Vegetative impacts upon bedload transport capacity and channel stability for differing alluvial planforms in the Yellow River Source Zone

Z. W. Li[1], G. A. Yu[2], G. Brierley[3], and Z.Y. Wang[4]

[1]{School of Hydraulic Engineering, Key Laboratory of Water Sediment Sciences and Water Disaster Prevention of Hunan Province, Changsha University of Science & Technology, Changsha, China}

[2]{Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China}

[3]{School of Environment, University of Auckland, Auckland, New Zealand}

[4]{State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing, China}

Correspondence to: G. A. Yu (yuga@igsnrr.ac.cn)

Abstract

The influence of vegetation upon bedload transport and channel morphodynamics is examined along a channel stability gradient ranging from meandering through anabranching through anabranching-braided to fully braided planform conditions along trunk and tributary reaches of the Upper Yellow River in western China. Although the regional geology and climate are relatively consistent across the study area, there is a distinct gradient in the presence and abundance of riparian vegetation for these reaches atop the Qinghai-Tibet Plateau (elevations in the study area range from 2800-3400 m a.s.l.). To date, the influence of vegetative impacts upon channel planform and bedload transport capacity of alluvial reaches of the Upper Yellow River remains unclear because of a lack of hydrological and field data. In this region, the types and pattern of riparian vegetation vary with planform type as follows: trees exert the strongest influence in the anabranching reach, the meandering reach flows through meadow vegetation, the anabranching-braided reach has a grass, herb, and sparse shrub cover, and the braided reach has no riparian vegetation. A non-linear relation between vegetative cover on the valley floor and bedload transport capacity is evident, wherein bedload transport capacity is highest for the anabranching reach, roughly followed by the anabranching-braided, braided and meandering reaches respectively. The relationship between the bedload transport capacity of a reach and sediment supply from upstream exerts a significant influence upon channel stability. Bedload transport capacity during the flood season (June-September) in the braided reach is much less than the rate of sediment supply, inducing bed aggradation and dynamic channel adjustments. Rates of channel adjustment are less pronounced for the anabranching-braided and anabranching reaches, while the meandering reach is relatively stable (i.e., this is a passive meandering reach).

1 Introduction

Transitions in river character and behaviour are a key focal point of enquiry in fields such as geomorphology, hydrology, and sedimentology. Such concerns have significant management applications, especially relating to issues such as management of flood risk and sedimentation hazards. These issues are likely to become even more pronounced in the future, as rivers adjust in response to climate and land use changes, and management actions. Putting aside concerns for terminological issues associated with differentiation of river types and their morphological attributes (see Lewin and Ashworth, 2014; Carling et al., 2014; Tadaki et al., 2014), process-based understandings of morphodynamic adjustments are required to address concerns for prospective future river changes (Beechie et al., 2010). Here we evaluate the influence of riparian vegetation upon process interactions along relatively understudied reaches of the Upper Yellow River atop the Qinghai-Tibet Plateau in western China. Qualitative description and analysis of this complex influence on bedload transport capacity remains unclear to our knowledge.

Channel bars are products of instream deposition of bedload materials, whether at the channel margin (bank-attached forms) or mid-channel bars (Brierley and Fryirs, 2005). Typically, bars mutually adjust with channel geometry, such that they scale to the size of the channel in which they form (Task Force on Bed Forms in Alluvial Channels, 1966; Nicholas et al., 2013). If these features become vegetated and stabilized, they are referred to as islands (Fryirs and Brierley, 2012). Unit bars (migrating lobate bed forms with heights and lengths that scale with channel depth and width) are differentiated from larger, more complex compound bars (e.g., Bridge, 1993; Brierley, 1989, 1991; Smith, 1974). Compound bars are products of multiple phases of accretion and reworking, with stacked sequences of unit bar, dune, and smaller bed form deposits that are often trimmed at their margins by bank erosion processes or dissected by chute channels (Ashworth et al., 2011; Best et al., 2003; Bridge, 2003; Brierley and Fryirs, 2005; McGowen and Garner, 1970; Reesink et al., 2014; Sambrook Smith et al., 2009). Various studies have characterized the main morphological elements of large bars and islands, while other studies have developed conceptual models of bar evolution (e.g., Ashworth et al., 2000; Gurnell et al., 2001; Latrubesse and Franzinelli, 2002; Mertes et al., 1996).

There is notable variability in the presence, form and hydraulic/sedimentologic (morphodynamic) role of bars along the continuum of channel planform (Bridge, 1993; Brierley, 1996). By definition, as suspended-load rivers have limited bedload-calibre materials, they have very few, if any, bars. The prominence of fine-grained (silt-clay) deposits under low energy conditions (often very low channel gradient) promotes passive channel behaviour, typically with a low sinuosity, passive meandering or anabranching (anastomosing) planform (Eaton et al., 2010; Fryirs and Brierley, 2012; Makaske, 2001; Wang et al., 2005). Patterns of bar formation in mixed- and bedload-dominated rivers reflect the flow-sediment balance along any given reach, with a spectrum of planform types ranging from active meandering and wandering variants through to fully braided rivers (see Ashworth, 1996; Ashworth and Lewin, 2012; Burge, 2006; Church and Rice, 2009). Braiding results from the inability of flow to transport all sediments that are made available to the channel, such that mid-channel sedimentation occurs (i.e., competence and/or capacity limits are exceeded). Recurrent reworking of bedload materials via thalweg shift during flood events alters the number, shape, and location of bars. Bar dissection and avulsion create multi-thread channel systems with a disorderly river planform, extremely unstable bars, and inconstant flow paths (Ashmore, 1991; Ashworth et al., 2000; Jerolmack and Mohrig, 2007).

If channel boundary conditions induce sufficient bank strength, and flows are able to transport available bedload sediments, the river adopts a configuration with better-defined, less mobile channels with a much lower width-depth ratio, whether within a single-channel configuration (typically passive meandering) or a multi-channel anabranching configuration (Eaton et al., 2010; Song and Bai, 2015). Controversy abounds in our theoretical understanding of process controls upon anabranching river behaviour (see Carling et al., 2014; Nicholas et al., 2013). While Huang and Nanson (2007) and Jansen and Nanson (2004, 2010) attribute an anabranching configuration to the least action principle, wherein channels adjust their form to transport available sediment in the most hydraulically efficient manner, Eaton and co-workers postulate an alternative theoretical framing in which anabranching channels adjust to minimize their capacity to transport materials (Eaton and Church, 2004, 2007; Eaton et al., 2010). It is not our concern here to address this issue directly. Rather, our focus lies with analysis of relationships between bedload transport capacity and channel morphodynamics along a continuum of channel planform types that is coincident with a gradation in riparian vegetation cover along the Upper Yellow River (Yu et al., 2014).

Bar stability is the key distinguishing attribute of braided and anabranching rivers. In some instances, vegetation may support the long-term development of stable sandbars within a stable multi-channel system – a variant of an anabranching river (Latrubesse, 2008; Nanson and Knighton, 1996; Murray and Paola, 2003; Tal and Paola, 2010). Vegetation increases flow resistance and stabilizes the channel bed and bank along anabranching rivers, thereby altering channel geometry, bedload transport rates, and the resulting rates and patterns of bed deposition or erosion. Once a particular morphology has been formed, the configuration of channels and associated distribution of bars and roughness elements fashions process responses to subsequent flood events (Hooke, 1986, 2015; Hooke and Yorke, 2011; Luchi et al., 2010). If critical threshold conditions are exceeded, alterations to the balance and patterns of erosion and deposition processes may bring about transitions to different planform types.

Mutual adjustments between patterns of vegetation types (size, spacing, and density) and flow-sediment dynamics (patterns and rates of erosion and deposition) vary at different positions on the valley floor. Vegetation encroachment by pioneer species and successional processes induce abiotic and biotic transitions in geomorphic processes from the unvegetated channel bed and bar surfaces to grassland, shrubs, and treed areas at the margins of bars/islands and on floodplains (Corenblit et al., 2007, 2011; Gurnell, 2014; Hickin, 1984; Hupp and Osterkamp, 1996; Millar, 2000; Tooth and Nanson, 2000). Vegetation attributes influence the pattern of roughness elements and the associated distribution of flow energy, thereby affecting the distribution of erosional and depositional processes, and resulting morphological attributes (including the grain size distribution of bed/bar materials). Hence, vegetative controls influence the stability and behaviour of alluvial bed and bars, and the influence of vegetation upon flow-sediment interactions, vary for differing planform types (Gran and Paola, 2001; Gradzinski et al., 2003; Jang and Shimizu, 2007; McBride et al., 2007).

Although the prominence of seasonal low flow stages and nutrient-rich fine sands may support the growth of annual or perennial herbs and shrubs on mid-channel and transverse bars in braided rivers, this sparse vegetation cover has negligible impact upon sediment deposition and erosion patterns, and is removed easily at flood stage (Coulthard, 2005). This mutual interaction between vegetation and erosion-deposition can be viewed as a threshold condition: if sufficient vegetation establishment occurs, resistance may exceed the erosion-deposition capability of a normal flood such that stabilization ensues, prospectively altering sedimentation patterns, increasing bank strength, and reducing channel width-depth ratio (Gran and Paola, 2001; Coulthard, 2005; Eaton et al., 2010). In anabranching channels the vegetation cover on mid-channel bars inhibits lateral migration, inducing a stable branching channel condition. During lower frequency floods, when bars are partially or completely submerged by flow, vegetation increases flow resistance, traps sediment, and inhibits erosion.

