate to altered boundary conditions (state T on Figure 5c,d). As the contemporary condition reflects improvement relative to this early transitional state,
the reach lies on a recovery pathway. The reach presently has a moderate condition in geo-eco-hydrological terms, with a limited range of instream geodiversity and associated seral stages of vegetation cover (state C1 on Figure 5c,d). Land cover on islands and compound bars within the active channel zone is 39% dense trees/shrubs, 23% pioneer shrub or semi-shrub plants (i.e., perennial plants with a woody base which produces stems each year), and 33% bare land surface. Given the lack of herbaceous vegetation cover on pioneer landforms, this anabranching reach is less healthy than it could be. Continuance of recovery envisages re-generation of the physical habitat mosaic of the river, reworking bar and island surfaces to enhance geodiversity (state C2 on Figure 5c,d). Managed wetlands in parkland areas on floodplains in downstream parts of the study reach already enhance recovery prospects. Maintaining the contemporary active channel width, and restricting instream manipulation of the river (e.g., gravel extraction) are key determinants of future condition. An alternative prospective river future shown on image A on Figure 5c,d envisages human activities that further restrict the function of the river, wherein channelization structures narrow the active channel zone and concentrate flow energy, further reducing habitat diversity.

4 | DISCUSSION

Findings from this study highlight the good condition of anabranching reaches of the Upper Yellow River in geo-eco-hydrological terms. Inherent environmental values have not been unduly compromised and the trajectory of adjustment indicates environmental improvement in recent years. Recovery takes different forms in the grazing adapted landscapes and ecosystems at Maduo, Dari, and Maqu, relative to the dam-impacted river system with intensively farmed horticultural lands at Guide. Overall, the limited extent of degradation and the vast extent of these largely disconnected landscapes (Nicoll et al., 2013) mean that off-site impacts and associated legacy effects have been limited.

Quite different pathways of adjustment and off-site impacts, with disastrous consequences for environmental values and human society, are evident for some of the river systems that emerge from the QTP (e.g., Pandit et al., 2014). In part this reflects instances where contested notions of the commons (Hardin, 1968) challenge prospects for coherent management practices. Framed in relation to a portfolio approach to conservation proposed by Hobbs et al. (2017), landscapes and ecosystems of the Upper Yellow River can be conceived as a high-value asset—a priceless masterpiece such as the Mona Lisa—for which prioritized programs already protect key values alongside concerns for other landscapes and ecosystems that make up the broader art collection. Targeted conservation of such majestic, minimally impacted areas is globally significant in light of inherent uncertainties in managing river futures in a no-analogue world (Hiers et al., 2012; Tonkin et al., 2019).

Although climate change has facilitated and supported recovery mechanisms for anabranching reaches of the Upper Yellow River, reduced land use pressures, especially management of stocking rates and creation of reserves, have been the primary drivers of improving river conditions (Jiang et al., 2016; Jiang & Zhang, 2015). While recent increases in precipitation and glacier melt have slightly enhanced flow discharge in spring and summer seasons, such increases will not be sustained into the future and will be impacted by enhanced/modified vegetation growth and human water uses (Cuo et al., 2014; Zhang et al., 2017). Climate warming may accelerate transitions between biogeomorphic phases, as increasing temperatures support encroachment of short shrubs at higher altitudes (Han & Brierley, 2021). Shrub encroachment and enhanced stability of instream features is already evident in rainfall rich areas such as Dari reach. Conversely, increased evapotranspiration may have exacerbated meadow degradation in rainfall poor areas such as Maduo reach, but these effects are likely mediated by enhanced permafrost melt (Qin, Wu, et al., 2017; Qin, Yang, et al., 2017).

The vast scale and scope of land use policies in the Sanjiangyuan seek to rehabilitate and revegetate grasslands and wetlands, managing stock numbers and densities in efforts to sustain grazing adapted ecosystems (Zhang et al., 2015). These measures support accessory habitats and resources for some species, provide opportunities for dispersal, and enhance prospects for climate change adaptation (cf., Kremen & Merenlender, 2018). Tackling issues at source and at the required scale increases prospects to maintain metapopulations while enhancing adaptive (buffering) capacity and mitigating prospective risks (Fausch et al., 2002; Palmer et al., 2014; Sundermann et al., 2011). Furthermore, self-sustaining processes that support the self-healing tendencies of rivers to look after themselves are cost effective (Fryirs et al., 2018; Kondolf, 2011; Wheaton et al., 2019; WWAP, 2018). Maintaining relatively intact systems is much less expensive than restoring an altered system (Hobbs et al., 2017).

