# PYANJ RIVER MORPHOLOGY AND FLOOD PROTECTION

John Field, Binsar Tambunan, and Philippe Floch

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Binsar Tambunan is lead portfolio management specialist at the Central and West Asia Department, Asian Development Bank.

#### ASIAN DEVELOPMENT BANK

Asian Development Bank 6 ADB Avenue, Mandaluyong City 1550 Metro Manila, Philippines www.adb.org

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#### FOREWORD

The loss of life, land, and property due to flooding is common, particularly along river systems. Asia is the most affected among all the continents, with more than 650,000 lives lost and economic losses estimated at \$687 billion over the 10-year period between 2004 and 2013. Various investments in infrastructure have been made to minimize flood losses.

The river morphology study was undertaken in the Pyanj River Basin as part of a regional technical assistance provided by the Asian Development Bank (ADB) in response to requests from the governments of Afghanistan and Tajikistan. Better flood management in the Pyanj River Basin became necessary after the two countries suffered significant damage as a result of a large flood during June–July 2005.

Flood and erosion risks have become an issue of significant mutual concern, particularly because the Pyanj River, a major tributary of the Amu Darya River, runs along the border of Afghanistan and Tajikistan. The Afghanistan side of the border has many low-lying, densely populated islands where the river reaches the flood plain from the mountains. The soil is soft and very productive in the delta and along the bank, but few formal flood protection works have been undertaken in the country. On the Tajikistan side, intensive irrigated agriculture was developed under the former Soviet Union, and an extensive system of flood embankments was put in place to protect the irrigation systems. During the post-Soviet era, the infrastructure deteriorated and eroded, particularly during the flood season.

The regional technical assistance for the Pyanj River Basin Flood Management was provided to improve knowledge, increase capacity, and strengthen institutions for planning and managing the Pyanj River Basin, focusing on flood management. This is consistent with ADB's country partnership strategy for Afghanistan, which emphasizes the urgency of improving the management and protection of water catchment areas; and the country operations business plan, 2012–2014 for Tajikistan, which underscores the need to build climate resilience in the Pyanj River Basin.

The results and recommendations of this river morphology study would be useful to all those who are concerned with reducing the negative impacts from floods and bank erosion, improving protection against floods and bank erosion, and establishing sustainable flood management systems.

Klaus Gerhaeusser Director General Central and West Asia Department Asian Development Bank

#### **EXECUTIVE SUMMARY**

Asia is hit hard by floods every year, causing loss of life and billions of dollars in damage. Much of the damage is related to bank erosion resulting from shifting channel positions on meandering channels, braided rivers, and alluvial fans. Understanding the natural processes that occur in these channel types is essential to improving flood hazard management in these environments. Past flood control efforts have often had only short-term success while exacerbating flooding and erosion problems elsewhere. A river morphology study conducted in 2009 on the Pyanj River Basin of Afghanistan and Tajikistan demonstrated how traditional flood and erosion control practices, such as embankments, bank armoring, and channel straightening, constrain natural river processes, and therefore are liable to result in channel responses that damage the flood control efforts themselves and transfer erosive forces to adjacent areas.

Alternative flood control methods are available, such as setback and overtopping embankments. These methods provide sufficient space for channel migration and flood attenuation and, as a result, have a greater likelihood of being sustainable without impacting adjacent areas. Sustainable flood management strategies will require difficult land use choices in order to provide the necessary space for channel migration. Difficult decisions in the near term, however, will ultimately yield long-term benefits in the form of reduced threats to human life, less damage to crops and other investments, and more limited environmental degradation. The threat of flood damage in Asia will remain high given the amount of seismic activity, the heavy land use and unpredictable settlement patterns in the floodplains, and the extreme weather events that impact much of the region. Excessive flooding will continue to drive dynamic channel change because of the high rate of sediment delivery to the sustainable techniques that accommodate natural river processes, so that flood risk can be reduced for extended time periods over the largest possible area.

#### I. INTRODUCTION

1. Flooding is the most common natural disaster, representing 40% of all disasters worldwide. Of the seven continents, flooding is worst in Asia with more than 650,000 lives lost and economic losses estimated at \$687 billion during 2004–2013. To limit flood losses, considerable expenditures have been made on flood control and other flood management approaches throughout Asia. The Indian state of Assam, alone, allocated more than \$2 billion for flood control programs between 2001 and 2010. Traditional flood control techniques, such as embankments that prevent floods from spreading out over a wide floodplain, often fail over time or require frequent maintenance. They also create new flooding problems elsewhere, increase damage during larger floods, and result in environmental degradation. The development of flood control measures that avert these problems should be informed by river morphology studies that reveal how rivers respond to natural events (e.g., floods) and human activities (e.g., flood control).

2. The river morphology study undertaken in 2009 on the Pyanj River Basin was part of a regional technical assistance project initiated by the Asian Development Bank (ADB) in response to requests from the governments of Afghanistan and Tajikistan (ADB 2008). The need for better flood management in the Pyanj River Basin became apparent after significant damage resulted from a large flood during June–July 2005. Reconstruction of the old Soviet embankments on the Hamadoni Fan in Tajikistan following the flood had raised concerns that river protection schemes in one area might be exacerbating flooding and erosion elsewhere. Consequently, a major goal of the ADB-funded Pyanj River Basin Flood Management regional technical assistance project, was to identify structural and nonstructural flood management approaches that are sustainable and do not exacerbate hazards elsewhere.

3. The results of the river morphology study provided information on (i) the major river processes and associated hazards active in the watershed, (ii) how the river has responded to past flood control efforts and other river management activities, and (iii) alternative flood control measures that will be less susceptible to damage while more effectively reducing flood and erosion hazards. Flood management efforts should ideally limit maintenance needs and recurrent costs, decrease hazards beyond the project site, and minimize threats to life and property during large floods. In as much as the Pyanj River Basin is similar to other watersheds throughout Asia, this report summarizes the results of the river morphology study with an emphasis on how the findings may be applied elsewhere in Asia.

#### II. PYANJ RIVER BASIN SETTING

4. The Pyanj River is the source and primary tributary of the Amu Darya River that ultimately flows into the Aral Sea in Uzbekistan. The Pyanj River, with a catchment area of 121,900 square kilometers, flows along the international border between Afghanistan and Tajikistan. The Amu Darya River begins where the Kunduz River in Afghanistan and the Vakhsh River in Tajikistan join the larger Pyanj River (Figure 1). For most of its length, the Pyanj River is confined to a narrow valley (referred to here as the Upper Basin) before emerging from the high mountains and becoming less confined (referred to here as the Lower Basin). Braided channels predominate in unconfined portions of the Upper Basin with more than 200 alluvial fans of varying size located on the flanks of the valley at the mouths of tributaries (Figure 2). The river in the Upper Basin is often narrowly confined between high bedrock cliffs, older river terraces, or landslide deposits, leaving little land available for settlement or farming. Human activities in the Upper Basin are therefore concentrated at the margins of braided channels and on alluvial fans—two areas at high risk of dangerous flooding and severe erosion.



Figure 1: Pyanj River Basin of Afghanistan and Tajikistan. Source: Asian Development Bank.



Figure 2: Braided section of the Pyanj River in the Upper Basin. Source: Getinsa Ingenieria.

The Lower Basin 5. is characterized by two distinct fan-shaped depressions that are surrounded by bedrock uplands and constricted at their downstream ends (Figure 3). The Karatoy Range separates the two lowland depressions. The upstream depression is referred to as the Hamadoni Fan and the downstream depression as the Kumsangir Fan, so named for significant Tajikistan settlements in each area. The Hamadoni Fan is formed where the river first emerges from the more confined Upper Basin and is characterized by three main flow paths on the southern half of the fan, referred



Figure 3: The Lower Basin of the Pyanj River. Source: Google Earth.

to as the northern, central, and southern channels. A long embankment, first built by the Soviets in the 1930s on the upper half of the Hamadoni Fan, has blocked the river's access to the northern half of the fan for several decades. Consequently, the active flow paths have been restricted to the southern portion of the fan throughout this period. The lower Kizilsu River in Tajikistan flows along the eastern flank of the Karatoy Range from north to south on the lower Hamadoni Fan.

#### III. CHARACTERIZATION OF CHANNEL TYPES

6. Three basic channel types are present in the Pyanj River Basin and, more broadly, throughout Asia: meandering channels, braided channels, and alluvial fans (Figure 4). The variations in channel type are largely a function of channel gradient, valley confinement, and particle size. Distinct fluvial processes and channel patterns characterize the three channel types. Identifying the dominant channel pattern in a given area provides clues to the types and severity of flood hazards present and the most appropriate flood management strategies to implement. The following description of the three basic channel types is drawn from published literature and illustrated with observations from the Pyanj River Basin.



Figure 4: Comparison of meandering channels, braided channels, and alluvial fans in terms of the location and character of erosion. Source: Getinsa Ingenieria.

#### A. Meandering Channels

7. Meandering channels are sinuous single-thread channels that are typically found on low slopes and in fine-textured floodplain soils, i.e., silt and clay (Ritter et al. 2005). Because the silt and clay banks are somewhat cohesive, meandering channels tend to have a relatively low width-depth ratio compared to braided channels, which often form in less-cohesive sand and gravel sediments. Point bars composed of sand and/or gravel form on the inside of meander bends with higher velocity flows focused on the outer bends where (sometimes rapid) bank erosion occurs. Despite the channel migration that results from this deposition and erosion, meandering channels tend to retain the same dimensions through time. While portions of braided channels will simultaneously erode both banks, meandering channels tend to erode the outside bend of the channel only, with the focus of erosion remaining constant for several years at a time.

8. Meandering channels develop worldwide on rivers of all sizes, reflecting the propensity for a sinuous planform to develop on rivers where the channel is free to migrate across an unconfined floodplain (Leopold 1994). A fully meandering river can ultimately develop from a straight channel alignment as small perturbations, such as sediment input from a tributary, grow into large-scale meanders. As meanders develop, they eventually adopt a stable configuration where the meander wavelength, amplitude, corridor width, and radius of curvature remain relatively constant despite continuing meander growth and channel migration. Although the time needed to reach an equilibrium state will vary by river, the river trends toward a condition where a minimum rate of energy dissipation occurs along its length (Xu et al. 2011). As such, sharp right-angle bends along unconfined rivers do not persist, because energy expenditure along the length of the channel is focused at one point—the sharp bend. Ultimately, given the sharpness of the bend, the river adjusts through erosion and deposition to form a smooth meander where the amount of turning, and therefore energy expenditure, at any given point in the bend is equal to all other points.