This study builds upon previously-reported exploratory analyses of river diversity in the source zone of the Yellow River (Blue et al., 2013; Brierley et al., 2016; Li et al., 2013; Yu et al., 2014). In this region, herbs and sparse shrubs that establish on the sand/gravel bars of braided rivers have a trivial influence upon channel morphodynamics, while establishment of dense shrubs and sparse trees on sand/gravel bars promotes the emergence of anabranching channel configurations. Building on these previous observations, here we appraise process interactions along a vegetative gradient of river morphologic adjustments for four reaches: Dari and Maqu reaches of the Yellow River main stream, and Daheba and Lanmucuo River tributaries of the Upper Yellow River (Table 1). Dari reach has a semi-stable braided channel, where sandbars are covered by herbaceous vegetation and sparse shrubs. Maqu reach has a very stable anabranching channel with dense willows (*Salix atopantha*) on sandbars. The study reach along Lanmucuo River has a stable gravel meandering river with herb coverage. The study reach along Daheba River has a very unstable gravel braided channel without vegetation cover. We develop and apply a simplified model to explain the interaction between sediment transport capacity and river bed deposition in these reaches, examining the effect of vegetation resistance and adjustment of fluvial hydraulic geometry. From this, we quantitatively analyse the stability and evolution of braided, anabranching, and meandering reaches during flood events.

2 Study area and methods

Upstream of Tangnaihai hydrological station the source zone of the Yellow River drains an area of 132,000 km^2 (see Fig.1(a)). In the 1950s the Yellow River Conservancy Commission established four hydrological stations along the Yellow River in this area, namely (from upstream to downstream), Huangheyan station in Maduo County, Jimai station in Dari County, Maqu station in Maqu County, and Tangnaihai station in Xinhai County. The reach from Huangheyan to Jimai station is 325 km long and drains an area of 24,089 km^2. In this reach the valley is quite wide, with semi-braided and semi-anabranching planform morphologies characterized by disordered channels with many bars (Brierley et al., 2016). The reach from Jimai to Maqu is 585 km long and drains an area of 41,029 km^2. The upper section of this reach has a deeply incised (confined), sinuous valley between the Anyemaqen and Bayan Har Mountains. Flowing into the Ruoergai alluvial basin, there is a diverse array of planform types (Blue et al., 2013; Brierley et al., 2016; Li et al., 2013). The reach from Maqu to Tangnaihai station is 373 km long and drains an area of 35,924 km^2. Most of this reach comprises a steep and incised canyon, with many deeply carved meander bends.

For this study, field investigations of vegetative influences upon bed/bar geomorphic processes were conducted four times in the summers of 2011-2014. Particle size distributions of bed and bank materials size were analyzed using a laser particle size analyzer (Mastersizer 2000) and field sieves were used to test ten samples of river bed and bank materials in each reach. As a supplement, photographs of gravel and cobbles on the bed/bar surface were taken to visually estimate bed particle size. To estimate bedload transport capacity, channel geometry was assessed in the field and from remote sensing images of the branching channel network (Google Earth images from 2005-2014, with a resolution of about 0.24 m).

The best available hydrological data that could be accessed for this study were daily stage-discharge data from Jimai (1964-1985), monthly stage-discharge data from Maqu (1959-1970), monthly cross-section elevation change data from Shangcun station along the Daheba River (1.8 km upstream from its confluence with the Yellow River, 2009-2011), and 2011-2014 field data for the Lanmucuo River (a tributary of the Yellow River in Maqu-Tangnaihai section, at an elevation of 3400-4200 m a.s.l., for which upstream and mid-catchment reaches have a typically meandering channel, while the downstream reach has a confined bedrock channel). There are no intensive human activities in this area of the Yellow River Source Zone.

3 Basic characteristics of four alluvial reaches

Fig.1 (b) shows the planform morphology of the four channel reaches. Figure 2 shows the channel morphology, pattern of bar types, and bed sediment. Basic channel characteristics of the study reaches are summarized in Table 2.

Dari reach has a semi-braided and semi-anabranching channel in a wide valley (Fig.1 (R1) and Fig. 2(R1)). This braided-anabranching transition zone is considered to be semi-stable, with an active channel zone that is around 1 km wide. The braided part of the channel is made up of many small longitudinal and transverse bars, with multiple connected branching channels. In the anabranching part, the large bars/islands have a dense grassland vegetation. Given the extensive width of the active channel zone, annual floods during June-September exert negligible impacts upon these relatively stable surfaces.

The Maqu reach is located in a wide alluvial valley (1.5-3.0 km wide). The dense tree cover of the vegetated islands is indicative of a stable channel configuration (see Fig. 1(R2) and Fig. 2(R2)). During the flood season, tree trunks are partly submerged into water, but the trees are sufficiently dense to limit erosion. As a result, the anabranching system as a whole is quite stable with high bedload transport capacity.

Lanmucuo River is a meadow meandering river with nearly 100% vegetation cover (see Fig. 1(R3) and Fig. 2(R3)). The root system of riparian grasses induces considerable protection from near-bank erosion. Field investigations from 2011-2014 indicate that the lateral migration induced by cantilever bank failure occurred at a rate of less than 0.2 m/yr. The gravel-bed channel has a low bedload transport rate in the flood season. In some local sections, mid-channel bars with dense grass coverage have developed at the apex of bends. The whole channel is quite stable, in spite of short-term outer bank failures and long-term meander neck cutoffs.

Daheba River has incised into the Gonghe-Xinhai sedimentary basin. Severe gully erosion has incised river-lacustrine sediments to a depth of 50-100 m, supplying large volumes of gravel/cobble to the middle and lower Daheba channel, inducing significant bed aggradation and the formation of a braided planform. Alluvial fans at gully outlets not only supply additional sediment, but also push the channel to the opposite side of the valley floor (a big fan is shown near D point in Fig. 1(R4) and Fig. 2(R4)). As a result, the main branching channels are subjected to frequent and recurrent avulsion. Flows erode new small branching channels during the flood season, but a main channel coexists with several branching channels in the non-flood season. Unstable mid-channel bars are unvegetated other than sparse vegetation coverage (grass and shrubs) on riparian banks. The gravel-cobble bed and high bedload transport rate restrict vegetation establishment and growth, resulting in a typically unstable braided river.

Bank strength induced by sediment material mix and vegetation root networks exerts a critical influence upon the stability of alluvial channels (Eaton and Giles, 2009). Reinforcement of bank strength reinforced by grass, shrub, and tree roots is related to the density, depth, and spatial structure of the root network (Abernethy and Rutherfurd, 2001). Fig. 3 shows representative photographs of river banks in the four study reaches. The diverse bank material composition and vegetation cover affect the relative strength of banks and their capacity to resist nearbank flow scour. The river bank in Dari reach has a two-layer structure, with a 20-30 cm deep soil-root layer (d_{50} is median size, $d_{50} = 0.02$ mm) lying atop a gravel-sand layer ($d_{50} = 6.0$ mm) (Fig. 3(a)). The river bank in Maqu reach has a dense grass, shrub, and tree cover (Figure 3(b)), with no indication of flow scour in the flood season. The study reach along the Lanmucuo River has a typical composite bank sedimentology of a mixed load river (Fig. 3(c)). An upward-fining sequence is characterized by a basal gravel unit ($d_{50} = 5.5$ mm) extending to a 10-30 cm thick silt/sand layer ($d_{50} = 0.03$ mm) that is capped by a 10-50 cm thick fine-grained soil-root complex ($d_{50} = 0.02$ mm). Conversely, the bank of the middle Daheba River has characteristic deposits of a bedload-dominated river, with non-cohesive gravels and a sparse grass cover (Fig.3(d)). Adjacent terraces that are more than 10m high limit the capacity for channel widening, while actively supplying gravels. Mobile gravel banks influence the braided characteristics of the Daheba River. In summary, bank strength of the four study reaches varies from high to low as follows: Maqu reach, Lanmucuo River, Dari reach, and Daheba River.

4 Estimation of bedload transport capacity

Given the lack of observed data of bed load transport rate, bedload transport capacity has been estimated for a rectangular cross-section using the theoretical bed load formulae outlined below. Channel flow follows the laws of flow continuity, flow resistance and sediment transport with flow continuity law taking the form:

$$Q = AV \quad (1)$$

where Q, A, and V are flow discharge (m^3/s), channel cross-sectional area (m^2), and average flow velocity (m/s), respectively, $A=WH$, W is channel width (m), H is water depth (m).

This study adopts the Manning formula to embody the law of flow resistance for uniform alluvial channel flow:

$$V = \frac{1}{n} R^{2/3} S^{1/2} \quad (2)$$

where R is hydraulic radius (m), $R=WH/(2H+W)$, S is flow energy slope, n is Manning's roughness coefficient. In this study, following Chow (1959), n = 0.050 if no vegetation in gravel-bed channels at high stages (i.e., Daheba reach), n = 0.030 in floodplain with short grass (i.e., Lanmucuo River), n = 0.050 in floodplain with scattered brush and heavy weeds (i.e., Dari River), and n = 0.150 in floodplain with dense willows at flood stage (i.e., Maqu reach).

Among numerous bedload formulae, the Meyer-Peter and Muller equation has been extensively and successfully applied (Meyer-Peter and Müller, 1948). The modification developed by Wong and Parker (2006) has been used in this study:

$$\Phi = 3.97(\Psi - 0.0495)^{3/2}. \quad (3)$$

where Φ and Ψ are the dimensionless bedload transport rate per unit channel width and the dimensionless flow shear stress, respectively, that are defined as

$$\Phi = \frac{q_b}{\sqrt{(\rho_s / \rho - 1) g d_{50}^3}}. \quad (4)$$

$$\Psi = \frac{RS}{(\rho_s / \rho - 1) d_{50}}. \quad (5)$$

where q_b is the dimensional bedload transport rate per unit channel width (kg/s/m), ρ_s is the density of sediments transported (kg/m^3), ρ is the density of water (kg/m^3), g is the acceleration of gravity (m/s^2), and d_{50} is the median sediment size (mm).

