

9.32 Large River Floodplains

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Glossary

Anabran An anabran is one of multiple bifurcating channel reaches.

Avulsion Avulsion is the formation of a new channel across a floodplain and the abandonment or partial abandonment of the former river channel. The term is commonly also used for the newly formed channel itself.

Crevasse A scroll bar is one of a sequence of asymmetrical ridges, separated by swales, that form on the inside of river bends as the channel migrates away from the point bar on which the ridges of bed material sediment are formed.

Abstract

The size and complexity of large floodplains result from the hydroclimatic and tectonic settings required to produce large rivers with copious sediment supplies and adequate accommodation space, and also from certain scale-dependent processes. Water and sediment exchanges with the channel determine the construction and preservation of floodplain landforms. The intensity of plant colonization as well as physical and chemical changes to the accumulated sediment, play important roles in stabilizing floodplain sediment, affecting its residence time and geomorphology. These features, together with the time available for the adjustment of tectonic, climatic, or eustatic changes, affect the geometry and behavior of large-river floodplains.

9.32.1 Definition and Scale

A floodplain is a sedimentary plain of low relief bordering a river channel, typically with topographic amplitude between ridges and the beds of floodplain water bodies of ~ 0.1 – 0.5 times the bankfull depth of the river, constructed by various sedimentation processes and inundated to some extent by most annual floods in the current hydroclimatic regime of the river's drainage basin. This definition is loosely useful for large river floodplains but is not as straightforward

to apply as in the case of a smaller river. The size of large rivers and the mass and age range of sediments involved in even a Holocene-age floodplain imply complexities such as: (1) large ranges in water-surface elevations and differences in the nature of inundation processes that alter some parts of a large floodplain but not others in single flood seasons; (2) disruption of alongstream trends in sediment sorting and sedimentation as a result of catastrophic internal processes as well as tributary junctions and other lateral supplies of runoff and sediment; (3) long periods of time required for changes to occur in some floodplain landforms; (4) recycling of sediments originally deposited under different circumstances; and (5) limited utility of the steady-state concepts that illuminate the formation and functioning of smaller floodplains.

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Thus, for example, it is rarely possible to recognize which parts of a large floodplain are adjusted to “the current hydroclimatic regime,” or even to define a single overbank discharge into the floodplain along rivers with natural degrees of complex channel–floodplain connectivity. At the same time, some parts of floodplains undergo sedimentation from tributaries and organic sequestration that are unrelated to the flood hydrology of the trunk stream. In fact, some floodplains are so extensive that they are unlikely to have been visited by the trunk river channel during the Holocene. The control of the river on sedimentation in these cases is indirect, through the hydraulic head of the channelized or overbank flow forcing deposition of sediment from tributaries and fringing uplands or through the hydraulic head of the groundwater, which affects the accumulation of organic sediment in lower areas of the floodplain.

Accepting these complexities, together with the essence of our original definition, we will emphasize only that a floodplain of a large river is the landform created by the temporary storage, redistribution, and sculpting of sedimentary packages of various textures during episodic transport through long lowland courses. The residence times of the transport and storage with which we will be concerned vary from centuries to the duration of the Holocene transgression.

Although over a range of smaller rivers and laboratory channels it is difficult to recognize the scale of fluvial features without an independent ruler, the floodplains of the largest rivers allow the development of a greater diversity of forms with a greater range of scales and ages than do the floodplains of smaller rivers. These larger floodplains are also subject to more complex hydrologic regimes (because they cross and integrate the response of more than a single climatic zone) and hydraulic regimes (because the interacting water sources flow across extensive and topographically complex surfaces). Moreover, because large river basins tend to intersect more than one geological province, their sediment supply and transport systems are more ‘piecewise continuous’ than is conceived of in generalized conceptual models of fluvial system behavior. The result is that the floodplains of large rivers yield a fascinating array of geomorphological features and behaviors, the understanding and prediction of which require the application of various theoretical and novel instrumental tools, but about which it is difficult at this time to construct simple, overarching theory.