9. Empirical studies of meander dimensions document several relationships that hold for rivers of all sizes, such as a value of 11 for the ratio between meander wavelength and channel width (Leopold 1994). The consistency of meandering relationships suggests meandering trends toward an ideal, or equilibrium, configuration (Garcia 2008), although the exact channel dimensions of any given meandering river will vary with valley gradient, bank materials, and other factors. This tendency can be used to identify rivers that are out of equilibrium and prone to rapid channel adjustments.

10. A common process on meandering rivers is the cutting off of meander bends and creation of oxbows (Figure 5). Cutoffs are an inherent part of meandering behavior (Hooke 2004) and help a river maintain a stable state by preventing the channel's length and sinuosity from becoming too great as would occur with uninterrupted meander growth (Camporeale et al. 2008). Two cutoff mechanisms are widely recognized: neck cutoffs and chute cutoffs (Constantine et al. 2010). Neck cutoffs occur through bank collapse when the banks of two adjacent meanders erode toward each other and eventually meet. Chute cutoffs result when a new channel carved across the inside bend of a meander becomes the dominant conveyor of river discharge. The processes of meander evolution ultimately enhance the likelihood of cutoffs developing by these two mechanisms.

11. Empirical studies of meander geometry show the radius of curvature of meander bends is generally 2.4 times the bankfull channel width (Garcia 2008), implying this is an equilibrium dimension to which meandering rivers evolve (Lagasse 2004). Numerous studies also demonstrate that the maximum bank erosion rates on meandering rivers occur in meander bends with a radius of curvature between 2 and 3 times the bankfull channel width (Begin 1981, Nanson and Hickin 1986,



Figure 5: Definition of meandering planform characteristics. Source: Getinsa Ingenieria.

Hooke 1997). Consequently, the rate of bank erosion, a process that ultimately results in neck cutoffs, increases as a meandering river approaches equilibrium condition. A similar inherent tendency in meander development also increases the probability of chute cutoffs. As channel sinuosity increases through meander growth, the corresponding decrease in channel slope leads to channel aggradations (i.e., deposition) (Knighton 1998), increasing the amount of overbank flow available to carve a chute cutoff channel across the inside of a meander bend (Thompson 2003).

12. Numerical modeling indicates channel sinuosity will increase along a meandering river until a critical sinuosity of 3.14 (pi) is reached (Stolum 1996). Once this critical value is reached or exceeded, a cluster of cutoffs, both in space and time, is likely to occur. While the idealized sinuosity value of 3.14 is rarely reached on real rivers, empirical evidence suggests clusters of cutoffs occur once a critical sinuosity value is reached (Hooke 2003).

13. Channel adjustments resulting from the decrease in channel length associated with a single cutoff tend to promote the development of additional nearby cutoffs shortly after the initial one occurs (Stolum 1996). As a result of multiple cutoffs, the channel's sinuosity will fall below the critical sinuosity and a period of meander growth will subsequently ensue, so the channel can once again approach the critical sinuosity (Hooke 2003). Consequently, meandering rivers oscillate in sinuosity, fluctuating around a critical sinuosity or equilibrium condition through alternating periods dominated by meander growth and cutoffs.

14. While intrinsic meandering dynamics control cutoffs and the formation of oxbows, the location and frequency of cutoffs is also controlled by external conditions. Vegetated floodplains are less likely to experience cutoffs because of the added floodplain resistance that slows the rate of

erosion (Constantine et al. 2010). Similarly, floodplain stratigraphy also controls cutoff development. Clay plugs resulting from the infilling of older oxbows are more resistant to erosion than the surrounding floodplain deposits, potentially reducing the rate of meander migration and frequency of cutoffs. Finer-grained sediment loads that might result from erosion of cohesive bank materials, such as clay, favor the development of meandering channels with a higher sinuosity (Schumm and Khan 1972). Channel sinuosity, and in turn the likelihood of oxbow formation, is also controlled by valley gradient, with higher sinuosities associated with lower gradients (Schumm 1979). High discharges accompanying floods often trigger cutoffs, although intrinsic meandering dynamics ultimately control the location and number of such cutoffs (Hooke 2004). Finally, human activities can alter the rate of meander migration and oxbow development. Watersheds with dams and channels that have been armored show decreased rates of channel migration, although the planform dimensions (e.g., wavelength, amplitude, and radius of curvature) may remain unchanged (Ollero 2010, Magdaleno and Fernandez-Yuste 2011).

15. Natural events (e.g., large floods) and human activities (e.g., channel straightening) can sometimes greatly alter the channel's configuration such that the river is temporarily removed from an equilibrium condition. Following the channel-altering disturbance, the river will undergo a series of adjustments that will bring the channel back into equilibrium (Petts 1994). The adjustments will initially be very rapid, but the magnitude and rate of change will decline through a relaxation period as the river once again approaches equilibrium (Figure 6). When a disturbance permanently alters watershed conditions, such as through urban development, the river will tend toward a new equilibrium condition with channel dimensions different from those associated with the earlier equilibrium state.



Figure 6: Magnitude of channel adjustments through time following a disturbance relative to an equilibrium condition.

Source: Petts, G.E. 1994. "Rivers: dynamic components of catchment ecosystems." In Calow, P. and G.E. Petts, eds. *River Handbook*. Volume 2: Oxford: Blackwell Scientific.

16. Bank erosion that accompanies meander growth is a natural part of meander evolution. Arresting erosion through bank armoring on a naturally meandering river will necessarily prevent the development or maintenance of an equilibrium channel configuration. While bank protection is unavoidable in many cases to protect significant human investments, the armoring of eroding banks leaves the channel prone to accelerated erosion in adjacent reaches as the river adjusts to a new equilibrium condition. The lateral extent of meander growth needed to develop an equilibrium condition can often be demarcated by the location of the outermost oxbows on the floodplain. Meander migration, and therefore bank erosion, must be considered possible anywhere within this so-called meander corridor, but is unlikely to move beyond the corridor unless significant watershed perturbations (e.g., climate change) occur that force a new equilibrium condition to be established with a broader meander corridor. Delineating the meander corridor is extremely useful in land use planning and erosion hazard mitigation, as human investments outside the corridor are likely to remain free of erosion hazards while erosion could threaten structures within the corridor. However, floodwater inundation is still a potential hazard outside the meander corridor, because the meander corridor generally occupies only a portion of the entire floodplain.

17. Meandering channels on the Pyanj River are restricted to the lower ends of the Hamadoni and Kumsangir fans where narrow valley constrictions lead to the development of wide meander corridors and high-amplitude meanders immediately upstream. Meander corridors tend to be much wider upstream of valley constrictions, because flood flows are unable to immediately transition from a wide floodplain to the narrow valley downstream. Consequently, floodwaters become impounded, flow is more easily deflected off of a straight course, and high-amplitude meanders are able to develop and grow at a rapid rate. The presence of oxbows in agricultural fields on the Kumsangir Fan highlights the potential for rapid meander growth to create severe erosion hazards along meandering channels (Figure 7).



Figure 7: A wide meander corridor upstream of a narrow valley constriction at the lower end of the Kumsangir Fan. Note: Dashed lines demarcate outer limits of meander corridor. Source: Google Earth.

18. Although meandering channels are not prevalent on the Pyanj River, meandering is more common on the Kunduz and Vakhsh rivers—two large tributaries that join together with the Pyanj River to form the Amu Darya River. Bank erosion associated with meander growth on these rivers has caused considerable damage to homes on the Vakhsh River in Tajikistan (Figure 8a) and irrigation canal intakes on the Kunduz River in Afghanistan (Figure 8b).



Figure 8: Bank erosion associated with meander growth. Source: Getinsa Ingenieria.

#### B. Braided Channels

Braided channels 19. are characterized by multiple channel threads that split and rejoin or interconnect with other braided channels contained within a wider braid plain (Figure 9). Mid-channel bars, primarily composed of sand and gravel, separate the various channel threads. The braided pattern develops as flood flows loaded with sand and gravel begin to lose their sediment-carrying capacity at the waning stages of floods. As sediment is deposited in the channel, the flow is split around the emerging midchannel bars, resulting in a simple braided pattern. Generally, one braid path conveys a greater portion of the



Figure 9: Braided channel in the Upper Basin of the Pyanj River. Source: Google Earth.

flow and has a deeper channel bottom, such that flow spilling out of adjacent shallower channels will preferentially flow toward the larger channel, giving rise to additional channels that cut across the mid-channel bars.

20. Meandering channel patterns sometimes form within a wide braid plain over several years of smaller flows (Kondolf and Curry 1986) due to fine sediment deposition (Osterkamp and Costa 1987) enhanced by vegetation growth on the downstream braid channels that are inundated less frequently (Friedman and Lee 2002). However, the meandering form can be quickly obliterated during subsequent high discharges and the braided pattern reestablished (Hickin and Sichingabula 1988). This transformation of channel patterns can lead to hazardous situations as long periods without a large flood will lure people to settle in portions of a still active, yet less recognizable, braid plain.

21. Like meandering channels, a fully braided pattern can become fully established from a straight, single-thread channel due to only a minor perturbation (Bernini et al. 2006) such as the local redeposition of sediment (Sambrook Smith et al. 2006). Numerical modeling indicates that the number of channels is initially high when braiding develops from a flat channel bed, but decreases over time even as the braid plain continues to widen. With the concentration of flow into a few channels, the likelihood decreases that a channel will flow along the margins of the braid plain where damage to infrastructure is most likely to occur. However, the intensity of erosion where a larger channel reaches the margins of the braid plain will be much greater than a smaller, more diffuse flow path. Hundreds of meters of bank erosion occurs annually on the Brahmaputra–Jamuna River in Bangladesh where large channels flow against the margins of the braid plain (Mosselman 2006).

22. Braided rivers of all sizes have similar appearance, suggesting braided channels evolve toward a universal equilibrium condition (Kelly 2006). One similarity between braided rivers from different regions is the channel length between the confluence point of two smaller braids and the subsequent downstream divergence of that channel into two new braids. The length of channel between these two points is approximately 5 times the channel's width regardless of river size (Hundey and Ashmore 2009). Hazard mitigation efforts that alter braid patterns in a manner inconsistent with the equilibrium tendencies of rivers will result in channel adjustments that cause damage to adjacent reaches as the river strives to reestablish equilibrium. The recognition of intrinsic equilibrium tendencies along braided rivers of all sizes also means management strategies that have proved effective along one river might be successfully applied on another river several times larger.