Cross-section and water depth were measured based on field survey and remote sensing images (see Table 2). Estimated hydraulic parameters and bedload transport capacity for the four reaches, derived using Eq.(1)-(5), are summarised in Table 3. Note that channel width is effective bankfull width in the flood season, not valley width. The adopted mean grain size is lower than bed sediment sizeResults shown here are considered to be approximations, and are analysed solely in relational rather than absolute terms. Results show that the bedload transport capacity of the four reaches from high to low is as follows: Maqu, Daheba , Lanmucuo, Dari reaches.

5 Effect of vegetation and bedload capacity on channel stability

5.1.1 Dari reach (braided/anabranching river with grass and shrub cover)

Dari reach is a wide semi-braided and semi-anabranching channel, where the channel width is up to 1600 m (Fig.2 R1(a)). Some large stable gravel bar or islands have a dense grass and sparse shrub cover. Many unstable bars with low vegetation cover are subjected to recurring erosion and channel adjustment. Vegetation may inhibit erosion and enhance bar stability at middle flood stage, but the resistance effect of vegetation at high flood stage is very limited. As a result, the whole channel may be eroded at high flow stage, resulting in disordered patterns of mid-channel gravel bars. The estimated bedload transport capacity per unit channel width is 1.77 kg/m/s for 2.0 m water depth (see Table 2). If the water depth increases to 3.0 m in the flood season, bedload transport capacity per unit width significantly increases up to 14.93 kg/m/s. It is likely that these flow depths cause intense erosion that divides the stable bars into many unstable bars.

Fig. 4(a) and (b) show monthly stage-discharge relationships for 1968 and 1984, respectively. Since Dari reach is a multi-thread channel system, the stage-discharge relationship is not a single function relationship. In non-flood months (December, January, February, March, and April) the river bed is frozen. May and November are pivotal times in the stage-discharge relationship (the former reflects ice melt, the latter freezing). In flood months (June, July, August, and September) the stage-discharge relationship adjusts due to strongly erosion and deposition within the channel. The stage-discharge data (June, July, August, and September) in the 1968 and 1984 are to run non-linear regression (power function, $Z = a*Q^b$, Z is water stage (m), Q is discharge (m^3/s), a is the coefficent and b is the exponent). Two coefficents of a (b) in 1968 are 4.7(0.09), 4.8(0.09), 5.4(0.07), and 4.5(0.10) for June, July, August, and September, respectively; and accordingly, 2.9(0.12), 2.8(0.13), 3.0(0.12), and 3.5(0.09) in 1984. The results of the regression show that a obviously decreased and b was almost unchanged, indicating the increase of water depth slowed down with the incoming discharge increasing from 1968 to 1984 because the sediment deposition leaded to the wider channel year by year.

For instance, different discharges for the same flow stage in June and July 1968 are considered to reflect erosion of the channel (Fig. 4(a)). In the other instance shown here, the maximum discharge in 1984 occurred in July (Fig.4(b)), probably marking the transition from erosion to deposition phases. The geomorphological significance of the two different trends is showed in Fig. 4 (a) and (b) (i.e., the trend formed by the data in March and April against the trend formed). Also, there is a difference between the high scatter trend for low discharges (probably low flood stages) and regular trends for high discharges (probably high flood stages) because the water submerged the bars in high dishcarge and the multi-thread channels apprears in low dishcarges. The Dari reach is defined in this study as semi-braided and semi-anabranching since vegetation (grass and some shrubs) partially develops on channel bars, and bars are relatively stable during low and middle flood stages, while are prone to change during high flood stages.

Fig. 5 shows the stage-discharge relationships of the Upper Yellow River at Dari from June to September in 1964-1984. Apparently, the stages of 1975 are out of line with 1978, perhaps indicating that the elevation benchmark of the station changed in 1976 or 1977. In the same month of different years, the stage-discharge relationship does not have a simple corresponding relation, especially in August and September. This may reflect: 1) responses of the channel bed to strong deposition in June and July, and thereafter the high stage corresponds to low discharge such as August in 1978-1984 and September in 1964-1975; 2) the channel bed strongly erodes in June and July, and thereafter the high stage corresponds to high discharge such as August in 1964-1975 and September in 1978-1984. Overall, Figure 2 R1(a) and (b) indicate that the channel of Dari reach is quite unstable during the flood season, with erosion and deposition changing the stage-discharge relationship. A sketch showing how flow erosion divides bars and deposits to form new bars is shown in Fig. 6. The stage-discharge data in July from 1964-1984 are to run power function regression ($Z = a*Q^b$). Two coefficents of *a* (*b*) are 5.3(0.08) in 1964, 4.7(0.10) in 1965, 5.4(0.07) in 1966, 4.8(0.09) in 1968, 5.2(0.07) in 1969, 5.3(0.07) in 1970, 5.3(0.06) in 1973, 4.6(0.10) in 1975, 2.9(0.11) in 1978, 2.7(0.13) in 1979, 2.7(0.13) in 1980, 2.4(0.15) in 1981, and 2.8(0.13) in 1984.

Obviously, this difference of *a* (*b*) is represented by the two different trends of the data before and after 1976, i.e, *a* decreased and *b* increased.

5.1.2 Maqu reach (anabranching river with tree cover)

Maqu reach in wide Ruoergai basin is covered by dense tress (*Salix atopantha*) and has a stable anabranching channel planform (Fig. 2 R2(a)). It is postulated that a herb and shrub cover gradually supports the stabilization of new bars, facilitating sediment deposition on the body of the bar during low and middle flood stages, and protecting the bar from erosion at high flood stages. Subsequent development of trees presents a tall green barrier in the flood period. Although the water floods trees, their density induces sufficient resistance to decrease the flow velocity and trap fine sand and gravel on the body of the bar. Therefore, this anabranching channel system is basically stable over a decadal timescale.

Water stage change at Maqu station from 1959-1970 is shown in Fig. 7. The stage peak occurs in July and September. The maximum difference of 2.43 m occurred between June and September in 1963. If the water depth increases to 8.0 m from 4.0 m, bedload transport capacity increases to 18.52 kg/s/m from 2.75 kg/s/m. As a result, the branching channel bed may erode if the transport capacity exceeds upstream sediment supply. However, protection by trees is strong enough to inhibit erosion of bars. In contrary, if the upstream sediment supply surpasses the transport capacity, increasing bed deposition with flow stage further increases the transport capacity of the reach.This agrees with analyses by Huang and Nanson (2007) who stated that anabranching channels can achieve the optimal transport efficient without increasing bed gradient. Even though these reaches may appear to promote deposition on the channel bed during extreme floods (see Fig. 8), the flow erodes the bed later in the flood season, thereby maintaining an equilibrium cross-section. As a result, the anabranching channel of Maqu reach maintains a long-term stable situation.

5.1.3 Lanmucuo River (passive meandering river with meadow cover)

Lanmucuo River is a typical meandering river covered by dense meadow. Although typically characterized by large bends in a flat valley, mid-channel gravel bar covered by herbs sometimes form at the apex of bends (Fig. 2 R3(a)). The meandering channel and bars are very stable because of low sediment supply in the flood season and good vegetation coverage.

The tight root-soil complex on concave banks inhibits flow scour. When cantilevered bank failures do occur, slump blocks restrict further erosion of the bank. Grass develops on the point bars of convex banks. When the overbank flow submerges the point bar, the herbaceous vegetation can increase flow resistance and promote fine sand deposition (Fig. 9), thereby maintaining channel geometry with a relatively low migration rate. Growth of herbs on mid-channel bars an apices (Fig.2 R3(b)) helps to increase the flow resistance and trap fine sediment, facilitating channel stability.

5.1.4 Daheba River (unvegetated braided river)

The gravel bed of Daheba River is characterized by deposition in the flood season and erosion in the non-flood season. This makes it difficult for vegetation to develop on bars and banks of the braided channels. Fig. 10 shows morphological changes of the riverbed before and after the flood season in 2005. The main branching and sub-branching channels of the channel completely changed, with an initial phase of sediment deposition followed by flood-induced division of bars and the re-emergence of a multi-thread braided system. Table 3 shows derived estimates of the bed load transport capacity per width, q_b=2.25 kg/s/m. This capacity is seemingly unable to efficiently transport the excess sediment supply from upstream. As a result, serious deposition occurs along Daheba River in the flood season.

Adjustments to channel geometry as a result of erosion and deposition processes before, during and after the flood season are shown in Fig. 11. The elevation of the riverbed on July 29 2009 was 0.27 m higher than on April 1 2009. Other than slight erosion of the left bank, the subsequent phase was depositional, with up to 1.59 m of aggradation occurring by October 23 2009. The elevation of riverbed was increased by 0.27 m after the flood season in 2010. The elevation of the riverbed in July 1 2011 was 0.26 m higher than on April 29 2011. Trivial deposition occurred from July 1 to July 8, but 0.24 m of erosion occurred by July 23, with subsequent deposition of 0.27 m by October 23. As a result, the riverbed elevation was 0.24 m higher after flood season in 2011, but multiple phases of deposition and erosion has occurred. The deposition-erosion-deposition phases may reflect lower bedload transport capacity relative to sediment supply in the early flood season, but widespread deposition increases the local bed slope, thereby increasing bedload transport capacity. According to Eq. (3), a 10% increase in bed slope increases the transport capacity by 85% in Daheba reach, so bed erosion occurs again. Bed erosion decreases the bed slope until the transport capacity has adjusted to reduced sediment supply, thereby inducing riverbed deposition once more. Consequently, alterative deposition and erosion leads to the extreme instability in the middle and lower Daheba River.