The scale of these lowland floodplains ranges up to ~4000 km in length in cases such as the Nile and Amazon rivers and from ~10 to 100 km in width, depending on how liberal is one’s definition of the current regime of floodplain formation. Because of the centuries-to-millennia age range of parts of a large floodplain, originally distinct fluvial features on older parts of the plain may be partially masked by thin layers of younger sediment, organic sediment accumulations, weathering, bioturbation, washing, and other diffusive redistribution of sediment. It is therefore useful to distinguish the modern (most recently active) “channel belt” landforms, which have been recently emplaced, shaped, or at least modified by the trunk stream, from the wider floodplain of Holocene, or even Pleistocene, age. This channel belt along a meandering (*see* Chapter 9.16) or braided (*see* Chapter 9.17) river may range from one to several times the width of the

channel bends, which themselves may range from ~10 to 100 bankfull channel widths on a larger river. It is more difficult to make similar generalizations about the width of channel belts in the floodplains of multi-threaded large rivers, except to say that the belts are generally wider than in the case of single-thread channels. Some large river floodplains, such as the middle Sacramento River in the Central Valley of California (see later discussion of Figure 25), include both a braid plain, the main features of which were emplaced thousands of years ago but which are occasionally inundated and altered with fine-sediment deposition, and a radically different meandering-channel floodplain. Even within modern meandering-river floodplains, it is sometimes possible to distinguish channel belts of various ages with differing sinuosities and other features resulting from fluctuations of hydroclimatology and riparian vegetation changes (*see* Chapter 9.14).

9.32.2 Conditions for Creation of a Large River Floodplain

The construction of an extensive floodplain requires: large supplies of water and sediment; basin boundaries that supply these large quantities of material and provide the accommodation space necessary for extensive sediment storage; and long periods of time for accumulation and storage change of the large masses of sediment incorporated into floodplains. In turn, these governing conditions depend on global tectonics (as it affects the existence and history of continental land masses) and the modern functioning and recent history of the global climate system, which affects both hydrology of the river and global sea level. Within the last century, the products of these two global-scale natural systems have begun to be altered by another pervasive, intensifying global influence, namely human development with its increasing demands and capacity for large-scale, planned and inadvertent manipulation of even the largest rivers on the planet (*see* Chapters 9.34 and 9.40). The fact that these floodplains have been productive, yet hazardous, homes for large numbers of people throughout history, and that they currently harbor hundreds of millions of people means that understanding and predicting the construction, functioning, destruction, and defensibility of floodplain landforms in the face of fluvial dynamics, hydroclimatic flood regimes, river basin change, and sea-level rise are all intensely important for the habitability of these landscapes. Nevertheless, this chapter will concentrate on natural features and processes, and leave engineering and other management issues for discussion elsewhere.

Systematic discussion of the geomorphology of large rivers was initiated by Potter (1978), who illustrated how the outlines of most of the largest river basins on the planet have been established through the tectonic assembly and deformation of continental land masses. The mouths of many of the largest river basins have been localized by grabens or crustal downwarps, and the alignment of some major rivers have been correlated with large-scale fracture patterns in Earth’s crust. Potter (1978, Figure 7, quoting de Rezende) illustrated this association in the case of the largest rivers of South America, and Schumm and Galay (1994, Figure 4-3, quoting

Youssef) demonstrated how reaches of the Nile River valley (extending over 2–4° of latitude) parallel major faults related to the Red Sea rifting and ongoing seismicity. Bedrock outcrops constrain both the floor and width of the valley and the alignment of the channel in some reaches. *Mertes and Dunne (2007)* reviewed three scales at which tectonics affects the large-scale features of the Amazon River and its floodplain: (1) the continental-scale (5×10^3 km) assembly of orogen, foreland basin, cratons, and grabens, which control runoff production, sediment supply, and accommodation space; (2) the intermediate (10^2 – 10^3 km) spacing of crustal warping transverse to the river course, which affects gradient and valley width and therefore channel sinuosity, accommodation space, and the hydrology and hydrodynamics of sediment distribution into the floodplain; and (3) the local (10s–100s km) scale of brittle crustal fracturing that affects channel orientation and gradients (*Tricart, 1977; Latrubesse and Franzinelli, 2002*).