23. Consistency in braided channel form through time and on rivers of different size, as discussed previously, does not equate with a static position, because individual bars and braid channels are prone to rapid migration. The largest channels within a braid plain carry the most sediment during a flood and infill with sediment during the waning stages of flow (Huggenberger and Regli 2006). Abandonment of a channel segment requires only the upstream end to become blocked by a growing sand and gravel bar (Bridge and Lunt 2006). The overbank flow generated by an infilling primary channel feeds a network of secondary channels that preferentially advance toward, and eventually capture, the flow from the main channel (Figure 9). Because the amount of lateral and downstream accretion on bars during a single flood can be in the order of kilometers on large rivers (Bridge and Lunt 2006), the location of the main channel can shift hundreds, if not thousands, of meters during a single flood event. If the position of the newly formed main channel is along the margins of the braid plain, bank erosion can cause severe damage to buildings and agricultural fields (Mosselman 2006).

24. While dramatic changes in channel and bar position should be expected even on braided rivers in equilibrium, braided rivers are sensitive to changes in watershed conditions, so they rarely attain an equilibrium state. Consequently, braided channels are also prone to rapid changes in their overall dimensions (e.g., braid plain width). Braided rivers often fluctuate between a contraction phase, where the overall width of the braid plain narrows, and expansion, where the braid plain widens (Piégay et al. 2006). Incision of the channel and narrowing of the braid plain occur where

sediment supply is in decline due to upstream dams or reforestation of the upper watershed; while aggradation of the channel bed results from deforestation, active tectonic uplift, or other factors that increase sediment supply (Kondolf et al. 2002). Tectonic subsidence also enhances the expansion of a braid plain by providing a gentler valley bottom slope to accommodate sediment deposition (Gregory and Schumm 1987). Given the active tectonism and steep, denuded mountain slopes in the region, braided channels of the Pyanj River Basin and elsewhere in the Himalayas must be considered to be undergoing an expansion phase. Consequently, floodplain developments along the margins of braid plains in these areas are subject to future damage from bank erosion as the braid plains continue to widen.

25. Braided channels are ubiquitous along the Pyanj River and its tributaries. Where the valley bottom is unconfined in the Upper Basin, braid plains extend across nearly the entire valley width with only alluvial fans or very narrow floodplains present along the valley margins. While the Lower Basin is dominated by the Hamadoni and Kumsangir fans, the active channels on these fans are characterized by braided conditions along most of their length.

#### C. Alluvial Fans

26. Alluvial fans are fan-shaped landforms found at the mouths of steep, confined, narrow valleys where they spread out onto flatter, unconfined valleys. Alluvial fans were first described scientifically from the Himalayan region of Asia (Drew 1873) and have since been described from around the world in various climates and settings (Harvey et. al. 2005, Nielsen and Moore 1984). The declining slope and flow expansion on alluvial fans result in sediment deposition and allow fans to build out on the valley bottom over long periods of time. Alluvial fans of all sizes and slopes, from experimental fans to the megafans of Bangladesh and India, share many traits, such as a radial drainage pattern, a concave-upward longitudinal profile, and a convex-upward transverse shape. The similarities in morphology imply that certain controlling factors govern the development of alluvial fans (Chakraborty and Ghosh 2010).

27. River channels flowing on an alluvial fan generally occupy only a portion of the fan surface at any given time (Figure 10a), with the periodic shifting of the active channel due to sediment infilling giving rise to the characteristic fan shape. In some instances, the entire fan surface can be active during larger floods, although flow is concentrated on a small portion of the fan surface during smaller discharges (Figure 10b). The channels crossing alluvial fan surfaces in dry climates are typically braided (Cazanacli et al. 2002), as in the Pyanj River Basin, but meandering channels may be present on alluvial fans in more humid regions (Stanistreet and McCarthy 1993). Alluvial fans are considered as a separate channel type herein, because of the unique process by which the channel shifts across the fan surface. Unlike braided channels on the valley bottoms, the position of the entire braid plain on an alluvial fan is subject to rapid shifting in a process known as channel avulsion (Field 2001).



Figure 10: Alluvial fans can be inundated over (a) a small portion of the fan surface, or (b) the entire fan surface during a large flood. Source: Google Earth.

28. An avulsion on an alluvial fan begins as sediment builds up over time in the active channel due to a loss in the river's capacity to transport material across the expanding fan surface (Figure 11a). The resulting channel infilling leads to a decrease in channel depth and an increase in the amount of overbank flow escaping onto the fan surface. While this overbank flow initially spreads out across a wide area, it eventually begins to reconcentrate in natural (or man-made) depressions on the fan surface (Field 2001). Since the overbank flow is relatively free of sediment, the reconcentrated sediment-free flow can be erosive and the initially small depression in which the flow is concentrated begins to widen, deepen, and advance headward toward the source of the overbank flow-the active channel that is filling in with sediment (Figure 11b). Eventually, the growing channel erodes back to the active channel and, since the bed level of the newly formed channel is generally lower than the actively infilling channel, the majority of the flow will preferentially shift to the position of the new channel, completing the avulsion process (Figure 11c).



Figure 11: Schematic diagram of a channel avulsion on an alluvial fan. Source: Getinsa Ingenieria.

29. The entire avulsion process can occur during a single large flood or over several decades, depending on numerous factors such as the depth of the active channel, sediment supply from the upper watershed, and sequencing of different-sized floods (Field 2001). Although channel avulsions

are not unique to alluvial fans (Schumann 1989, Gay et al. 1998, Cazanacli et al. 2002), avulsions result in considerable movement of the channel position on alluvial fans. Several avulsions, each of which has caused shifts in channel position by several kilometers, have occurred during 1976–2006 on the Hamadoni Fan (Figure 12). Frequent large-scale avulsions have also occurred on other alluvial fans in Asia (Wells and Dorr 1987). Unlike braided channels on the valley bottom where erosion hazards are typically restricted to the margins of the braid plain, any portion of an active alluvial fan surface can suddenly become subject to flooding and erosion due to an avulsion. A minor change in the location of the channel at the upstream end, or head, of a fan can result in a shift of several hundred meters, if not several kilometers, further downstream.



The mapping of the historical changes in river morphology is based on land cover classification of multispectral and multitemporal satellite imagery for 1975, 1990, 2001, and 2006.

Figure 12: Changes in the position of the Pyanj River channel on the Hamadoni Fan due to avulsions. Source: Global Land Cover Facility.

30. Channel avulsions are potentially extremely hazardous, but are restricted to the active areas of alluvial fans. Large portions of alluvial fans in some regions have been isolated from active flooding and deposition for tens of thousands of years through the formation of fanhead trenches and are thus no longer at risk from avulsions or other flood hazards (Field and Pearthree, 1997). A fanhead trench is an incised channel at the head of the fan that forms when alluvial fan deposition eventually increases the surface slope to a critical threshold that results in channel downcutting (Eckis 1928, Wasson 1977, Clarke et al. 2010). Fanhead trenches confine flow and continue sediment transport past the fanhead, so the focus of sediment deposition is transferred further out into the valley and away from the mountain front. Fanhead trenches are sometimes only transient features that are backfilled in a single flood due to dramatic increases in sediment delivery from the mountains (Pack 1923, Blackwelder 1928). However, many fanhead trenches are permanent features that persist for thousands of years due to long-term reductions in sediment supply associated with climate change (Silva et al. 1992) or tectonic quiescence (Eckis 1928, Harvey 1987). Proper identification of the

extent and genesis of a fanhead trench, therefore, has important implications for understanding the potential distribution of flood and erosion hazards across a fan surface.

Fanhead trenches formed by short-term processes, such as incision at the waning stages of a 31. flood, are susceptible to infilling during a single flood, resulting in flooding of the adjacent surfaces (Beaty 1963). In contrast, flooding is unlikely on surfaces adjacent to permanent fanhead trenches, because the existing sediment and hydrological regime is insufficient to cause their backfilling or overtopping during a single large flood or even a millennia-long sequence of large floods. Permanent fanhead trenches can be distinguished from temporary ones by the character of the adjacent fan surfaces. Inactive portions of alluvial fans that have not been flooded for tens to hundreds of thousands of years have surfaces with tightly interlocking desert pavement, rock varnish formed on the surface of cobbles, severely weathered boulders, and well-formed soils-features absent from recently flooded active surfaces adjacent to temporary fanhead trenches (Field and Pearthree 1997). The depth of the fanhead trench should not be considered alone in assessing the permanence of fanhead trenches, as deposits from a single flood on alluvial fans can be several meters thick (Blissenbach 1954) and clog fanhead trenches up to 8 meters deep in a single event (Pack 1923, Blackwelder 1928). The primary controls on the existence and longevity of fanhead trenches include tectonism, climate, rock type, and other factors controlling the water and sediment discharge to the fan. In general, alluvial fans adjacent to steep mountains experiencing active uplift and capable of generating debris flows are more likely to have only temporary fanhead trenches with flooding possible across the entire fan. In contrast, alluvial fans in tectonically quiescent regions with lower sediment production and more fluvially dominated processes are more likely to have permanent fanhead trenches that restrict flooding to the lower fan (Field and Pearthree 1997).

32. Alluvial fans are often appealing areas for human settlements as the fan surfaces are elevated above the more frequently flooded valley bottoms. However, channel avulsions can cause severe damage to homes and agricultural fields far from the previously active channel. Consequently, areas that have been free of flooding, erosion, and deposition for decades or even centuries can suddenly be incorporated into an active braid plain draining a steep mountain drainage basin. In recently settled areas where no recollection exists of prior avulsions, the alluvial fans could easily be misconstrued as free of flood and erosion hazards. Given the seriousness and often poorly understood nature of avulsions, flood management plans should identify the location of alluvial fans and make contingencies for how to address rapid shifts in channel position, potentially spanning several kilometers. Assessing the permanence of fanhead trenches, and mapping the distribution of active and inactive alluvial fan surfaces are an important element of comprehensive flood hazard assessments on alluvial fans (Pelletier et al. 2005).