6 Discussion and Conclusions

This study has outlined the complex interplay between flow and sediment supply in the flood season, and the geomorphic/hydrodynamic role of vegetation cover on the valley floor, as determinants of channel morphodynamics/stability and bedload transport capacity for four alluvial reaches of the Yellow River source zone. Although the elevation of four reaches is different (Dari = 3960 m, Maqu = 3465 m, Lanmucuo River = 3604 m, and Daheba = 2832 m), the precipitation, temperature, and bed sediment size are basically similar (Yu et al., 2014). Nevertheless, vegetation coverage in the four reaches is quite different. The Dari reach (anabranching-braided) has a herb and shrub cover, Maqu (anabranching) reach has trees, Lanmucuo River (meandering) has meadow, and Daheba River (braided) has no vegetation cover. As shown elsewhere, bar morphodynamics vary markedly for differing planform types, with key differences outlined here for braided, anabranching, and meandering channels (cf., Hooke, 1986; Kleinhans, 2010; Kleinhans and van den Berg, 2010; Church and Ferguson, 2015). Bar development and stability reflect the ability of vegetation to trap sediments and stabilize banks, which in turn is directly influenced by flow energy relationships (i.e., these are mutual adjustments; Corenblit et al., 2007; Gurnell et al., 2012; Gurnell, 2014; Osterkamp and Hupp, 2010; Pietsch and Nanson, 2011). In this study, riparian vegetation and its root network are considered to restrict channel width and increase hydraulic efficiency, inducing greater bedload transport capacity in multi-thread channels (Allmendinger et al., 2005; Huang and Nanson, 2007). Islands and floodplains are able to trap more fine-grained sediment in the flood season, enhancing the longer-term (decadal) stability of anabranching channels, as shown by the stable islands of Maqu reach.

Relative to the passive (resisting) role of vegetation, bedload transport actively affects short-term patterns and rates of bed erosion and deposition. This, in turn, is affected by relationships between the flow regime (especially flood events and formative flows) and the influence of sediment supply upon bedload transport for differing river types (Church and Ferguson, 2015; Dunne et al., 2010). The supply of bed material sediment to an alluvial channel accelerates the growth of longitudinal, transverse, and point bars, thereby enhancing thalweg development and locally increasing flow velocity. Non-equilibrium between sediment supply and transport induces local channel instability, accentuating either bed erosion or deposition (Jansen and Nanson, 2010; Nanson and Huang, 2008). In this study, a channel stability gradient accords with both sediment movement and vegetation cover, wherein bedload transport capacity (a function of bed slope, hydraulic geometry, and sediment particle size) is related to the influence of riparian vegetation upon channel geometry/planform. We contend that the differing vegetation cover and planform response reflects the delicate balance between erosion and deposition on the channel bed and bank as influenced by bedload sediment supply in the flood season. Only when the bedload transport capacity is equivalent or greater than sediment supply, does vegetation act as a key determinant of channel stability.

Author contributions. Z.W. Li and G.A. Yu designed and conducted the field investigations. G. Brierley and Z.Y. Wang supervised the research and helped to contextualize the findings. Z.W. Li prepared the manuscript with contributions from all co-authors.

Acknowledgements

This study is funded by the CRSRI Open Research Program (Program CKWV2016369/KY), Alexander von Humboldt Foundation, the Natural Science Foundation of China (NSFC, 41571009; 41330751; 91547112; 91547113), and the Key Laboratory of Water Sediment Sciences and Water Disaster Prevention of Hunan Province (2016SS04). X.Z. Wang, C.D. Zhang, and X.D. Zhou are acknowledged for field assistance (2011-2014). We deeply appreciate the constructive comments and suggestions from two reviewers (Prof. Peng Gao and Prof. Coenders-Gerrits M.).

References

Abernethy, B. and Rutherfurd, I.D.: The distribution and strength of riparian tree roots in relation to riverbank reinforcement. Hydrol. Process., 15(1), 63–79, 2001.

Allmendinger, N.E., Pizzuto, J.E., Potter, N. Jr., Johnson, T.E., and Hession, W.C.: The influence of riparian vegetation on stream width, eastern Pennsylvania, USA. GSA Bulletin, 117, (1–2), 229–243, 2005.

Ashmore, P.E.: How do gravel-bed river braid? Canadian J. of Earth Sci., 28, 326–341, 1991.

Ashworth, P.J.: Mid-channel bar growth and its relationship to local flow strength and direction. Earth Surf. Proc. and Landforms, 21, 103–123, 1996.

Ashworth, P.J., Best, J.L., Roden, J.E., Bristow, C.S., and Klaassen, G.J.: Morphological evolution and dynamics of a large, sand braid-bar, Jamuna River, Bangladesh. Sedimentology, 47, 533–555, 2000.

Ashworth, P.J. and Lewin, J.: How do big rivers come to be different? Earth-Science Reviews, 114, 84–107, 2012.

Ashworth, P.J., Sambrook Smith, G.H., Best, J.L., Bridge, J.S., Lane, S.N., Lunt, I.A., Reesink, A.J.H., Simpson, C.J., and Thomas, R.E.: Evolution and sedimentology of a channel fill in the sandy braided South Saskatchewan River and its comparison to the deposits of an adjacent compound bar. Sedimentology, 58, 1860–1883, 2011.

Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., Roni, P., and Pollock, M.M.: Process-based principles for restoring river ecosystems. BioScience, 60(3), 209–222, 2010.

Best, J.L., Ashworth, P. J., Bristow, C.S., and Roden, J.E.: Three-dimensional sedimentary architecture of a large, mid-channel sand braid bar Jamuna River, Bangladesh. J. of Sedimentary Res., 73, 516–530, 2003.

Blue, B., Brierley, G.J., and Yu, G.A.: Geodiversity in the Yellow River source zone. J. of Geographical Sciences, 23(5), 775–792, 2013.

Bridge, J.S.: Description and interpretation of fluvial deposits: a critical perspective. Sedimentology, 40(4), 801–810, 1993.

Bridge, J.S.: Rivers and Floodplains: Forms Processes and Sedimentary Record, Blackwell Publishing, London, 2003.

Brierley, G.J.: Bar sedimentology of the Squamish River, British Columbia: Definition and application of morphostratigraphic units. J. of Sedimentary Petrology, 61, 211–225, 1989.

Brierley, G.J.: Floodplain sedimentology of the Squamish River, British Columbia: relevance of element analysis. Sedimentology, 38, 735–750, 1991.

Brierley, G.J.: Channel morphology and element assemblages: A constructivist approach to facies modelling. In: Dawson, M. and Carling, P.A. (Eds.). Recent advances in fluid mechanics and alluvial stratigraphy. Chichester, Wiley Interscience, 1996.

Brierley, G.J. and Fryirs, K.A.: Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publications, Oxford, UK, 2005.

Brierley, G.J. and Hickin, E.J.: Channel planform as a non-controlling factor in fluvial sedimentology: The case of the Squamish River floodplain, British Columbia. Sedimentary Geology, 75, 67–83, 1991.

Brierley, G.J., Li, X.L., Cullum, C., and Gao, J.: Landscape and ecosystem diversity, dynamics and management in the Yellow River source zone. Springer, Switzerland, 2016.

Burge, L.M.: Stability, morphology and surface grain size patterns of channel bifurcation in gravel-cobble bedded anabranching. Earth Surf. Proc. and Landforms, 31, 1211–1226, 2006.

Carling, P., Jansen, J., and Meshkova, L.: Multichannel rivers: their definition and classification. Earth Surf. Proc.and Landforms, 39, 26–37, 2014.

Chow, V.T.: Open Channel Hydraulics, McGraw-Hill, New York, 1959.

Church, M. and Ferguson, R.I.: Morphodynamics: River beyond steady state. Water Resour. Res., 51: 1883–1897, doi: 10.1002/2014WR016862, 2015.

Church, M., Rice, S.P.: Form and growth of bars in a wandering gravel-bed river. Earth Surf. Proc. and Landforms, 34, 1422–1432, 2009.

Corenblit, D., Baas, A.C.W., Bornette, G., Bornette, G., Darrozes, J., Delmotte, S., Francis, R.A., Gurnell, A.M., Julien, F., Naiman, R.J., and Steiger, J.: Feedbacks between geomorphology and biota controlling earth surface processes and landforms: A review of foundation concepts and current understandings. Earth-Science Reviews, 106(3–4), 307–331, 2011.

Corenblit, D., Tabacchi, E., Steiger, J., and Gurnell, A.M.: Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. Earth-Science Reviews, 84(1–2), 56–86, 2007.

Coulthard, T.J.: Effects of vegetation on braided stream patterns and dynamics. Water Resour. Res., 41, W04003, doi:10.1029/2004WR003201, 2005.

Dunne, T., Constantine, J.A, and Singer, M.B.: The role of sediment transport and sediment supply in the evolution of river channel and floodplain complexity. Transactions, Japanese Geomorphological Union, 31–32, 155–170, 2010.

Eaton, B.C., Church, M., and Millar, R.G.: Rational regime model of alluvial channel morphology and response. Earth Surf. Proc. and Landforms, 29(4), 511–529, 2004.

Eaton, B.C. and Church, M.: Predicting downstream hydraulic geometry: A test of rational regime theory. J.of Geophys. Res., 112, F03025, doi: 10.1029/2006JF000734, 2007.

Eaton, B.C. and Giles, T.R.: Assessing the effect of vegetation-related bank strength on channel morphology and stability in gravel-bed streams using numerical models. Earth Surf. Proc. and Landforms, 34(5), 712–724, 2009.

Eaton, B.C., Millar, R.G., and Davidson, S.: Channel patterns: braided, anabranching, and single-thread. Geomorphology, 120, 353–364, 2010.

Fryirs, K.A. and Brierley, G.J.: Geomorphic analysis of river systems: an approach to reading the landscape. Wiley-Blackwell, Chichester, UK, 2012.

Gradzinski, R., Baryla, J., Doktor, M., Gmur, D., Gradzinski, M., Kedzoir, A., Paszkowski, M., Soja, R., Zielinski, T., and Zurek, S.: Vegetation-controlled modern anastomosing system of the upper Narew River (NE Poland) and its sediments. Sedimentary Geology, 157, 253–276, 2003.

Gran, K. and Paola, C.: Riparian vegetation controls on braided stream dynamics. Water Resour. Res., 37(12), 3275–3283, 2001.