These structural constraints involving fracturing and downwarping, together with the large-scale tectonic assembly of mountain ranges and other high-standing topography, then determine the water and sediment supplies of the river basin. Large river floodplain formation requires large discharges and sediment supplies, although the range of each input to large floodplains is remarkably wide (*Milliman and Farnsworth, 2011*). River basin margins, and therefore discharge and sediment supplies, can evolve over millions of years (*Brookfield, 1998; Hoorn, 1994; Clark et al., 2004*), so that size, sediment load, gradients, and other factors that affect the river's modern behavior, including floodplain forming processes, have been set by large-scale geological processes acting throughout the late Cenozoic. Large climate changes can be related to tectonism (*Brookfield, 1998*) or glaciation. Singular geological events can establish a major river and floodplain, such as when the drying up of the Mediterranean Sea ~ 5 – 6 Mya lowered the base level of a local proto-Nile River, triggering headward erosion of a modern northward-flowing river that beheaded the former westward-flowing rivers draining toward the general vicinity of modern Lake Chad (*McCauley et al., 1986*). These large-scale processes are fundamental to explaining intriguing differences and similarities between the floodplains of large rivers, including deep sedimentary accumulations beneath the valleys and deltas of some large rivers. Many texts and monographs in stratigraphy and sedimentology have been written on facies analysis of fluvial sediments. This chapter concentrates on events sufficiently recent to affect visible surface morphology of floodplains, mainly during the Holocene postglacial transgression and climate.

Potter pointed out that there is considerable variability between large rivers according to the direction of their trend with respect to orogens, or whether they drain one at all. *Milliman and Meade (1983)* and many successors (*Milliman and Farnsworth, 2011*) have quantified the dominant role of active orogens in sediment supply, whereas large rivers draining cratons, such as the Congo (upstream of $\sim 2^\circ$ S $16^\circ 20'$ E in Google Earth™), Negro (upstream of $\sim 3^\circ$ S $60^\circ 30'$ W), Niger (upstream and downstream of Niamey, Niger at $13^\circ 30'$ N $2^\circ 09'$ E) have much smaller sediment loads. *Jung et al. (2010)* have illustrated differences in the floodplain

topography of the sediment-rich central Amazon valley and the central Congo valley, which has a much lower sediment supply. However, crustal deformation within and on the margins of cratons, such as the foreland basins east of the Andes (south and west of Riberalta, Bolivia, $11^\circ 00'$ S $66^\circ 03'$ W in Google Earth™) and south of the Himalaya (the Ganga River plain upstream and downstream of Patna, India, $25^\circ 40'$ N $85^\circ 04'$ E in Google Earth™), or basin downwarps such as that localizing the Inland Delta of the River Niger in Mali (downstream of $13^\circ 43'$ N $6^\circ 05'$ W in Google Earth™), can force rivers to reduce their sediment loads, creating extensive floodplain deposits. In other large river basins, such as the Missouri–Mississippi system, the modern, especially pre-regulation, sediment supply is determined mainly by a combination of the extensive erodible sedimentary rocks of the upper Great Plains and the Pleistocene climatic perturbations that generated large volumes of regolith and distributed it by ice sheets, meltwater rivers, and wind across the upper Midwest (*Meade and Moody, 2009*).

Large floodplains require not only large supplies of water and sediment, but space for the storage (on differing time-scales) of each of these inputs. The largest river basins, and particularly those likely to have long, low-gradient reaches along which extensive sedimentary deposits can accumulate, drain the trailing margins of continents (*Potter, 1978*). Those rivers that head in orogens have high sediment supplies, but even among these cases there are important differences between their floodplains. Some rivers with large floodplains flow directly away from the orogen, including the Amazon (east of Iquitos, Peru, $3^\circ 45'$ S $73^\circ 15'$ W in Google Earth™) and the pre-development Rhine (downstream of Duisburg, Germany, $51^\circ 26'$ N $6^\circ 46'$ E in Google Earth™), are free to spread broad aprons of sediment and reduce their loads as they cross orogen-margin basins. Other rivers with large floodplains flow parallel to the orogen, receiving sediment from tributaries along much of their length, such as the Paraguay (downstream of Asunción, Paraguay, $25^\circ 17'$ S $57^\circ 38'$ W in Google Earth™), Orinoco (downstream of Puerto Ayacucho, Venezuela, $5^\circ 40'$ N $67^\circ 38'$ W in Google Earth™), and Ganga (upstream and downstream of Patna, India, $25^\circ 40'$ N $85^\circ 04'$ E in Google Earth™). The floodplains of these orogen-parallel rivers tend to be strongly asymmetric, with transverse ramps of coalescing fans punctuating their courses and imposing on the trunk stream variable longitudinal gradients where fans of coarse sediment accumulate at tributary mouths, or rapids where the river is pinned against the opposite side of the bedrock valley. The Orinoco, for example, is confined to the southern edge of its valley by the wedge of sediments spreading from the Venezuelan Andes (Google Earth™ coordinates $\sim 7.5^\circ$ N 65.5° W). The river has only a 5–10 km wide floodplain (*Hamilton and Lewis, 1990*) fringing a ramp of southward-sloping tributary-mouth fans, and is confined to flow across the margin of the Brazilian craton over eight bedrock outcrops that create major rapids and reduce channel migration (*Warne et al., 2002, Figure 3*). *Potter (1978)* also pointed out that still other rivers draining orogens, such as the Magdalena (downstream of $6^\circ 30'$ N $74^\circ 24'$ W in Google Earth™) and the Mekong (downstream of Pakse, Laos, $15^\circ 07'$ N $105^\circ 49'$ E in Google Earth™), flow along the strike directions between mountain ranges, and thus build long, narrow floodplains within the