33. More than 200 alluvial fans, many of them with some human settlement, are found along the flanks of the Pyanj River in the Upper Basin. Most of the settlement is situated on active alluvial fan surfaces, as evidenced by the poorly developed soils and the potential for rapid sediment delivery from the tectonically active, landslide-prone mountains to infill the shallow channels during a single flood. The stark contrast between the steep mountains and flat valley bottom means the fans have not yet reached an equilibrium state when fanhead trenches are most likely to form. Consequently, the settings of nearly all of the settlements on the Upper Basin fans must be considered hazardous, even in areas that have been free of flooding for decades. In addition to the direct threats to human developments on the alluvial fans themselves, the largest alluvial fans in the Upper Basin strongly alter the morphology of the Pyanj River by growing into the river's path along the valley bottom (Figure 13). Bank erosion caused by this forced migration of the Pyanj River threatens agricultural fields, roads, and some settlements along the narrow floodplains across from and adjacent to these large fans.



Figure 13: Large alluvial fans in the Upper Basin growing into the Pyanj River's path at the bottom of the valley. Source: Google Earth.

In addition to the Upper Basin fans, the Hamadoni and Kumsangir fans represent large 34. valley-bottom fans formed in tectonic depressions downstream of confined reaches of the Pyanj River. The control fanhead trenches exert on the distribution and types of flood hazards on alluvial fans is well illustrated by comparing the Hamadoni and Kumsangir fans. Several damaging avulsions, including the collapse of Soviet embankments in 2005, have occurred at the upstream end of the Hamadoni Fan where no fanhead trench is present. Flood inundation over the entire fan, several kilometers in width, is possible because of the very low surface relief. Avulsions are most likely to occupy existing channels or depressions (Field 2001), but on the Hamadoni Fan could still lead to shifts in channel position of several kilometers. In contrast, a fanhead trench is present in the Kumsangir Fan (Figure 14), so kilometer-scale shifts in channel position have been largely restricted to the meandering lower fan (Figure 15). While individual braids shift across the braid plain within the fanhead trench on the upper fan, the position and overall width of the braid plain has changed very little in several decades. Bank erosion along the margins of the braid plain is significant, but the potential for flood inundation of the higher surface flanking the fanhead trench is remote—in stark contrast to conditions on the Hamadoni Fan. The reasons for the morphological differences in the Hamadoni and Kumsangir fans are unclear, but they may be related to a reduction in sediment supply to the Kumsangir Fan resulting from temporary landslide or tectonic damming just upstream where the river is narrowly confined by the Karatoy Range.



The mapping of the historical changes in river morphology is based on land cover classification of multispectral and multitemporal satellite imagery for 1975, 1990, 2001, and 2006.

Figure 14: The position of active channels on the Kumsangir Fan between 1975 and 2006. Source: Global Land Cover Facility.



Figure 15: A fanhead trench on the upper Kumsangir Fan has left the adjacent surface several meters above the valley bottom in places. Source: Getinsa Ingenieria.

#### D. Comparison of Processes and Hazards

35. While bank erosion and floodwater inundation are hazardous conditions present on meandering channels, braided channels, and alluvial fans, the character of these problems is different on each. Bank erosion on meandering channels is generally limited to the outside bends of meanders where erosion remains focused for several years at a time until a cutoff shifts the location of meander growth and bank erosion to an adjacent area. Large floods can cause significant bank migration, but the relatively competent' silt or clay bank material maintains the channel's dimensions such that excess discharge overtops the banks, causing extensive floodwater inundation. While inundation hazards are also present on braided channels, the greater concern is usually associated with bank erosion. The position of erosion hazards along the margins of a braid plain can change with each flood as the formation of mid-channel bars redirects flows to new areas. Erosion can occur simultaneously along both banks for long reaches of the channel, especially on braid plains in an expansion phase. The exact location of erosion is far less predictable from year to year on braided rivers as the processes governing the shifting and growth of mid-channel bars is not as well understood as meander evolution.

36. Flood and erosion hazards are least predictable on alluvial fans. Channel avulsions can shift the entire position of the channel to a new locality far from the original channel. The new channel experiences rapid incision and widening of both banks following an avulsion. Consequently, homes or other investments situated far from the channel may suddenly be threatened by bank erosion from the opposite side as the new channel widens to a dimension similar to that of the previous channel. Although careful mapping of depressions on the fan surface can be used to anticipate the potential locations of future avulsions (Field 2001), the timing and exact location of avulsions are still difficult to predict, especially in steep, denuded mountains with high sediment production rates such as in the Pyanj River Basin.

#### IV. TRADITIONAL FLOOD CONTROL APPROACHES

37. This section describes the adverse channel responses resulting from the use of traditional flood control measures in the hope that similar problems do not recur in future projects elsewhere in Asia. Channels are dynamic systems with frequently shifting positions that result in flood inundation and erosion of adjacent human investments. Several problems associated with traditional flood control approaches make their continued widespread use unviable: (i) alteration of natural channel processes, (ii) increased flooding and erosion downstream, (iii) costly project maintenance, (iv) exacerbation of hazards if projects fail, and (v) environmental degradation. These issues are illustrated by five flood and erosion control techniques that have been widely utilized in the Pyanj River Basin: embankments, bank armoring, spur deflectors, channel blocks, and channel straightening.

38. Anticipating and understanding a channel's response to flood control measures built into or adjacent to a river channel requires an appreciation of the concepts of river equilibrium. Rivers always trend toward an equilibrium condition where the rate of change and energy expenditure from one point to the next along a river is minimized. For example, a sharp right-angle bend in a river where energy expenditure is focused at the bend will slowly be transformed through bank erosion into a smooth meander where energy expenditure is distributed evenly throughout. Similar adjustments occur when rivers encounter any rapid change in flow direction, channel width, or bed slope in order

<sup>&</sup>lt;sup>1</sup> Competence in geomorphology refers to the relationship between the sizes of the particles. It is the maximum size of material that a river can transport.

to spread the changes out over a greater distance. Consequently, flood control structures in one location may initiate unintended channel adjustments in areas far from the structure. The erosion and deposition that result from a river's effort to undo the fast changes often imposed by traditional flood control measures are the driving forces behind the undermining and outflanking of the structures themselves. Projects that counter river equilibrium principles are susceptible to catastrophic damage and long-term maintenance needs. Long-term project sustainability depends on an understanding of how rivers achieve equilibrium so that projects can be designed to allow natural channel adjustments to continue as unimpeded as possible.

The dynamic nature of the Pyanj River reflects ongoing morphological adjustments to past 39. tectonism, climate change, and human activities. These external forces have been on a scale so significant relative to the river's capacity to adjust that much of the river is considered to be in a perpetual state of disequilibrium, since thousands, if not millions of years will be necessary to achieve equilibrium in the tectonically active region. Therefore, the erosion and rapid shifts in channel position that threaten to undermine, outflank, and otherwise damage past flood control measures must be viewed as ongoing processes that will continue far beyond the design life of any engineering project. While avoiding areas of active channel adjustment might not be possible in all instances, flood control projects will be more sustainable if implemented in a way that allows the ongoing morphological adjustments to continue unimpeded. Projects that impose fast changes on the river channel will set in motion a series of adjustments to counter the imposed change, particularly in areas that are already in a state of disequilibrium. Flood management plans should bear in mind the principles of river equilibrium and prioritize projects that minimize rapid changes in planform, slope, width, and bank or bed composition. Past flood control measures on the Pyanj River have done a poor job in this regard and, as described in this section, have performed poorly as a result.

#### A. Embankments

40. Embankments (also known as levees, dikes, bunds, or berms) are linear ridges of earthen material typically constructed with local riverbed and floodplain sediments. The purpose of embankments is to prevent flow from accessing side channels or spilling out onto the adjacent flood-prone surface (be it a floodplain or alluvial fan), thus protecting vast areas of arable and developable land. In mountainous countries, such as Tajikistan, there is a great deal of pressure to settle and farm in flood-prone areas, so embankments are often used as a flood control technique. Embankments in the Pyanj River Basin are found on the river's mainstream (Figure 16a) and on alluvial fans at the terminus of smaller tributaries (Figure 16b). The longest and largest embankment is on the Hamadoni Fan. This embankment, first built during Soviet times in the 1930s, blocks access to nearly half of the fan area (including two former channels) and allowed the development of an extensive irrigation system and associated villages on the northern half of the fan (Figure 17). The river has been restricted to the unprotected areas to the south for more than 70 years with no major avulsion of the channel persisting north of the embankment since its construction.



Figure 16: Embankments in the Pyanj River Basin found on (a) the mainstream, and (b) alluvial fans at the terminus of smaller tributaries. Source: Getinsa Ingenieria.



Figure 17: Satellite imagery of the Hamadoni Fan showing location of two overflow channels (arrows).

Note: Position of Soviet-era embankments (shown in red) and embankment rebuilt after 2005 (shown in orange and with dashes where still incomplete in 2010). Portions of irrigated areas protected by embankment can be seen at the top of the image. Source: Getinsa Ingenieria.

41. Natural channels migrate laterally, occupying over time a zone greater than the width of the channel itself (i.e., the meander corridor, braid plain, and alluvial fan surface). In the Pyanj River Basin, embankments are built along the channel margins or even within the channel, constraining the natural migration of the channel (Figure 18). As a consequence, embankments in the Pyanj River Basin, and more broadly throughout Asia, are prone to failure and require frequent, sometimes emergency, maintenance (Figure 19). Embankments in the Pyanj River Basin and elsewhere in Asia are often breached in one of three ways: seepage and piping, overtopping by high water, or scour and undermining. The sandy river materials in the Pyanj River Basin, as in other areas of Asia, allow flow to pass under or through embankments constructed with such permeable sediments. High flows create a hydraulic pressure differential between the river and the backside of the embankment,

allowing flows to more readily pass under or through the flood control structure. The problem is particularly acute in lower-gradient areas where prolonged high flows lead to saturation and weakening of the embankment materials. However, seepage or piping can also occur in highergradient settings, such as the Pyanj River (Figure 20a). By confining flows, embankments increase flow velocities in the channel itself, which in turn enhances scour, undermining, and potentially embankment collapse (Piégay et al. 2006). Embankment undermining is a problem in the Pyanj River Basin and elsewhere in Asia (Figure 20b).



Figure 18: The embankment on the Hamadoni Fan, as shown by the global positioning system track (hard line), was built into an active channel and has cut off several meanders. Source: Google Earth.



Figure 19: Breach in an embankment in the Pyanj River Upper Basin. Source: Getinsa Ingenieria.



Figure 20: Potential modes of embankment collapse: (a) seepage and piping as on the Hamadoni Fan during the 2010 flood (arrow shows seepage flow in old channel north of embankment), and (b) scour and undermining as in the Pyanj River Upper Basin. Note: Overtopping is not illustrated. Sources: (a) Google Earth; (b) Getinsa Ingenieria.