Gurnell, A.: Plants as river system engineers. Earth Surf. Proc. and Landforms, 39(1), 4–25, 2014.

Gurnell, A.M., Bertoldi, W., and Corenblit, D.: Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. Earth-Science Reviews, 111,129–141, 2012.

Gurnell, A.M., Petts, G.E, Hannah, D.M., Smith, B.P., Edwards, P.J., Kollmann, J., Ward, J.V., and Tockner, K.: Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surf. Proc. and Landforms, 26, 31–62, 2001.

Hickin, E.J.: Vegetation and river channel dynamics. Canadian Geographer, 28(2), 111–126, 1984.

Hooke, J.M.: The significance of mid-channel bars in an active meandering river. Sedimentology, 33, 839–850, 1986.

Hooke, J.M.: Variations in flood magnitude-effect relations and the implications for flood risk assessment and river management. Geomorphology, 251, 91–107, 2015.

Hooke, J.M. and Yorke, L.: Channel bar dynamics on multi-decadal timescales in an active meandering river. Earth Surf. Proc. and Landforms, 36, 1910–1928, 2011.

Huang, H.Q. and Nanson, G.C.: Why some alluvial rivers develop an anabranching pattern. Water Resour. Res., 43(7), doi: 10.1029/2006WR005223, 2007.

Hupp, C.R. and Osterkamp, W.R.: Riparian vegetation and fluvial geomorphic processes. Geomorphology, 14, 277–295, 1996.

Jang, C.L. and Shimizu, Y.: Vegetation effects on the morphological behavior of alluvial channels. J.of Hydrau. Res., 45(6), 763–772, 2007.

Jansen, J.D. and Nanson, G.C.: Anabranching and maximum flow efficiency in Magela Creek, northern Australia. Water Resour. Res., 40(4), doi: 10.1029/2003WR002408, 2004.

Jansen, J.D. and Nanson, G.C.: Functional relationships between vegetation, channel morphology, and flow efficiency in an alluvial (anabranching) river. J. of Geophys. Res., 115, F04030, doi: 10.1029/2010JF001657, 2010.

Jerolmack, D.J. and Mohrig, D.: Conditions for branching in depositional rivers. Geology, 35(5), 463–466, 2007.

Kleinhans, M.G.: Sorting out river channel patterns. Progress in Physical Geography, 34(3), 287–326, 2010.

Kleinhans, M.G. and van den Berg, J.H.: River channel and bar patterns explained and predicted by an empirical and a physics-based method. Earth Surf. Proc. and Landforms, 36(6), 721–738, 2010.

Latrubesse, E.M.: Patterns of anabranching channels: The ultimate end-member adjustment of mega rivers. Geomorphology, 101,130–145, 2008.

Latrubesse, E.M. and Franzinelli, E.: The Holocene alluvial plain of the middle Amazon River, Brazil. Geomorphology, 44, 241–257, 2002.

Lewin, J. and Ashworth, P.J.: Defining large river channel patterns: Alluvial exchange and plurality. Geomorphology, 215, 83–98, 2014.

Li, Z.W., Wang, Z.Y., Pan, B.Z., Du, J., Brierley, G., Yu, G.A., and Blue, B.: Analysis of controls upon channel planform at the First Great Bend of the Upper Yellow River, Qinghai-Tibet Plateau. J.of Geographi. Sci., 23(5), 833–848, 2013.

Luchi, R., Zolezzi, G., and Tubino, M.: Modelling mid-channel bars in meandering channels. Earth Surf. Proc. and Landforms, 35, 902–917, 2010.

Makaske, B.: Anastomosing rivers: a review of their classification, origin and sedimentary products. Earth-Science Reviews, 53, 149–196, 2001.

McBride, M., Hession, W.C., Rizzo, D.M., and Thompson, D.M.: The influence of riparian vegetation on near-bank turbulence: a flume experiment. Earth Surf. Proc. Landforms, 32, 2019–2037, 2007.

McGowen, J.H. and Garner, L.: Physiographic features and stratification types of coarse-grained point bars: Modern and ancient examples. Sedimentology, 14, 77–111, 1970.

Mertes, L., Dunne, T., and Martinelli, L.: Channel floodplain geomorphology along the Solimões–Amazon River, Brazil. Geological Society of America Bulletin, 108, 1089–1107, 1996.

Meyer-Peter, E. and Müller, R.: Formulas for bed load transport, paper presented at 2nd Meeting, International Association for Hydraulic Environmental Engineering and Research, Madrid, 1948.

Millar, R.G.: Influence of bank vegetation on alluvial channel patterns. Water Resour. Res., 36(4), 1109–1118, 2000.

Murray, A.B. and Paola, C.: Modelling the effect of vegetation on channel pattern in bedload rivers. Earth Surf. Proc. and Landforms, 28,131–143, 2003.

Nanson, G.C. and Huang, H.Q.: Least action principle, equilibrium states, iterative adjustment, and the stability of alluvial channels, Earth Surf. Proc. Landforms, 33, 923–942, 2008.

Nanson, G.C. and Knighton, A.D.: Anabranching rivers: their cause, character and classification. Earth Surf.Proc. and Landforms 21, 217–239, 1996.

Nicholas, A.P., Ashworth, P.J., Smith, G.H.S., and Sandbach, S.D.: Numerical simulation of bar and island morphodynamics in anabranching megarivers. J. of Geophys.Res.: Earth Surf., 118, 2019–2044, 2013.

Osterkamp, W.R. and Hupp, C.R.: Fluvial processes and vegetation-Glimpses of the past, the present, and perhaps the future. Geomorphology, 116, 274–285, 2010.

Pietsch, T.J. and Nanson, G.C.: Bankfull hydraulic geometry: the role of in-channel vegetation and downstream declining discharges in the anabranching and distributary channels of the Gwydir distributive system, southeastern Australia. Geomorphology, 129, 152–165, 2011.

Reesink, A.J., Ashworth, P.J., Sambrook Smith, G.H., Best, J.L., Parsons, D.R., Amsler, M.L., Hardy, R.J., Lane, S.N., Nicholas, A.P., Orfeo, O., Sandbach, S.D., Simpson, C.J., and Szupiany, R.N.: Scales and causes of heterogeneity in bars in a large multi-channel river: Río Paraná, Argentina. Sedimentology, 61, 1055–1085, 2014.

Sambrook, S.G.H., Ashworth, P.J., Best, J. L., Lunt, I.A., Orfeo, O., and Parsons, D.R.: The sedimentology and alluvial architecture of a large braid bar Río Paraná, Argentina, J. of Sedimentary Res., 79, 629–642, 2009.

Smith, N.D.,: Sedimentology and bar formation in the Upper Kicking Horse River, a braided outwash stream. J. of Geology, 82, 205–223, 1974.

Song, X.L. and Bai, Y.C.: A new empirical river pattern discriminant method based on flow resistance characteristics. Catena, 135, 163–172, 2015.

Tadaki, M., Brierley, G., and Cullum, C.: River classification: theory, practice, politics. Wiley Interdisciplinary Reviews: Water, 1(4), 349–367, 2014.

Tal, M. and Paola, C.: Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments. Earth Surf.Proc. and Landforms, 35, 1014–1028, 2010.

Task Force on Bed Forms in Alluvial Channels: Nomenclature for Bed Forms in Alluvial Channels. J. of the Hydrau. Division, 92(3), 51–64, 1966.

Tooth, S. and Nanson, G.C.: The role of vegetation in the formation of anabranching channels in an ephemeral river, Northern plains, arid central Australia. Hydrol. Process., 14(16–17), 3099–3117, 2000.

Wang, S.J., Chen, Z.Y., and Smith, D.G.: Anastomosing river system along the subsiding middle Yangtze River basin, southern China. Catena, 60,147–163,2005.

Wong, M. and Parker, G.: Reanalysis and correction of bed load relation of Meyer-Peter and Müller using their own database, J. of Hydrau. Engineering, 132(11), 1159–1168, 2006.

Yu, G.A., Brierley, G., Huang, H.Q., Wang, Z., Blue, B., and Ma,Y.X.: An environmental gradient of vegetative controls upon channel planform in the source region of the Yangtze and Yellow Rivers. Catena, 119, 14–153, 2014.

Table 1. Characteristics of the four study reaches (Flood season = June-September)

Alluvial reach	Planform type	Catchment area (km^2)	Flood-season mean discharge (m^3/s)	Channel gradient	Vegetation cover
Dari	braided-anabranching	45020	270	0.0012	dense grasses/ sparse brush
Maqu	anabranching	86000	920	0.0005	dense trees
Lanmucuo	meandering	660	15	0.0015	dense grass
Daheba	braided	5200	70	0.0018	non-vegetation

Table 2. Characteristics and bed material of alluvial channels in the four study reaches

Alluvial reach	Channel width (m)	Water depth (m)	Bed material d_{50} (m)	Branching channels	Stability
Dari	450-1600	1.0-3.0	0.025	>5	semi-stable
Maqu	300-1000	2.0-5.0	0.015	>3	very stable
Lanmucuo	10-20	0.3-1.0	0.030	<=2	very stable
Daheba	150-500	0.5-2.0	0.060	>3	unstable

Table 3. Estimation of hydraulic coefficients and bedload transport rates

River reach	Bankfull channel width (m)	Bankfull water depth (m)	Channel gradient	Median grain size (m)	Manning coefficient	Average velocity (m/s)	Channel discharge (m^3/s)	q_b (kg/s/m)
Dari	200	2.0	0.0012	0.015	0.05	0.90	269.67	1.77
Maqu	400	4.0	0.0005	0.015	0.15	0.37	593.14	2.75
Lanmucuo	20	0.8	0.0015	0.010	0.03	1.06	16.91	2.35
Daheba	50	1.5	0.0018	0.016	0.05	0.96	71.75	2.25