orogen and extensive plains at their exits. These rivers also have strong transverse asymmetries and longitudinal profiles punctuated by tributary sediment inputs and imposed changes of gradient (Garcia Lozano and Dister, 1990; Winkley et al., 1994).

Rivers with high sediment loads emanating from orogens typically fill the adjacent structural basins and build extensive floodplains that may coalesce as internal sedimentation dynamics drive them across the basins (Aalto et al., 2003; Gautier et al., 2007) or they may be separated by low terraces on tectonically uplifted blocks of consolidated bedrock or weathered, cohesive alluvium (e.g., Dumont, 1994). However, other large rivers flow within valleys that were not eroded by liquid or frozen water discharges from the basin, as envisioned in standard cyclic models of landscape evolution. Instead, they flow into large, tectonically created troughs between mountain ranges or within cratons, which they are gradually filling to various degrees. These large rivers may have channel belts that are 'overfit' with respect to their valley widths as, for example, is the middle and lower Amazon River (see discussion of Figures 7, 8, 10, 11), which frequently encounters cohesive Pleistocene terraces or faulted and warped crustal blocks (Latrubesse and Franzinelli, 2002; Mertes et al., 1996; Mertes and Dunne, 2007). Or, in the case of other rivers such as the Sacramento and San Joaquin rivers of the Central Valley of California, their channel belts may be 'underfit' with respect to the dimensions of a long, wide valley, created by Mesozoic and Tertiary tectonics and sedimentation. Rivers filling tectonically created lowlands often flow on long, narrow ramps of near-channel sediments, 5–10 m above the lateral margins of their floodplains, which can be filled only very slowly by tributary fans and fine mineral and organic sediments that are distributed into these lateral flood basins by overbank and tributary floods. Interconnected flood basins, sometimes engineered into flood bypass channels through excavation and diking, may convey more water during extreme floods than is discharged along the trunk stream, which therefore may decrease in size in the downstream direction (Singer and Dunne, 2001; Singer et al., 2008, Figure 1).

9.32.3 Distinctive Characteristics of Large Rivers and Floodplains

There are several distinctive characteristics of regional- to continental-scale rivers that have not yet received systematic treatment in the theory of large floodplain rivers or even in descriptive textbooks of geomorphology or sedimentology. The first is that their low gradients (in the range of 1–50 cm km⁻¹) make them susceptible to modification by even slow, small tectonic movements within continental interiors or to the excavation of resistant materials. These gradient changes, in turn, affect the sediment transport capacity and flow-driven bend mechanics of the river. Schumm et al. (1994), for example, illustrated how gradients between 5 and 25 cm km⁻¹ along the pre-engineering Mississippi River were associated with various faults and domal uplifts, and in turn were related to changes in channel sinuosity and bend migration rate. The positive association between gradient and sinuosity, at least up to the transition to braiding, had been observed by Schumm

and Kahn (1971) in laboratory experiments, and has been observed on other rivers, although not yet explained rigorously. In the case of the Nile, Schumm and Galay (1994) found that the river, which generally has a sinuosity of approximately 1.1, became slightly more sinuous and actively migrating where the gradient increased downstream. Dunne et al. (1998) showed that gradient changes are imposed on the Amazon River where its sinuosity is limited by the river's encounter with cohesive valley walls. As the river crosses structural upwarps transverse to its course (Figure 1), it incises the underlying cohesive lacustrine sediments, and the resulting narrower valley forces the river to be straighter and steeper, with a relatively narrow and morphologically simple floodplain. Between the upwarps, the valley is much wider and the river is free to develop large, meandering, multi-threaded reaches with significantly greater morphological complexity. The differences between adjacent reaches are also illustrated in Figures 7–9.