Embankments are generally constructed to withstand floods much smaller than the 100-year 42. flood. In India, for example, embankments in agricultural areas are designed to protect against a 25-year flood, where as those in urban areas are designed to protect against a 50-year flood. Consequently, embankments can be overtopped during large floods with the flows capable of quickly eroding through an embankment's steep backside, resulting in a breach. The risk of overtopping increases in sediment-laden rivers, especially alluvial fans, where years of sediment accumulation can raise the channel bottom higher than the areas protected behind the embankments. On the Fraser River in British Columbia, Canada, in a setting similar to the Hamadoni Fan, embankments have concentrated coarse sediment deposition in the main channel (Church and McLean 1994). The accumulation of sediments over time increases the risk of more catastrophic flooding. On the Hamadoni Fan, where an embankment has been in place for 70 years, portions of the northern protected areas are several meters lower than the active fan to the south. In addition, traditional embankments typically fail at one spot. This allows flood flows to break through at concentrated areas with greater force and velocity, thus creating life-threatening hazards. Under natural conditions, inundation typically causes only property and crop damage, because flow can overtop the banks simultaneously everywhere and spread out at low velocity over the wide floodplain.

Embankments can also impact adjacent 43. areas that remain unprotected by flood control structures. Evidence for such interactions is present on the Hamadoni Fan. Embankment reconstruction along the northern channel caused significant morphological impacts on the adjacent central channel, because long, temporary spurs were built during construction to divert flows away from the northern channel. In direct response to these actions, the southern bank of the central channel receded almost 1,000 meters during 2006-2010, corresponding with the time of embankment reconstruction (Figure 21). The continuing channel adjustments resulting from the embankment reconstruction on the northern channel are also responsible for eroding croplands (Figure 22a) and undermining bridge abutments on the central channel (Figure 22b). In contrast, the large 2005 flood, which breached the embankment and reactivated old channels north of the embankment, caused no significant damage along the central channel despite the record discharge. Therefore, the dramatic changes since that time must be related to reconstruction of the embankment and concentration of flow into the central channel.

disruption of 44. The natural river resulting from embankment processes construction has negative consequences for ecosystem function. Critical side-channel habitat is cut off, nutrient-rich sediments and overbank flows to support riparian vegetation cannot spread across the floodplain, and higher velocities in the main channel tend to homogenize habitats and provide little refuge for aquatic organisms during flood flows (Piégay et al. 2006). Channel areas cut off by the embankments also suffer environmental degradation as wetland habitats sustained by periodic flooding from the river suffer from the loss of connection to the channel.



Figure 21: Satellite images of the Hamadoni Fan through time, showing recession of the southern bank of the central channel caused by embankment reconstruction: (a) 30 April 2005, (b) 22 July 2006, (c) 6 July 2009, and (d) 1 July 2010.

Note: The black star is in the same location on each image.

Source: Google Earth.



Figure 22: Effects of embankments on adjacent areas include bank erosion that threatens (a) croplands, and (b) other investments such as bridges. Source: Getinsa Ingenieria.

#### B. Bank Armoring

45. Bank armoring involves the lining of a riverbank with hard materials that will resist the forces of erosion acting on the bank (Figure 23a). Concrete blocks, large boulders, or gabion baskets are the materials most frequently used to arrest bank erosion and protect agricultural fields and human infrastructure. Armoring is also commonly used on embankments to prevent the scouring and undermining that lead to structure collapse (Figure 23b). Bank hardening causes increased local scour that can sometimes "attract" the river to the protected area by scouring a deeper channel to which the main flow path migrates (Mosselman 2006). Four reasons have been identified for deeper scour along armored banks: (i) loss of sediment supply from the once-eroding bank; (ii) channel narrowing and concentration of flow as a point bar on the opposite bank grows toward the armored bank; (iii) local scour effects caused by flow deflection into the channel bed; and (iv) bend deformation, leading to greater energy expenditure due to local prevention of channel migration (Mosselman 2006). As a result of these factors, the greatest scour along the river can occur in the least desirable location—along the



Figure 23: Armoring of (a) river banks with gabion baskets, and (b) embankments with concrete blocks, in the Pyanj River Basin. Note: Large boulders are used for armoring elsewhere in the Pyanj River Basin.

Source: Getinsa Ingenieria.

protected bank or embankment. The undermining of armored embankments is common in the Pyanj River Basin, as elsewhere in Asia, and has been identified as one of the primary mechanisms for the failure of bank-armoring efforts (Fischenich 2003) (Figures 20b and 24). Launching aprons can increase the depth of scour protection where it is not feasible to excavate to an adequate depth to provide the necessary scour protection (Maynord and White 1995, 47).



Figure 24: Undermining of concrete blocks armoring the embankment on the Hamadoni Fan has caused their collapse into a scour hole. Source: Getinsa Ingenieria.

46. Bank armoring in the Pyanj River, as elsewhere, is often done in a piecemeal fashion with protection placed only on the outside bend of a meander or where bank erosion is occurring along an active braid channel on the margins of the braid plain. An immediate insistence on armoring an eroding bank, even when the nearest infrastructure is still tens or hundreds of meters from the bank, may be unwarranted if such structures are outside the meander corridor or braid plain, because the channel is likely to shift the focus of erosion to a new area before any damage occurs. The armoring of only a portion of a riverbank can lead to increased erosion in unprotected downstream areas. Bank erosion reflects a river's capacity to entrain additional sediment. When a portion of a riverbank is armored, the river will ultimately entrain the additional sediment elsewhere, whether derived through additional bed scour at the base of the armored bank or from bank erosion further downstream.

47. Attempting to avoid the downstream consequences of bank armoring by extending bank protection over long, continuous lengths of riverbank further hinders natural channel processes and exacerbates the potential severity of the existing erosion hazards. If the bank armoring fails at a specific point, the severity of bank erosion will be much greater than if the bank had remained unprotected, because the river will focus its capacity for sediment entrainment at the single point of failure rather than evenly over a long length of unprotected bank. The result is potentially rapid and aggressive erosion that can threaten lives and property in areas that are meant to be protected by the bank armoring. Along long, continuous lengths of protected bank, the exact location of failure cannot be predicted, and therefore

the site of severe erosion is difficult to anticipate and ample warnings cannot be provided in time. The embankment on the Hamadoni Fan is armored along its more than 20-kilometer length. During a flood in 2010, emergency maintenance was needed to close an emerging breach caused by aggressive erosion where a small portion of the embankment was undermined. Leaving the embankment unarmored is not an option in its current location, but the incident provides evidence of how lengthy sections of armored riverbanks (or embankments) invariably require costly maintenance expenditures. Failure of such structures would cause more severe flooding and erosion than would occur under natural conditions where erosion would be more evenly spread along the length of the bank.

#### C. Spur Deflectors

48. Flow deflection spurs in the Pyanj River Basin are generally narrow linear structures extending from the bank out into the river channel, and composed of gabion baskets and concrete blocks. By redirecting flow away from the bank, a series of multiple spurs can be used to protect an eroding bank (Figure 25a), and can also be incorporated into embankments to prevent scour and undermining of those structures (Figure 25b). If working properly, spurs reduce the velocity of flow near the bank and facilitate sediment deposition between the spurs. Scour at the tips of the spurs helps to shift the thalweg (line following the lowest part of a valley) away from the bank and out to the ends of the spurs. In some cases, as in Figure 25b, concrete blocks armor the tips of spurs, which are built primarily with earthen materials.



Figure 25: Flow deflection spurs in the Pyanj River Basin are built using (a) gabion baskets in Afghanistan, and (b) concrete blocks in Tajikistan. In some cases, as in (b), the concrete blocks armor the tips of spurs built primarily with earthen materials. Source: Getinsa Ingenieria.

49. Other names used for flow-deflection spurs include groins, vanes, deflectors, and bendway weirs. The terms are essentially interchangeable, but, beyond terminology, the critical factors when designing spurs are their orientation, height, and spacing (as spurs are rarely used in isolation). Attracting spurs are angled downstream and must be constructed to a sufficient height to capture (or attract) all flows within the channel, including flood flows, and push water away from the bank (Figure 26a), while repelling spurs are built much lower and angled upstream in order to turn (or repel) water away from the bank (Figure 26b). Floods that overtop repelling spurs flow off the structure perpendicular to its orientation. In the Pyanj River Basin, the spurs have almost exclusively been angled downstream and are intended to function as attracting spurs.



Figure 26: Spurs can be oriented (a) downstream as attracting spurs, or (b) upstream as repelling spurs. Source: Getinsa Ingenieria.

50. Spurs in the Kunduz and Pyanj river basins have suffered severe damage at many locations. The undermining of spurs is a persistent problem that occurs nearly everywhere they are used and often begins during the first large flood after construction (Figure 27). The causes of undermining are similar to those described for bank armoring. Spurs on the Hamadoni Fan embankment are keyed in below the channel bed by up to 4 meters, but most spurs elsewhere in the basin are keyed in by less than 2 meters, largely due to the limited technical capacity of the construction equipment. In comparison, predicted scour depths estimated from hydraulic modeling exceed 6 meters on the Hamadoni Fan (Japan International Cooperation Agency 2007). The actual depth of scour is likely to be even greater near the spurs themselves, because of flow concentration and local scour near hard

armored surfaces. Scour occurs both on the upstream ends of attracting spurs, where flow is partially directed downward into the channel bed, and at the tips of the spurs where the deflected flow is concentrated. Often, after high flows recede, a continuous scour hole is seen that extends from the upstream face of the spur and wraps around its tip. Spurs should not extend across more than onethird of the channel's low-flow wetted width in order to reduce flow concentration, limit scour at the spur tips, and avoid deflecting flow into the opposite bank.



Figure 27: Scour and undermining on a spur on the Hamadoni Fan embankment has caused collapse of concrete armoring blocks. Source: Getinsa Ingenieria.

51. Although the purpose of spurs is to arrest bank erosion, their spacing, height, and orientation must all be correct or the erosion can be made worse. Flow redirected off the tip of an attracting spur will not maintain that flow line indefinitely and a portion of the flow will, after a short distance, return toward the bank. A series of spurs must be spaced close enough together such that the next downstream spur intercepts the return flow before it impinges on the eroding bank. A series of spurs

should maintain a low-velocity zone near the bank and promote deposition. Depending on site conditions, such as the curvature of a meander bend, spurs should be spaced from 1 to 5 times the distance that they protrude into the channel (Fischenich 2003). For example, a spacing of 10–50 meters should be used for a series of spurs that extend 10 meters into the channel, with closer spacing recommended on tighter river bends. Because individual spurs should not extend into the channel more than one-third of the channel width, increasing the length of the spurs unreasonably cannot reduce the number of spurs needed in a project.