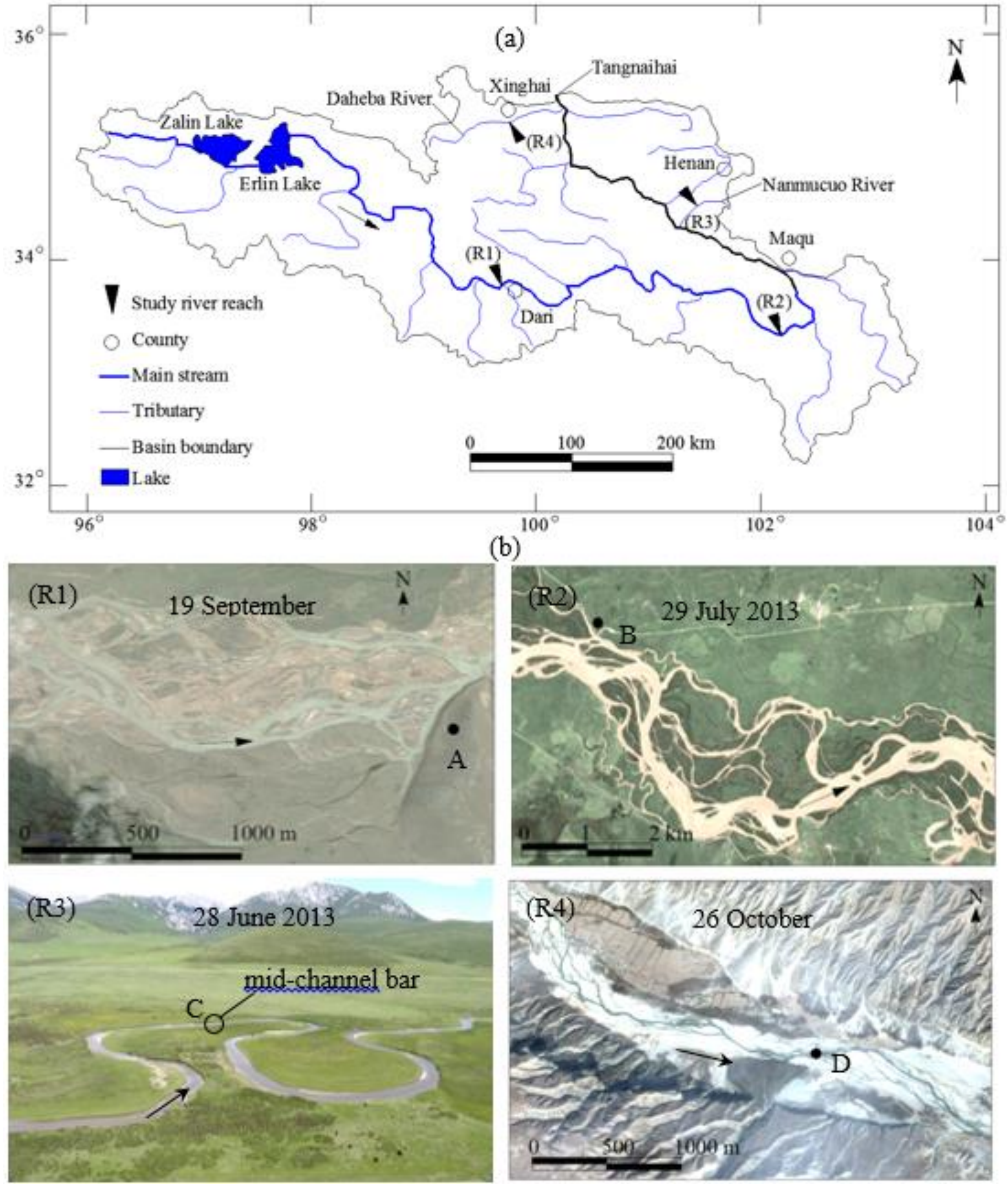

Figure 1. (a) The course of the Upper Yellow River. R1 is Dari reach, R2 is Maqu reach, R3 is Lanmucuo River, and R4 is Daheba River, (b) Planform morphology of the study reaches (R1 is Dari reach , R2 is Maqu reach, R3 is Lanmucuo River reach, and R4 is Daheba River reach). R1, R2, and R4 are Google Earth images and R3 is a photograph taken from nearby hills. Points A, B, C, and D are the location of photographs shown in Figures 2.

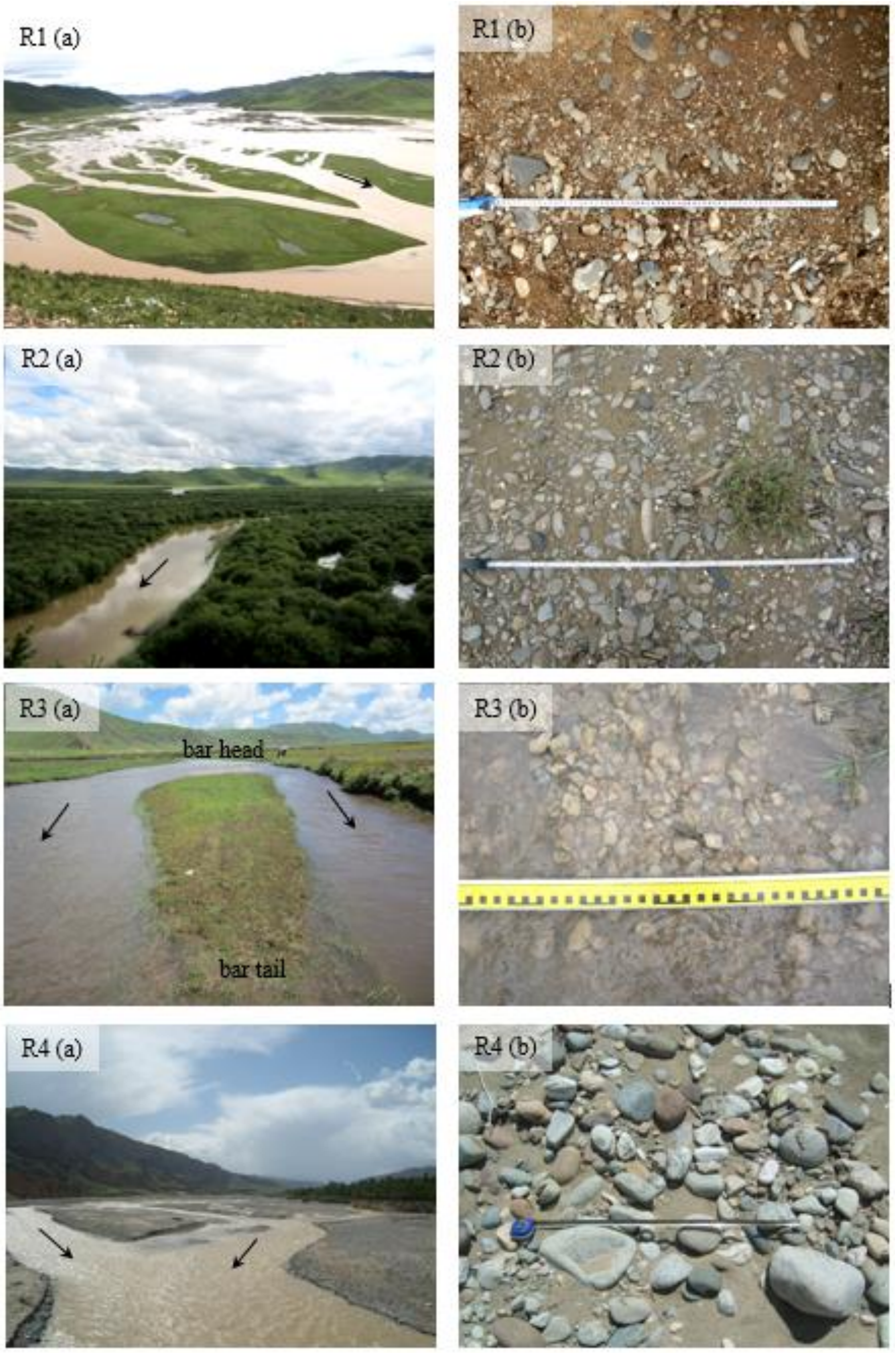

Figure 2. (R1) Channel morphology and gravel bed of Dari reach (photographs taken on 2 July, 2012, 33.7553 °N, 99.6414 °E, 3960 m elevation), (R2) Channel morphology and gravel bed of Maqu reach (photographs taken on 8 July, 2012, 33.3594 °N, 102.0553 °E, 3465 m elevation), (R3) Channel morphology and gravel bed of a grass covered bar in middle Lanmucuo River (to photographs taken on 5 July, 2012, 34.4287 °N, 101.4663 °E, 3604 m elevation), (R4) Channel morphology and gravel bed of middle Daheba River (photographs taken on 6 August, 2011, 35.5169 °N, 100.0183 °E, 2832 m elevation).