A second distinctive characteristic of large rivers related to their low gradients is that Quaternary sea-level changes propagated great distances upstream. The Last Glacial Maximum decline in sea level was approximately 120 m, and the response of individual rivers to the lowering of base level was significantly complicated by the lower-river and off-shore gradients, the magnitude of river discharge and sediment load, and isostatic effects of sediment loading and removal (Blum et al., 2008). However, there is morphological and stratigraphic evidence that in some large rivers, channels and valley floors were degraded at least several tens of meters, and the upstream limit of degradation extended for hundreds of kilometers. For example, Saucier (1994) and Blum et al. (2008) reconstructed evidence of degradation of the lower Mississippi River extending ~800 km upstream of the shelf margin (~600 km upstream of New Orleans), whereas Mertes and Dunne (2007) summarized field evidence and interpretations by themselves and others to conclude that in the lower Amazon River, with a gradient almost 10 times lower than that of the Mississippi, eustatically driven valley incision extended approximately 2000 km upstream of the shelf edge. In both of these rivers, sedimentation has filled in most of the resulting accommodation space during the Holocene transgression, but in the case of the lower Amazon the floodplain remains incompletely filled, with large lakes and complex sedimentary landforms (Figure 11). The degree of Holocene filling of each degraded lower valley must depend largely on the sediment supply and neotectonic activity. Large sediment supplies have re-established deltas, while in other rivers the estuary that was excavated during glacial periods, with or without tectonic subsidence, remains largely unfilled. The lower Amazon appears to be intermediate on this scale of recovery, with vertical accretion rates averaging several mm per year (Mertes and Dunne (2007, pp. 136–138)).

A third distinctive feature of large rivers and their floodplains is the strong, complex hydrologic interactions between channel and floodplain. The large drainage area produces gradually rising and receding hydrographs because of the long translation times of flood-wave passage that integrates the response of many tributaries, over a range of latitude and elevation, and because of the storage of flood waters in extensive floodplains can comprise 10–20% of the river's annual