52. The height and orientation of the spurs are also important design considerations. Attracting spurs must be built to at least the floodplain height, because if flows within the channel overtop a low spur angled downstream then flow will be redirected into the bank and will aggravate the erosion (Figure 28a). Flows higher than the floodplain level spread out over a wide area, so the overtopping of attracting spurs at this height will redirect low-velocity flows over the bank but not directly into it. Another potential problem with attracting spurs results from the long-term settling of spurs due to undermining. In the Kunduz River Basin, 40-year-old spurs remain just slightly above the current bed level after years of undermining and collapse (Figure 28b). Although these attracting spurs may have originally been built to a proper height, flows now crossing the structures are redirected toward the bank and, as a result, may be contributing to bank erosion downstream.



Figure 28: Spurs angled downstream that are too low can aggravate bank erosion when overtopped whether they (a) were originally constructed too low, or (b) become lower due to settling.

Source: Getinsa Ingenieria.

53. Flow deflection spurs are also susceptible to outflanking. The spurs are generally constructed flush against the bank but are not keyed back into the bank (Figure 25a), so continued recession of the bank could eventually erode around the spur. The problem is likely to be most acute at the spur farthest upstream, since downstream spurs will presumably have some level of protection from upstream spurs. Typically, spurs should be keyed into the bank by excavating and later backfilling a trench at least half of the length that they protrude into the channel, such that a spur protruding 10 meters into the channel should also extend 5 meters back into the bank. Situating the first spur upstream of active bank erosion can greatly reduce the risk of spur outflanking. Outflanking of downstream spurs is less likely as the expected deposition between the spurs will prevent further bank erosion around the structures.

#### D. Channel Blocks

54. Channels that form along the margins of a wide braid plain can erode agricultural fields and buildings along the banks. In the Pyanj River Basin, gabion, earthen, and sandbag walls have been constructed across the upstream ends of at least four braid channels to prevent flows from entering the channel and eroding the banks (Figure 29a). By preventing flow from entering the channels, the channel dries out and the banks stabilize in the absence of erosive flows. Channel blocks are similar to embankments, but are generally shorter as they run across the opening of a channel rather than along its length. To be effective, the channel blocks must extend from the floodplain, or other higher surface, on one side of the channel to the other side of the channel.

Channel blocks generally impede only a small percentage of flow, since the blocked channels 55. represent only a small number of the numerous braid paths through which flood flows pass. However, the flow diverted by the channel blocks increases in adjacent unobstructed channels where erosion can be initiated or exacerbated. Flow diverted by the wall shown in Figure 29a directly entered another channel that approaches the opposite margins of the braid plain at a meander 3.3 kilometers downstream (Figure 29b). At least 50 meters of bank erosion occurred on this meander bend in the 2 years following wall construction, and this has resulted in the border road being washed away. Given that no erosion had occurred in the previous 5 years, including during the large 2005 flood, the wall, despite its distance from the site, is the likely trigger for the bank erosion. This example shows how this flood control technique can potentially exacerbate erosion in areas several kilometers downstream. Attempts to close off the upstream end of channels on the Brahmaputra-Jamuna River in Bangladesh merely transferred openings to the channel further downstream (Mosselman 2006), demonstrating that channel blocks are sometimes ineffective at reducing hazards in the areas they are meant to protect. The potential for similar cause-and-effect relationships with other channel blocks is high and demonstrates the need for a comprehensive approach to managing erosion that considers the potential impacts of a proposed project before it is implemented.



Figure 29: Walls (a) built across the upstream end of braid channels prevent erosive flows from entering the channel (note the collapse of the gabion wall), but (b) can transfer flow to other channels where bank erosion accelerates.

Note: The red line is the gabion wall shown in (a) and the pin marker is the site of accelerated erosion after the wall was built.

Sources: (a) Getinsa Ingenieria; (b) Google Earth.

56. Another consideration in site prioritization is the potential sustainability of the proposed structures. Like embankments, channel blocks constrain the river's natural processes, and therefore are prone to undermining and outflanking. The presence of a wall may "attract" the river, because local scour along the wall may deepen the channel sufficiently to shift most of the flow to the base of the structure (Mosselman 2006). Consequently, a wall originally built in a secondary channel with a bed level higher than the main flow path may, over time, come under attack from the lower main flow path and be undermined by scour. Such a process can be seen in the Pyanj River Basin where channel blocks have experienced undermining. These structures will not continue to function as intended without costly maintenance.

#### E. Channel Straightening

Another common flood and erosion control 57. method used in the Pyanj River Basin and elsewhere in Asia is channel straightening, whereby meanders are artificially cut off to shorten the river's length. Channel straightening in the Pyanj River Basin has occurred on the Kizilsu River, the lower Kumsangir Fan, and many alluvial fans in the Upper Basin. When a channel is artificially straightened, its length is decreased and its gradient, consequently, is increased. Since flow velocities are faster on a steeper slope, a river's stage<sup>2</sup> will initially be less for the same discharge along a straightened channel relative to the longer meandering configuration. The decrease in stage may be sufficient to contain a given flood within the channel that might previously have inundated a wide floodplain, therefore straightening has been widely used as a flood control technique in the past (Bridge and Demicco 2008). Many of the tributaries in the Upper Basin are straightened where they cross alluvial fans, and are often accompanied by embankments to prevent flow and sediment from spreading across the alluvial fan surface.

58. Channel straightening is also used to alleviate bank erosion by cutting off meanders so erosive forces are no longer focused on the outside of meander bends. Erosion on the outside bend of a meander on the lower Kumsangir Fan ended when a trench was cut across the inside of the bend between July 2001 (Figure 30a) and April 2005 (Figure 30b). The trench immediately diverted a portion of the river's flow. It was then widened and captured during the 2005 flood



Figure 30: Erosion on the outside bend of a meander on the lower Kumsangir Fan was halted after a trench was cut across the inside bend of a meander to straighten the channel. Source: Getinsa Ingenieria.

<sup>&</sup>lt;sup>2</sup> A river stage is the water level at certain points, usually with the zero height being near the river bed.

(Figure 30c), and now conveys most of the river's flow with the meander largely abandoned (Figure 30d). Almost the entire length of the channel on the lower Kumsangir Fan has been straightened since 1959 in a similar piecemeal fashion (Figure 31). Anecdotal reports indicate that at least some of the straightening is the result of local residents digging hand-dug trenches across the inside bends of the meanders. The river enlarges these trenches and abandons the meanders during subsequent floods. While meander cutoffs and the creation of oxbows also occur naturally, the cutting off of multiple meanders on the lower Kumsangir Fan and sharp decrease in overall channel length since 1959 is a strong indication of human intervention. Under natural conditions, the overall sinuosity over several meanders remains the same over time because the loss of channel length at one cutoff is offset by the growth of other nearby meanders (Hooke 2003).



Figure 31: The Pyanj River on the lower Kumsangir Fan straightened over time by cutting off individual meanders. Source: Google Earth.

59. The Kizilsu River provides an example of more extensive and concerted straightening. The channel was completely realigned against the eastern edge of the Karatoy Range to maximize agricultural lands on the lower Hamadoni Fan. Numerous abandoned oxbows remain in the agricultural fields and represent vestiges of the previous meandering planform of the river (Figure 32).



Figure 32: Abandoned oxbows are an indication of the former meander corridor on the Kizilsu River before straightening. Note: New meanders reforming along straightened channel are of much lower amplitude. Source: Google Earth.

60. While short-term flood control benefits may accrue locally, channel straightening engenders a series of channel responses that ultimately exacerbate flooding and erosion problems. The steeper gradient associated with straightening increases the river's sediment carrying capacity, leading to a period of channel incision and widening that can begin almost immediately. The increase in gradient at the site of straightening represents a fast change in bed slope compared with the upstream and downstream reaches. As a result, the channel incision can migrate far upstream as the river attempts to minimize the change in slope at any one point (Zawiejska and Wyżga 2010). Channel adjustments in response to straightening also impact downstream areas where the excess sediment from the incision and widening is deposited, exacerbating flooding and erosion in these areas (Brookes 1985, Rhoads 1990).



Figure 33: Severe bank erosion at Qadam Jai, Afghanistan. Source: Getinsa Ingenieria.

A straightened channel configuration 61. is not an equilibrium channel form and will not persist in unconfined settings where channel migration is not constrained by higher valley sides (Leopold 2004), especially where a downstream valley constriction enhances meander formation. As a consequence, meanders invariably reform after a channel is straightened. The reformation of meanders on artificially straightened channels has been documented elsewhere in the world (Field 2007, Ollero 2010), as well as in the Pyanj River Basin, and is likely to have occurred on straightened rivers throughout Asia. The straightening of the meander that was cut off between 2001 and 2005 on the Kumsangir Fan

has led to the growth of a small meander at the sharp bend created where the straightened segment reenters the original channel (Figure 30d). While not yet problematic, continued growth of this new

meander may ultimately impact agricultural fields and villages that were meant to be protected by the straightening. Elsewhere on the lower Kumsangir Fan, severe and rapid bank erosion at Qadam Jai, Afghanistan, is occurring along a growing meander bend located at the upstream end of a previously straightened reach (Figure 33) and provides further evidence of meander reformation in areas adjacent to past channel straightening.

62. On the Kizilsu River where straightening occurred decades earlier, the reformation of meanders has progressed further and is more extensive than on the lower Kumsangir Fan. Despite the reformation of numerous meanders, the amplitude of the meanders is much less than it was before straightening, so the river has yet to fully reoccupy the historical meander corridor as can be seen from active erosion on the outer banks of the meanders (Figure 34). Therefore, the meander



Figure 34: Satellite images from (a) 1975, and (b) 2009 showing the reformation of meanders along straightened reaches of the Kizilsu River. Source: Getinsa Ingenieria.

reformation process is just beginning and will continue, if unchecked, until the original sinuosity with higher amplitude meanders is reestablished. Agricultural fields and small villages developed within the former meander corridors on the Kizilsu River and lower Kumsangir Fan must be considered susceptible to erosion given a river's propensity to reestablish its original equilibrium sinuosity. When viewed over the long term, channel straightening ultimately exacerbates erosion and leads to increased flooding and erosion elsewhere (Brookes 1985, Rhoads 1990).