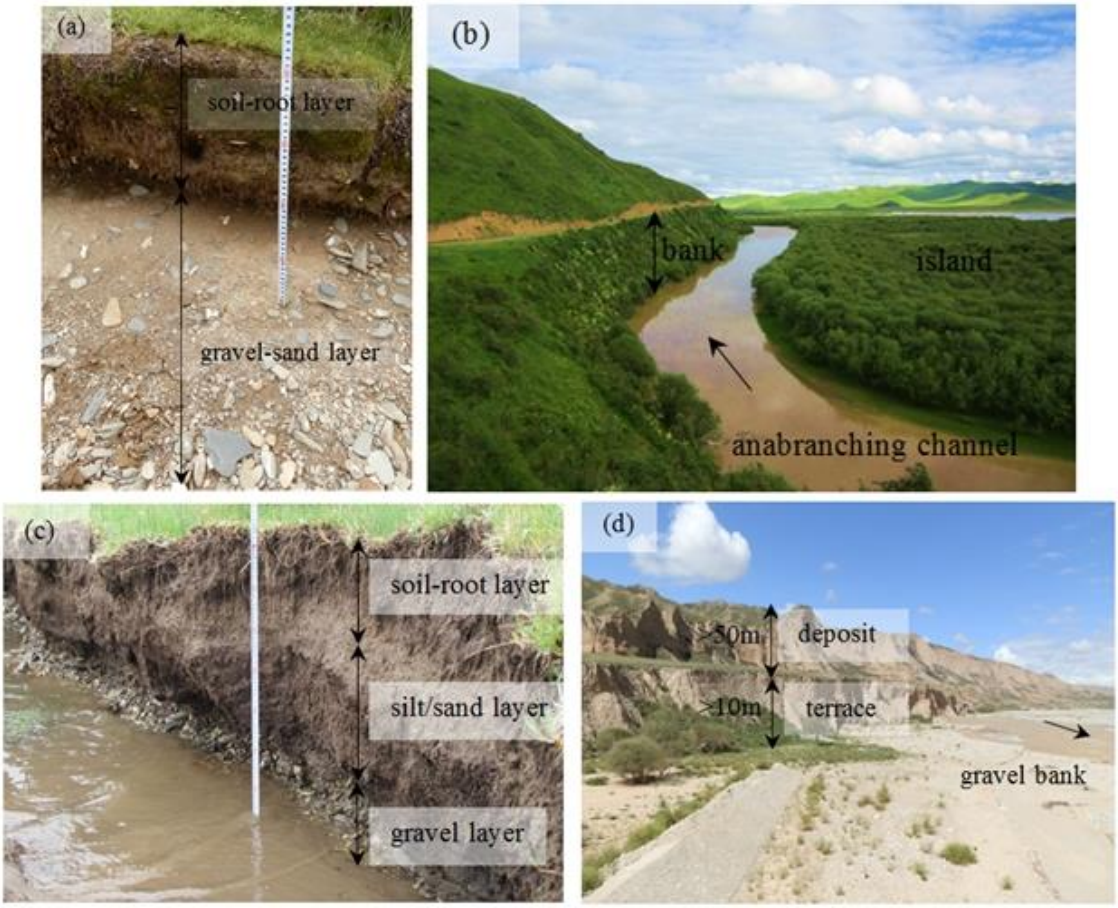

Figure 3. River bank of the study reaches (a) Dari reach, (b) Maqu reach, (c) Lanmucuo River reach, and (d) Daheba River reach.

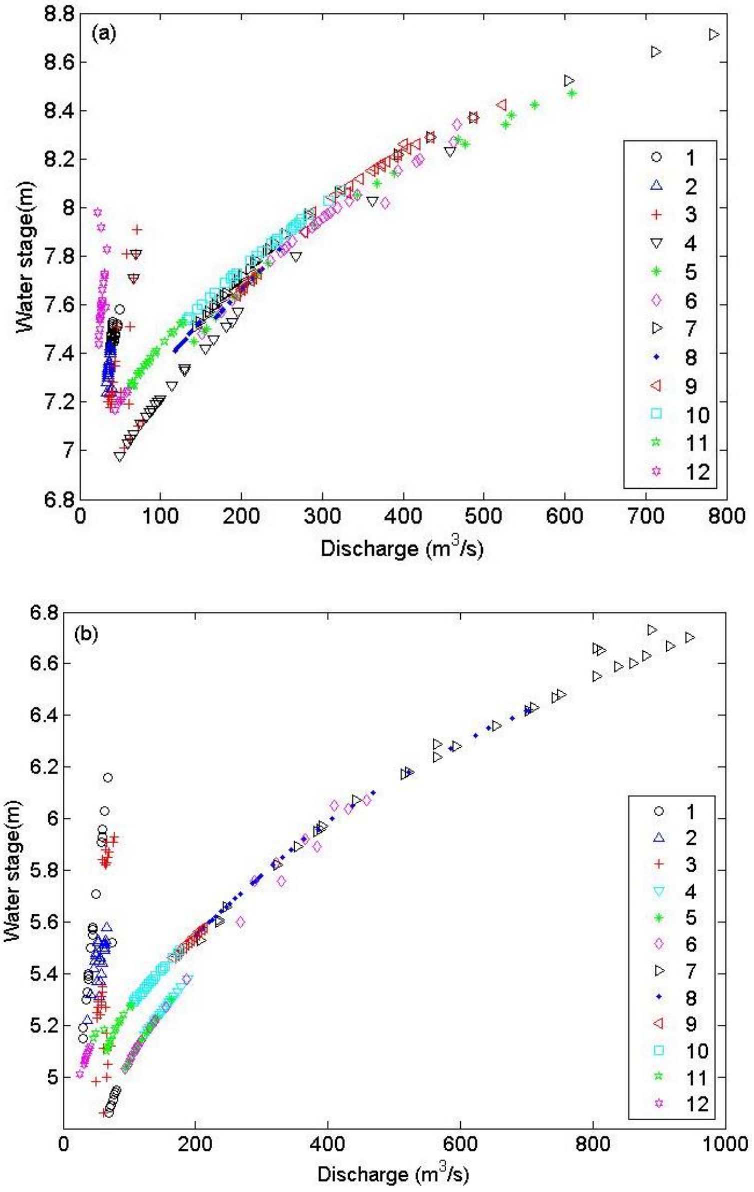

Figure 4. Monthly stage-discharge relationships for Jimai hydrological station in Dari reach (a) 1968 (b) 1984 (Note: number refers to month, e.g., 1 for January and 12 for December).

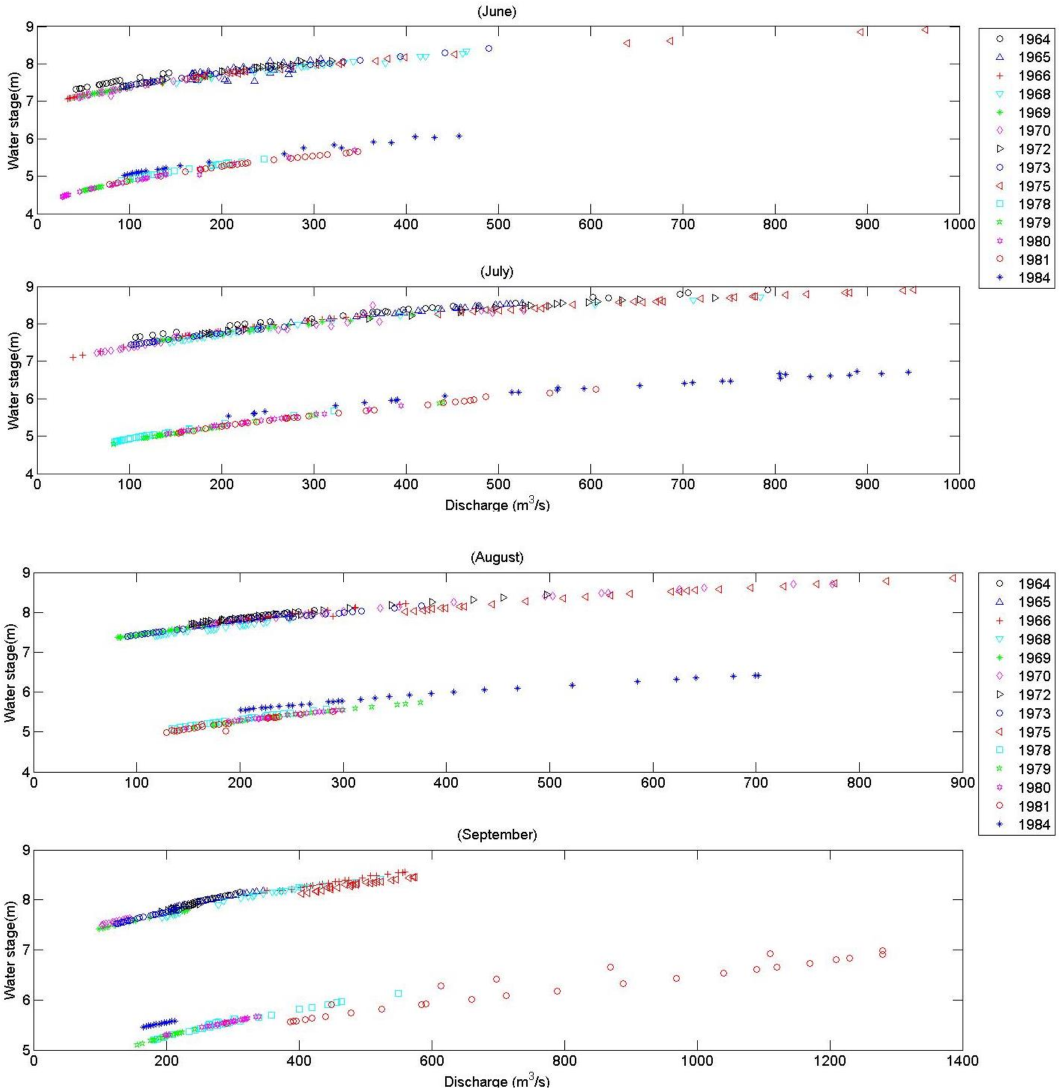

Figure 5. Annual stage-discharge relationship (1964-1984) of Dari reach in Jimai hydrological station.

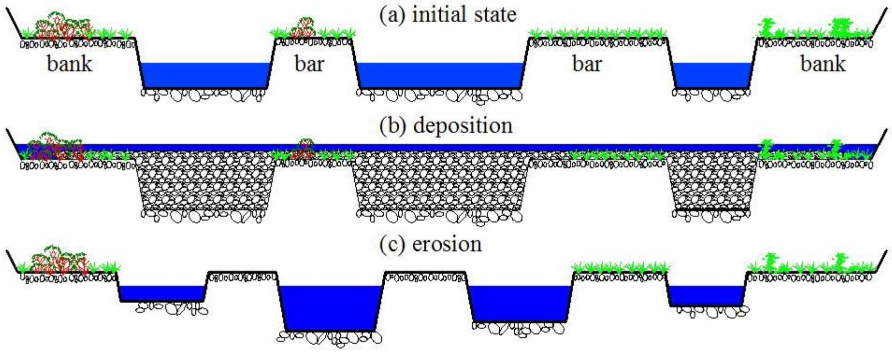

Figure 6. Sketch of channel bed deposition and erosion in flood season in Dari reach.