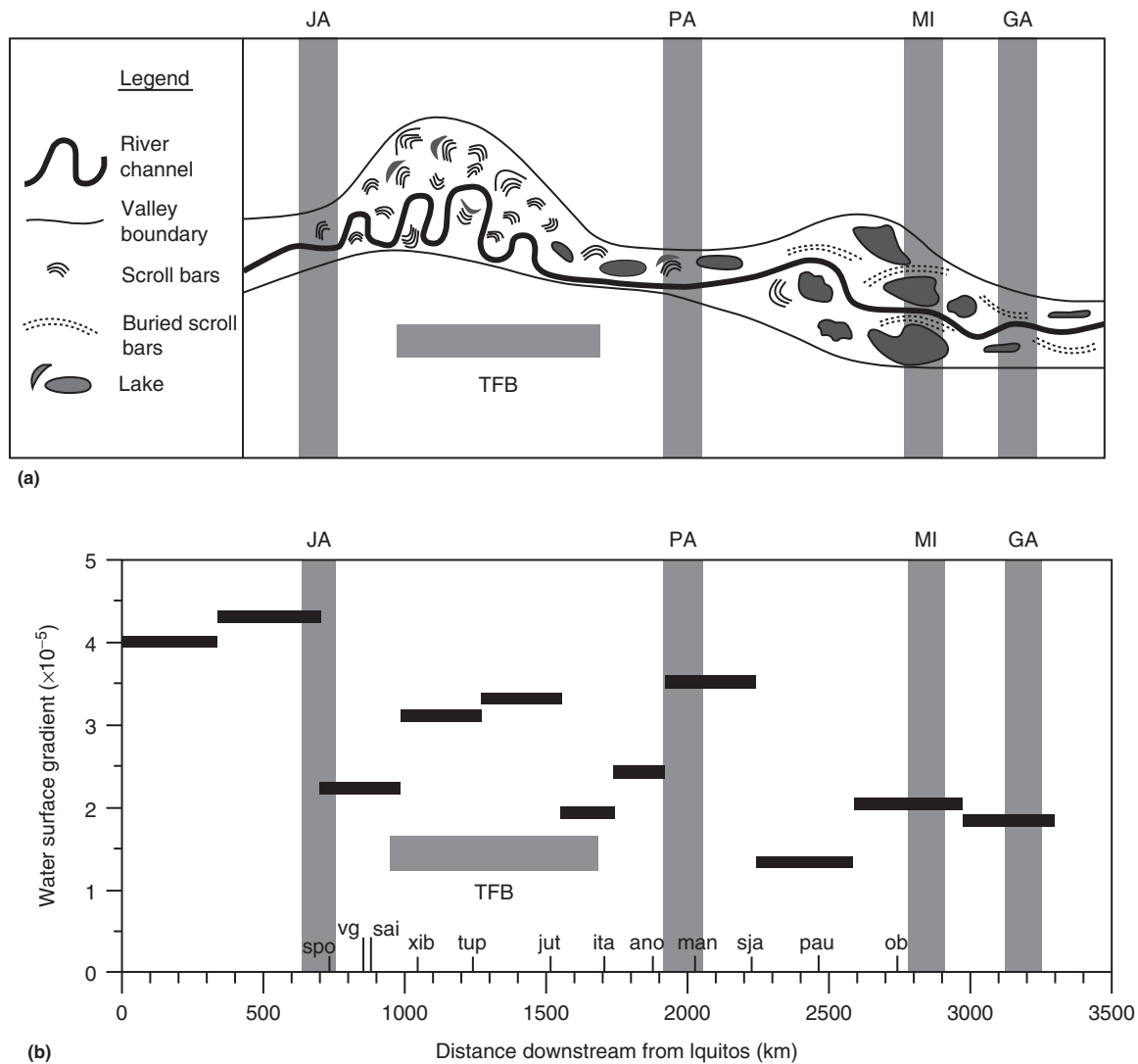


Figure 1 (a) Schematic illustration of the variation of channel and floodplain features in relation to structural features along the Amazon River valley, Brazil. The four vertical gray bars indicate the approximate locations of the axes of arches and structural highs crossed by the valley: JA, Jutaí Arch; PA, Purús Arch; MI, Monte Alegre Intrusion and ridge; GA, Gurupá Arch. The horizontal bar labeled TFB indicates the approximate extent of a tilted fault block, recognized by Tricart, J.F., 1977. *Types de lits fluviaux en Amazonie brésilienne. Annales de Géographie* 86, 1–54. (b) Water-surface gradient at low flow along a 3200 km-long reach of the Amazon River based on radar altimetry. More extensive documentation of water-surface gradients along this reach is provided by Birkett et al. (2002). Abbreviations on the abscissa indicate sediment sampling stations referred to in the original text. Reproduced from Dunne, T., Mertes, L.A.K., Meade, R.H., Richey, J.E., Forsberg, B.R., 1998. Exchanges of sediment between the flood plain and the channel of the Amazon River in Brazil. *Geological Society of America Bulletin* 110, 450–467.

discharge. As a result, overbank flow may last for many weeks in each year. For the Amazon, probably an extreme case for reasons of drainage area, hydroclimatology, and floodplain complexity, Richey et al. (1989, Figure 4) calculated that water flows out of the main channel into the floodplain for 5–6 months per year. Furthermore, the sediment loads of large rivers are dominated by fine-grained particles with low settling velocity, which are therefore carried relatively high in the water column. Both the overbank flow regime and the low settling velocities favor large volumes of sediment transport into the floodplain (Kesel et al., 1992; Dunne et al., 1998).

9.32.4 Sedimentation Processes and Forms of Large Floodplains

Floodplain landforms are created from sediment deposited (1) by flow within and along the margins of the main channel, and (2) by flow into and on the floodplain itself, from either the main channel or the marginal tributary drainage area. Survival of the floodplain is then favored by a set of hydraulic, chemical, and biotic processes. If the sediment has accumulated in some relatively low-shear stress part of the valley floor, such as far from the channel, a valley widening, or a location from which the channel retreats, the probability of