#### V. CORRIDOR PROTECTION

63. Combating severe flooding and bank erosion in the Pyanj River Basin will result in frequent maintenance needs unless a more comprehensive flood and erosion management plan is developed that recognizes the limitations and negative consequences of traditional flood control approaches. Given the limited long-term success of traditional flood control techniques in the Pyanj River Basin, a number of alternative approaches have been recommended that are (i) less disruptive to natural channel processes, (ii) more sustainable, (iii) capable of reducing the most dangerous flood and erosion risks, and (iv) less harmful to the environment. Considering their potential value elsewhere in Asia where problems with traditional flood control approaches have also been experienced, four alternative approaches are detailed in this section: (i) setback embankments, (ii) overtopping embankments, (iii) bank protection alternatives, and (iv) attenuation zones. These management options are collectively referred to as "corridor protection."

64. While basin-wide flood management efforts should consider other structural measures (e.g., dams) and nonstructural interventions (e.g., sediment management through reforestation), the focus here is only on alternatives that can be implemented within the river's meander corridor (or braid plain or alluvial fan surface). Piégay et al. (2006) discuss numerous strategies for watershed-wide protection used in Asia and worldwide that reduce downstream flooding and erosion over several decades. Limiting sediment supply from steep, mountainous watersheds will be a critical component of any program aiming to reduce bank erosion along the dynamic and frequently shifting valleybottom rivers of Asia. Targeted efforts to control sediment production can be achieved through detailed geomorphic mapping that identifies active landslides and other areas where high sediment loads are derived (Sarker and Thorne 2006). However, actions taken within the river corridor have a more immediate effect on the proximal channel conditions and a generally greater role, at least in the short term, in reducing flood and erosion hazards. Furthermore, given the social and political pressures at the local, national, and international level that will likely dictate that engineered structures continue to be built adjacent to flood-prone areas, most of the corridor protection methods described in this section represent only adjustments to traditional structural approaches that are intended to increase their sustainability and minimize adverse impacts.

#### A. Setback Embankments

65. In general, options that reduce or minimize encroachment on the river have a greater likelihood of success than those that constrict the river channel. In unconfined settings, a river naturally has access to a floodplain, braid plain, or alluvial fan surface over which flood flows can spread, reducing flow velocities and supporting a complex ecosystem dependent on periodic inundation of overflow channels (Figure 35a). In the past, embankments have been built that encroach on the river and completely block access to the floodplain, overflow channels, and meanders (Figures 18 and 35b). Traditional embankments, as well as the alternatives discussed in this section, are often built on both sides of a river, but are shown on only one side of the river in Figure 35 for simplicity. Traditional embankments encourage the development of agricultural fields and

settlements in areas that were only recently occupied by the river, and therefore such embankments increase the risk of life-threatening floods if the structures are breached. Vestiges of old meanders amid agricultural fields on the Kumsangir Fan are the only evidence remaining that the river recently occupied this low area now protected by poorly constructed earthen embankments in Afghanistan (Figure 36). By constricting the channel, the more erosive flows put the embankments at greater risk of undermining and collapse (Figures 20b and 24). Embankments that encroach on the river can also create higher flood stages for the same discharge, so are also prone to overtopping.

Figure 35: Schematic sketches of a channel (a) under natural conditions with no embankment, (b) with a traditional embankment encroaching on the river, (c) with an overtopping embankment allowing high flows to pass through overflow channels, and (d) with a setback embankment giving the river greater access to overflow channels and the floodplain. Source: Getinsa Ingenieria.





Figure 36: Vestiges of old meanders (arrows) amid agricultural fields and villages indicate this low area protected by poorly constructed earthen embankments was recently part of the active river channel on the Kumsangir Fan. Source: Google Earth.

66. To reduce hazards and alleviate other problems associated with traditional embankments, new embankments, where feasible, should be set back from the banks of the river to allow the river access to overflow channels and a portion of the floodplain (Figure 35d). Ideally, setback embankments should be built beyond the margins of the meander corridor or braid plain, so as to reduce conflicts with natural channel processes and reduce the risk of undermining and collapse. However, extensive setbacks to the edge of the corridor are impractical given the potential lost economic benefits in areas no longer protected by an embankment. The greater the distance an embankment is set back from the riverbanks the less likely it is that the embankment will exacerbate flood hazards or transfer those hazards elsewhere.

For any given discharge, 67. embankments that are set back from the river will decrease the river's stage and flow velocity, thereby reducing the chances of undermining and overtopping. Preliminary hydraulic modeling of the Hamadoni Fan demonstrates that a setback embankment following the edge of an overflow channel north of the northern channel (highlighted by the arrow in Figure 20a) can decrease the flood stage by 0.4 meters and flow velocities by 0.12 meters per second for a discharge comparable to the 2005 flood (Figure 37). While the reductions do not initially seem significant, the river stage for the modeled discharge of 5,000 cubic meters per second was close to the



Figure 37: Simplified cross section of the Hamadoni Fan used in HEC-RAS hydraulic model to compare river stage for a 5,000 cubic meters per second flood contained by the existing embankment and setback embankment. Source: Getinsa Ingenieria.

embankment crest in 2005, so the minor reduction in stage resulting from the setback embankment would greatly reduce the risk of embankment overtopping. Similarly, undermining necessitated emergency repairs to the embankment during the 2010 flood, but the scour at the base of the structure would have been greatly reduced by the slight decreases in flow velocity realized with a setback embankment.

68. Ecological benefits would also be achieved with a setback embankment as increased access to the currently cut off side channel would provide unique animal habitats, such as gravel bars for avian resting, or in-channel rearing and spawning areas for fish species (Piégay et al. 2006). Given that the proposed setback alignment would only increase flows to the overflow channel, no impacts to agricultural lands, roads, or buildings would result. Greater reductions in flow stage and velocities could be realized by setting back the embankment even further, but difficult trade-offs would have to be made as significant human investments would be impacted. In recognition of the flood loss reductions and ecological benefits that can be realized by removing or setting back berms, such restoration measures are being implemented in Austria, France, New Zealand, and elsewhere. Swiss law now requires river activities to respect or restore the natural pattern of the river (Piégay et al. 2006).

69. Unfortunately, setback embankments are difficult to construct in many areas, because agricultural fields and settlements are already developed up to the edge of the riverbank. In some

instances, agriculture can continue in the area between the riverbank and the setback embankment if the increased risks of flooding are acceptable or if crops can be grown in seasons where the risk of flooding is low. Where new embankments are contemplated, priority should be placed on constructing setback embankments. While existing land uses will present challenges to implementing setback embankments, flood management plans should identify areas where setback embankments are currently feasible and outline steps that should be taken to ensure future activities do not preclude their construction.

#### B. Overtopping Embankments

70. Where space is not available for setback embankments, overtopping embankments provide another alternative to minimize many of the negative impacts of traditional embankment designs. Overtopping embankments are constructed with one or more notches on the top of the structure to allow high flows to pass over it with less risk of catastrophic breaching (Figure 35c). The notches and the backside of the embankment where water passes over the structure can be armored to prevent a breach. Embankments of all types should ideally be constructed with a gentler backside, so flow velocities can be kept below a threshold level that will initiate erosion through the embankment's earthen material. However, construction of a gentler backside requires more space and may not be feasible in many locations. If space is limited, the gentler backside could be constructed only near the notches in an overtopping embankment, where flow is most likely to pass over the structure, rather than along the embankment's entire length.

71. The notches in overtopping embankments can be carefully positioned to ensure overflow is directed into natural side channels or constructed flood diversion channels. In this manner, flows overtopping the embankments can be controlled, and inundation of agricultural fields and villages minimized. Recent upgrades to embankments on the Waipaoa River in New Zealand incorporated diversion cuts to reduce the amount of flow contained by the flood control structures (Piégay et al. 2006). Maintaining periodic flow in natural side channels has the added ecological benefit of improving critical side-channel habitats. The location where traditional embankments will be overtopped is less predictable and can lead to catastrophic breaches at, potentially, the least desirable locations where the most lives and property are at risk. By purposefully directing overflows to side channels and flood diversion structures, overtopping embankments reduce the risk to the most valuable assets and to the structure itself while minimizing damage to the environment.

72. Despite their many advantages, overtopping embankments built directly on the riverbank still constrain channel migration and will, therefore, be subject to erosion, undermining, and collapse. Consequently, overtopping elements are best incorporated into setback embankments, so the advantages of both alternative embankment designs are realized. Although the alternative embankment designs often require sacrificing valuable agricultural lands, they are more economically beneficial over the long term given the lower maintenance costs and reduced risk of catastrophic damage during the largest floods. When also accounting for the reduced threats to human life, minimal impact to adjacent areas, and limited damage to the environment, the use of setback and overtopping embankments must be given high priority in the development of flood management plans.

#### C. Bank Protection Alternatives

73. Since setback and overtopping embankments are largely designed to prevent flood inundation, alternative methods of constructing spurs and armoring banks are needed to protect critical assets from bank erosion while reducing many of the problems associated with the traditional

bank protection methods. Using repelling spurs that are angled upstream instead of attracting spurs (Figure 26) can greatly reduce the amount of scour around the structures and are, therefore, more sustainable, because floods of all sizes pass over them. In contrast, attracting spurs must withstand the full force of even the largest floods. Another potential advantage of repelling spurs is that they can remain effective even if they settle slightly, because they will continue to direct flows away from the bank. In contrast, attracting spurs can end up turning erosive flows toward an unstable bank if they settle enough to be overtopped.

74. The height, length, and spacing of repelling spurs are important design considerations. Repelling spurs are most effective if they are built no higher than one-third of the height of the adjacent floodplain and protrude beyond the bank less than one-third of the channel width. To avoid being outflanked by continuing bank erosion, the spurs should also be keyed into the bank at least half of the distance they protrude into the channel. This is especially important for the spur farthest upstream, since the first spur will not benefit from the protection of upstream spurs. For the same reason, the spur farthest upstream should be positioned upstream of the eroding bank being protected so the likelihood of outflanking by bank erosion is reduced. The spacing of the spurs will vary based on the curvature of the bank being protected, with closer spacing recommended for tighter meander bends. In general, though, repelling spurs, as with attracting spurs, should be spaced 1–5 times the distance that the spurs protrude into the channel (Fischenich 2003). The amount of scour can be reduced and the success of spurs greatly improved if their spacing, length, and orientation are carefully considered (Kinzli and Thornton 2010).