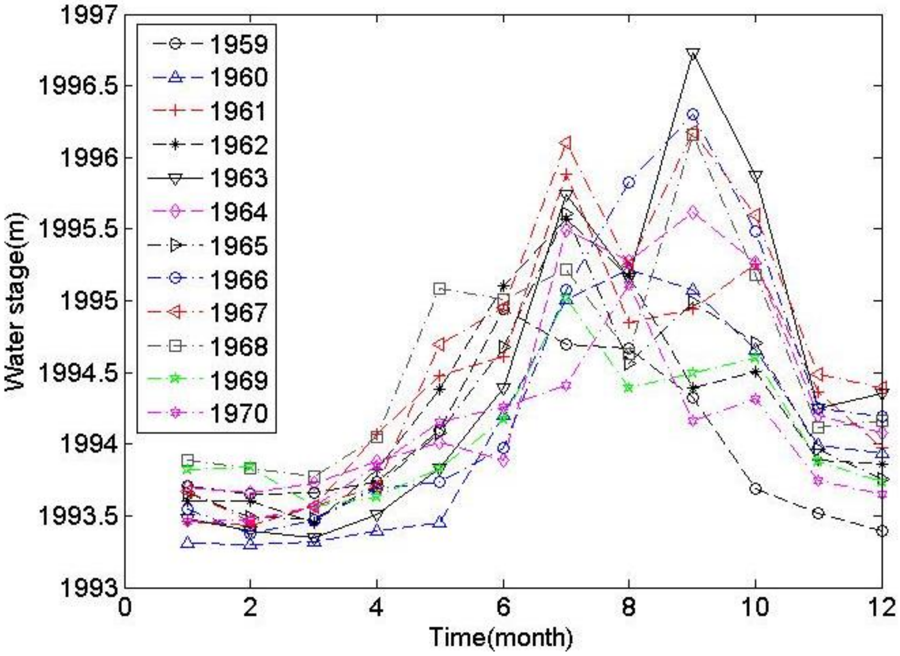

Figure 7. Monthly stage change of Maqu hydrological station (1959-1970).

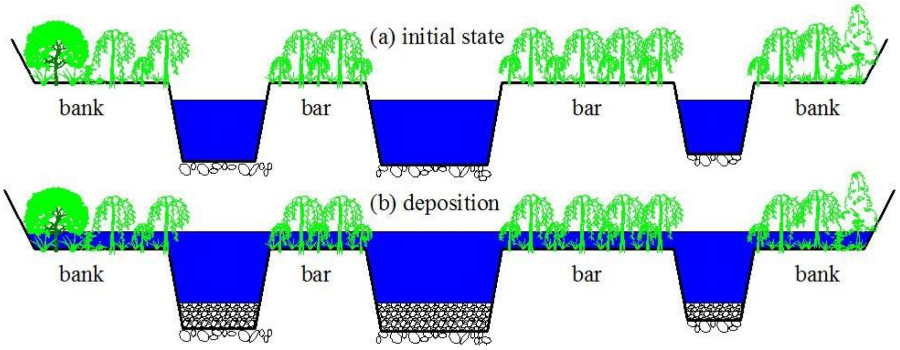

Figure 8. Sketch of branching channel deposition and stage increasing in flood season in Maqu reach

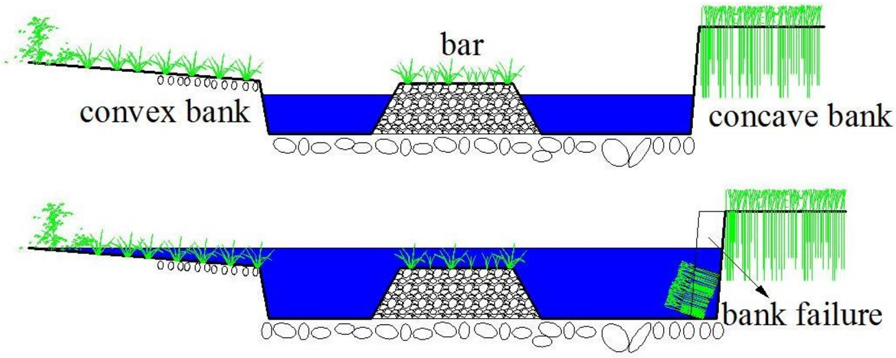

Figure 9. Sketch of submerged bend apex with a mid-channel bar in the Lanmucuo River

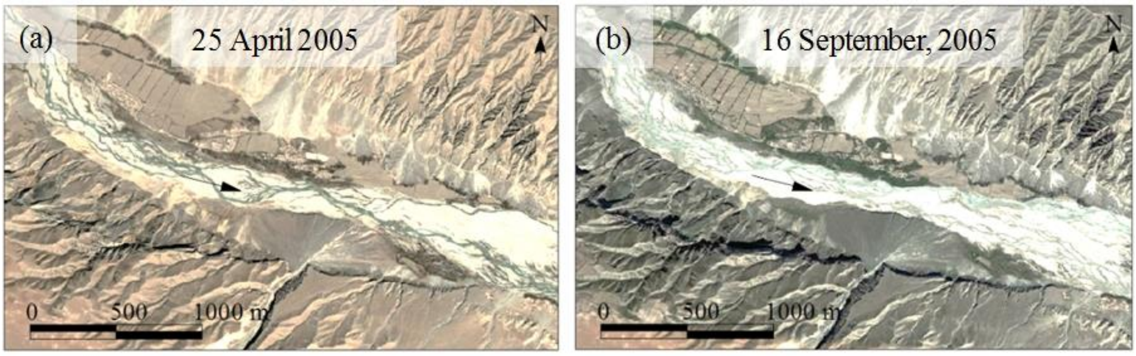

Figure 10. Braided channels evolution of the middle Daheba River in 2005 (a) in non-flood season, (b) in flood season

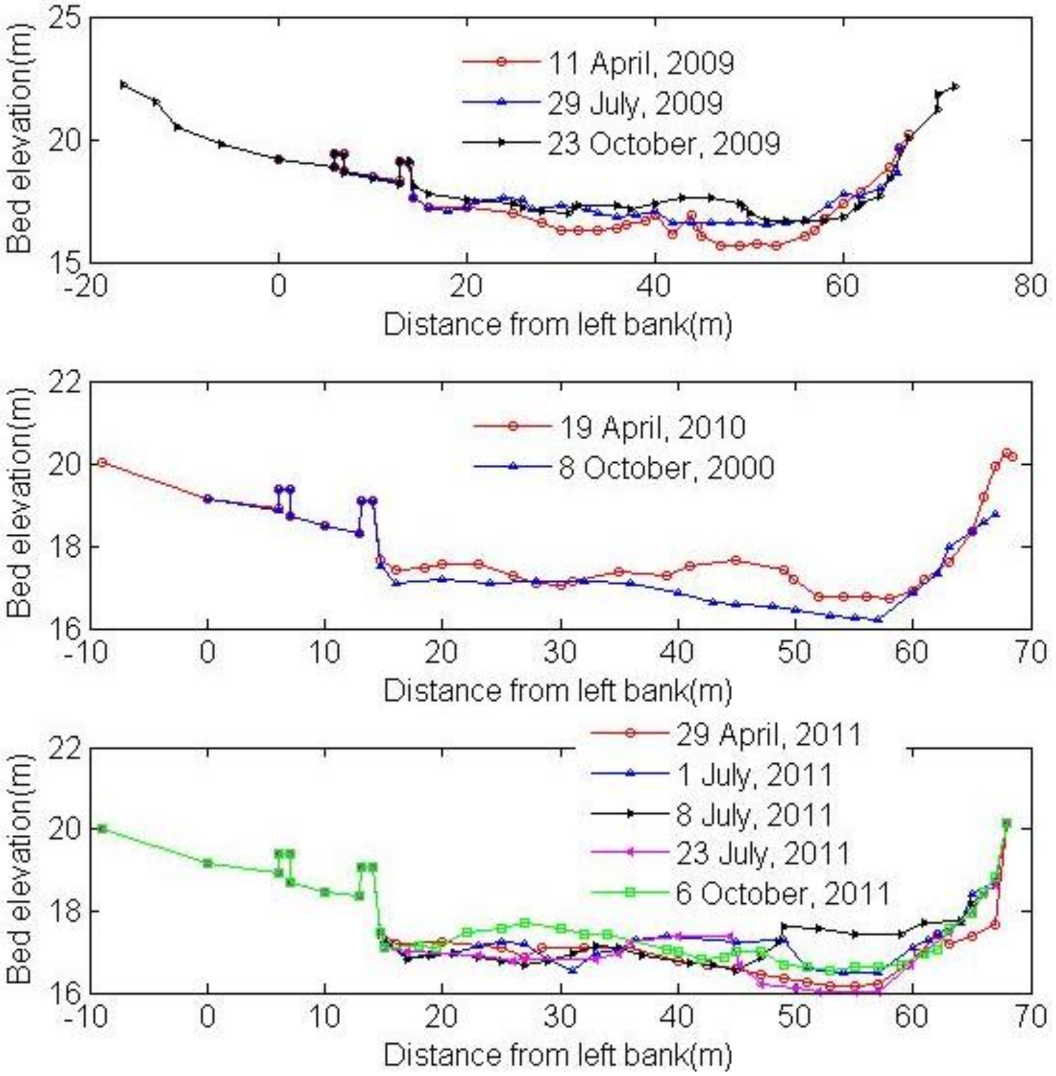

Figure 11. Elevation change of cross-section in Shangcun hydrological station (2009-2011) (left for left bank, right for right bank)