By definition and design, sustainability goals will not be achieved unless socio-cultural values are meaningfully incorporated within conservation plans (Ascensão et al., 2018; Bryan et al., 2018). Ultimately, local people lie at the
heart of such endeavours, in what Büscher and Fletcher (2019) refer to as convivial conservation. In context of the QTP, such framings give due regard for the livelihoods of local herders, living with nature rather than isolating nature in parks or reserves separated from society by fences (Foggin, 2018). In the SYR, further research is required to explore and incorporate socio-cultural relations to the river, appraising the benefits and limitations of land sharing and land sparing practices (Du, 2012; Foggin, 2008; Ptackova, 2011; Wang, 2019; Wang et al., 2010). To date, community-based conservation practices are under-developed in this area (Foggin, 2018; Shen & Tan, 2012). Related to this, despite the coherence of national and state-wide policies and environmental protection programs, some local practices may compromise the effectiveness of whole of system applications. For example, construction of local embankments (stopbanks) and instream gravel extraction contradict programs that seek to protect ecological values. Ultimately, it pays to heed lessons of co-evolutionary practices that recognize concerns for mutual interdependence and reciprocity in working with nature, as exemplified elsewhere in China by the world’s longest continuously operating large-scale irrigation system at Dujiangyan (Cao et al., 2010; Qian & Wan, 1983).

In scientific terms, three research gaps emerge from this study. First, explicit articulation of biodiversity values, and associated measures of ecosystem functionality, is yet to be specifically tied to understandings of the geo-eco-hydrological template of anabranching reaches of the Upper Yellow River. Second, there is a paucity of research on linkages between terrestrial and aquatic ecosystems in this region, although evidence from this study suggests that increasingly healthy grassland and wetland conditions are accompanied by healthy geo-eco-hydrological river conditions. Third, despite increasing availability of monitoring data, early warning systems that guard against potential ecological risks are yet to emphasize concerns for whole of system understandings that incorporate analyses of tipping points and threatening processes.

5 | CONCLUDING COMMENT

This overview indicates that a coherent package of broad-scale policies of unprecedented scale and scope is facilitating the protection of environmental values in the SYR on top of the QTP (Jiang & Zhang, 2016; Pan et al., 2017; Shao et al., 2016, 2017). Evolutionary trajectories show that recovery mechanisms are maintaining and/or enhancing the geo-eco-hydrological condition of four anabranching reaches of the Upper Yellow River. While climate change has supported these adjustments in recent decades, altered land use practices have been the key determinant of environmental improvement. Proactive and precautionary approaches to environmental protection apply nature-based solutions that manage issues as source. In large part, such measures look after the land to look after the river, allowing the river to look after itself as far as practicable. The quest for sustainability requires that national scale imperatives support concerns for local socio-cultural values and demands of regional economic development. Strong foundations are in place to facilitate such prospects in the SYR.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Gary Brierley: Conceptualization (lead); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (lead); resources (equal); software (supporting);
supervision (lead); validation (lead); visualization (supporting); writing – original draft (lead); writing – review and editing (lead). **Meiqin Han:** Conceptualization (supporting); data curation (equal); formal analysis (equal); investigation (equal); resources (supporting); software (supporting); supervision (supporting); validation (supporting); visualization (lead); writing – original draft (supporting); writing – review and editing (supporting). **Xilai Li:** Conceptualization (supporting); data curation (supporting); formal analysis (supporting); funding acquisition (lead); investigation (supporting); methodology (supporting); project administration (equal); resources (equal); software (supporting); supervision (supporting); validation (equal); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Zhiwei Li:** Conceptualization (supporting); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (supporting); methodology (supporting); project administration (supporting); resources (equal); software (supporting); supervision (supporting); validation (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **He Qing Huang:** Conceptualization (supporting); data curation (supporting); formal analysis (supporting); funding acquisition (supporting); investigation (supporting); methodology (supporting); project administration (supporting); resources (supporting); software (supporting); supervision (supporting); validation (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting).

**DATA AVAILABILITY STATEMENT**

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

**ORCID**

Gary J. Brierley https://orcid.org/0000-0002-1310-1105
Meiqin Han https://orcid.org/0000-0002-4880-4628
Xilai Li https://orcid.org/0000-0001-9171-2481
Zhiwei Li https://orcid.org/0000-0002-8270-7265
He Qing Huang https://orcid.org/0000-0001-7788-6549

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