75. Traditional approaches to the armoring of riverbanks (and spurs) with gabion baskets and rectangular concrete blocks have not always been successful in the Pyanj River Basin (Figures 24 and 27). Alternative materials for armoring include various shapes of concrete dolos. Dolos blocks have been more commonly used in the past in coastal settings but have also been used as bank armoring (Figure 38a) and spurs (Figure 38b) in riverine environments. The units are able to interlock and therefore act together as a combined entity able to withstand greater forces than individual boulders or blocks. Their added roughness reduces flow velocity, promotes deposition at the base of an eroding bank, and provides important habitat-improving flow complexities. Dolos blocks are equivalent to pyramids in their purpose of promoting deposition, but are designed for high-velocity



Figure 38: Dolos blocks of different shapes as (a) bank armoring (Taipei, China), and (b) repelling spurs (Washington State, United States) in riverine environments. Source: Getinsa Ingenieria.

environments where traditional pyramids constructed of bamboo might be washed away. Dolos units can also be placed in front of a bank as individual roughness elements to promote deposition and prevent the river from being attracted to an armored bank because of deep scour. Increased local scour along an armored bank creates a deeper portion of the channel to which the channel will naturally migrate, potentially causing damage to flood control efforts (Mosselman 2006).

76. Scour protection in the Kunduz and Pyanj river basins has largely been inadequate to prevent undermining of flood control structures (Field 2010). Increasing the depth of scour protection would improve the longevity of many bank protection projects, but the technical difficulties of excavating deeply enough below the channel bed to set the base of the structures may be insurmountable on the Pyanj River where extreme scour depths occur (Japan International Cooperation Agency 2007). Deep excavations can be avoided by using launching aprons, whereby large boulders or concrete blocks extend out from the structure at a low angle on or slightly below the channel bed (Figure 39a). A distinction is made in some areas between a falling apron composed of individual boulders and launching aprons composed of in terconnected elements (Mosselman 2006), but no distinction is made by others (Maynord and White 1995) or in this report. Launching aprons enable boulders or blocks to fall into an emerging scour hole as the apron is undermined (Figure 39, b-d). Gabion spurs should not be used to construct launching aprons as they tend to break apart, especially when tumbling into a scour hole, allowing the constituent cobbles to be transported out of the scour hole. Using launching aprons only at the tips and upstream side of attracting spurs, where the deepest scour



Figure 39: Launching aprons extend out from a structure at a low angle (a) with boulders or concrete blocks falling into the growing scour pit as the launching apron is undermined (b-d). Note: Actual launching aprons would not extend as far across channel as shown in this schematic diagram.

Source: Getinsa Ingenieria.

is most likely, could minimize the cost of their use. Also, where several spurs are used in series, the spur farthest upstream should be prioritized for a launching apron as the downstream spurs will have some level of protection from those upstream. When using launching aprons, 25% more material is needed compared to the more standard practice of extending scour protection below the channel bed on a steeper slope (Maynord and White 1995).

#### D. Attenuation Zones

77. Setback levees, overtopping levees, and alternative bank stabilization techniques cannot be implemented in isolation, but must be part of a larger coordinated effort designed to attenuate flood flows and allow natural channel processes to occur unencumbered by human constraints. The creation of attenuation zones, areas for flood flows to safely spread out across the floodplain without threatening human life or investments, must be incorporated into flood hazard management plans.

Attenuation zones provide benefits to human settlements by reducing flood stages and flow velocities to upstream and downstream areas. Larger attenuation zones provide greater flood relief, but even small, isolated areas should be established where possible with the intention of connecting them into contiguous tracts over time.

78. Ideally, attenuation zones should encompass the entire meander corridor, braid plain, or active floodplain surface to allow natural, unconstrained channel migration. Such zones have been proposed in other parts of the world and have been referred to as "fluvial territory," "mobility space," "streamway space," "room for river," and "channel migration zones," among other terms (Ollero 2010). Figure 40 illustrates how a large attenuation zone can encompass most of a meander corridor. Population centers can be excluded from such areas given the potential losses, while other land uses, such as agriculture, can continue within the zone but without protection from flood and erosion hazards. Older flood control structures preventing channel migration can also be removed within the attenuation zone to restore natural channel processes more quickly.



Figure 40: Fluvial territory, or attenuation zone, delimitation in a reach of the middle Ebro River, Spain. Source: Ollero, A. 2010. Channel changes and floodplain management in the meandering middle Ebro River, Spain. Geomorphology. 117. pp. 247–260.

79. A number of steps can be taken to modify land uses inconsistent with the establishment of attenuation zones, including rezoning, resettlement, land purchases, and easement programs that compensate landowners for relinquishing "flooding and erosion rights" on their land. Many of these approaches are often controversial, must be voluntary and instituted slowly, and must be preceded by a public information campaign to explain the benefits of attenuation zones and alternative embankment designs. Compensating landowners for use of flooding and erosion rights is perhaps the least controversial of the options, because it represents a voluntary mechanism for establishing attenuation zones. Forming attenuation zones in heavily settled regions requires taking some agricultural lands out of production or exposing them to increased flood risks. Economic and social impact studies are essential for completing cost-benefit analyses of proposed attenuation zones.

In the long run, the benefits accrued from reduced flooding to adjacent areas may outweigh the financial losses associated with removing land from production to create the attenuation zones. Depending on the size and distribution of attenuation zones, setback embankments may be needed to protect adjacent areas, but they are not always required. Attenuation areas are a nonstructural approach to flood control that requires no long-term maintenance costs. Their only upfront costs are those that are necessary to purchase land rights or move homes or other structures—expenses that are likely to be far less than the construction and long-term maintenance of structural approaches. Additional costs may be associated with removing flood control structures that constrain channel movement and adversely impact other areas.

80. In undeveloped areas that may become settled over time, zoning regulations controlling future land use should be instituted that could accommodate future attenuation zones near the river. Prioritization of the best locations for attenuation zones, whether in developed or undeveloped areas, can be done with hydraulic modeling to identify areas that produce the maximum reductions in flood stage and flow velocity. Areas immediately upstream of large settlements are potentially good locations for attenuation zones because they can alleviate pressures on downstream embankments and flood control structures by reducing flow velocities. Other potentially good locations for attenuation zones are areas adjacent to heavily armored banks or embankments. Increased flooding and erosion might be expected across the channel from bank protection projects that use spurs, while projects without spurs are more likely to exacerbate problems downstream. Understanding how a given flood control project may impact adjacent areas can help identify the areas in greatest need of mitigation. Where attenuation zones are established, adjacent developed areas may be exposed to greater risks. In these locations, more traditional flood control measures may be necessary to protect human lives and investments.

81. If attenuation zones can be successfully created over a large area, the need to control erosion or flooding at any one spot is diminished. For example, if attenuation zones can be created along a long length of the Kumsangir Fan, channel blocks will no longer be needed as bank erosion on the margins of the braid plain will be allowed. Rather than constructing channel blocks that require frequent maintenance and negatively impact adjacent areas, attenuation zones provide a more sustainable approach. However, such zones cannot be established at once because of the land use conflicts present. Flood hazard management plans must set in motion policies that will allow attenuation zones to be developed over time, so that several decades later significant progress might be made at removing the human conflicts that currently preclude natural channel evolution toward an equilibrium condition.

82. Attenuation zones do not necessarily need to be contiguous with the active river channel. On alluvial fans, the best locations for attenuation zones are low areas, such as older, abandoned channels, where future channels on the alluvial fan surface are most likely to form in the event of an avulsion. The southern flow path on the Hamadoni Fan, although abandoned since the 1970s, remains a likely location of a future avulsion. Efforts should focus on keeping assets out of this area so an avulsion into this former channel path will not cause extensive damage. Setback berms could be constructed near developments along this flow path to protect against an eventual avulsion, and crossing points could be established in advance to ensure continued access to the numerous villages that would be isolated if the channel were to become active once again. While this would require quite considerable investments, the losses resulting from such an avulsion, if not planned for, are likely to be even greater and potentially life-threatening.

#### VI. CONCLUSIONS

83. Channel migration is an essential natural process on meandering channels, braided rivers, and alluvial fans. Traditional structural approaches used to control flooding and erosion in these environments often constrain the river's natural movement. Without maintenance, such flood control efforts are not sustainable as the river returns to a natural form, whether reestablishing a meandering pattern along a straightened channel or reactivating braid paths blocked by embankments. Long-term success in flood control will be realized through solutions that leave natural channel processes undisturbed. The greatest reductions in flood damage will result from flood hazard management programs that maximize the amount of land available for attenuating flood flows.

84. Given the pressures to utilize floodplain lands for agriculture and settlement, both public and technical education campaigns will need to play an essential part in implementing flood management plans that incorporate alternative flood control strategies. Public education will be required to convince stakeholders within the river basin that sacrificing agricultural lands along the river to accommodate natural channel processes makes long-term economic sense in the form of reduced threats to human life and property. Once public support is garnered, technical training for flood control managers can begin the process of identifying mechanisms for establishing flood attenuation zones. Unlike traditional flood control techniques that tend to increase flood stage and velocity by constraining the river, flood attenuation can reduce flood stage and flow velocity with consequent benefits to adjacent areas.

85. In addition, flood control efforts that allow channel migration and other natural processes to occur unencumbered require minimal maintenance, pose less risk to human life, and cause less damage to the environment. While different processes are associated with meandering rivers, braided rivers, and alluvial fans, all three channel types require ample space for channel migration in order to establish an equilibrium condition. Consequently, the alternative flood management approaches proposed here are applicable to all three channel types, although the exact location and distribution of such approaches will vary in each case. In view of the potential benefits of flood control approaches that accommodate natural channel processes, flood control management plans throughout Asia should endeavor to reduce flooding and erosion without altering existing meander corridors, braid plains, and active alluvial fans—the zones within which natural channel migration generally occurs.

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#### Pyanj River Morphology and Flood Protection

The Pyanj, on the border between Afghanistan and Tajikistan, is a dynamic river system that has caused considerable damage to life and property in both countries due to flooding and riverbank erosion. Flood management efforts have often been short-lived and expensive to maintain, and have worsened hazards in adjacent areas because of the river's sudden shifts in channel position, rapid bank erosion, and continual meander growth. This report presents more sustainable approaches to better understand river processes and help anticipate how the river channel will respond to management efforts at the project sites and along nearby reaches.

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