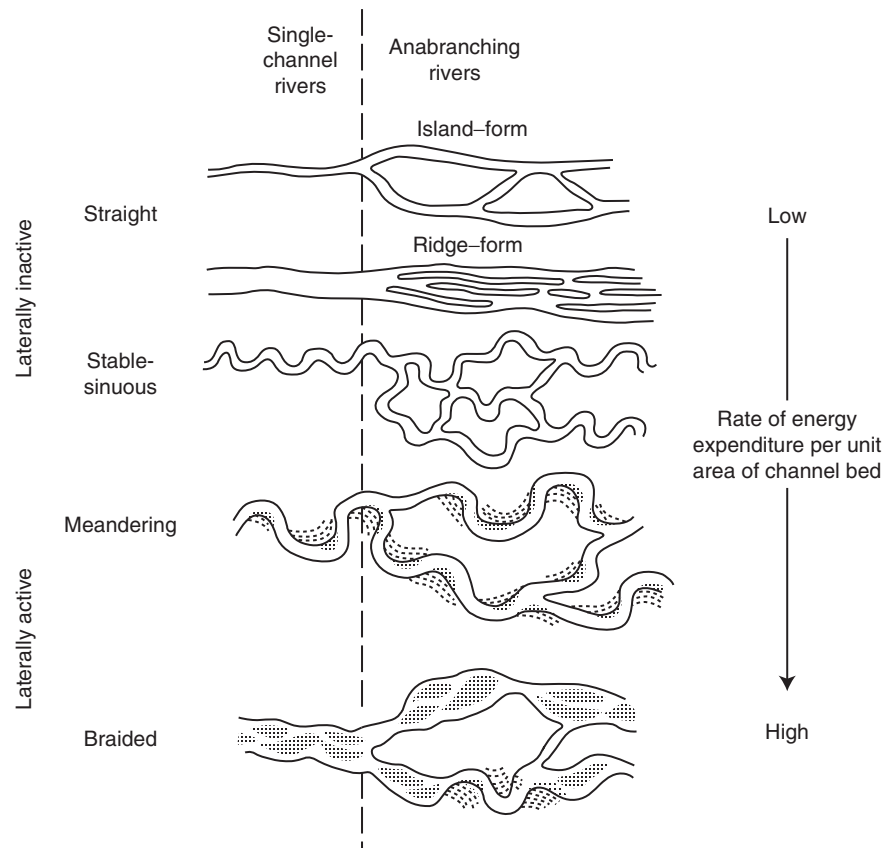


Figure 2 Classification of river patterns including single-channel and anabranching forms. Laterally inactive channels consist of straight and stable-sinuuous forms, whereas laterally active channels consist of meandering and braided forms. Reproduced from Nanson, G.C., Knighton, A.D., 1993. Anabranching rivers: their cause, character and classification. *Earth Surface Processes and Landforms* 21, 217–239, with permission from Wiley.

re-entrainment will be low for some considerable time. During its residence, the sediment can be rendered more stable by drainage, settling, and compaction, by the development of cohesive chemical weathering products, and by plant colonization.

This distinction between sedimentary forms that are constructed by the mainstem river or by other flows, and then stabilized to varying degrees, suggests that the planform and migration mechanisms of the main channel are a useful starting point for organizing knowledge of floodplain formation. Although there is no universally accepted classification of river planforms or interpretation of the mechanics governing them, the scheme proposed by Nanson and Knighton (1996), reproduced as Figure 2, is a useful starting point, although only its application to large lowland rivers will be discussed here. Alabyan and Chalov (1998) summarized Russian research on river planforms, relating them to combinations of valley gradient and mean annual flood (Figure 3).

The basic distinction made in the classification scheme is between single-thread channels and anabranching channels (see Chapter 9.19), which are “systems of multiple channels characterized by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull. These islands may be excised by channel avulsion from

extant floodplain, (or) developed from within-channel deposition.... In any anabranching, as opposed to braiding, system, the islands usually persist for decades or centuries, support well-established vegetation and have relatively stable banks. They are at approximately the same elevation as the floodplain, and the channels between the islands can be braided, meandering, or straight” (Nanson and Knighton, 1996, p. 218).

In this classification, braided channels are referred to as single-threaded, whereas in other discussions, especially of smaller rivers, they are defined as multi-threaded. Nanson and Knighton (1996, p. 219) specifically excluded the large Indo-Gangetic rivers from the classification, which will later cause some difficulty in unifying discussion of the largest braided rivers in the world. The difficulty arises because of differences in emphasis about the longevity and degree of vegetative stabilization of large bars in rivers such as the Jamuna–Brahmaputra. Some investigators (e.g., Coleman, 1969) report the astonishing mobility of mid-channel bars during intra- and inter-annual flow variations in a wide corridor (braid plain) that extends between distinctive banks. Few secondary channels are formed by avulsion across the surrounding vegetated floodplain surface, which is inundated by floods with multi-decadal recurrence intervals. By contrast, Latrubesse (2008) refers to the Brahmaputra in the same reach

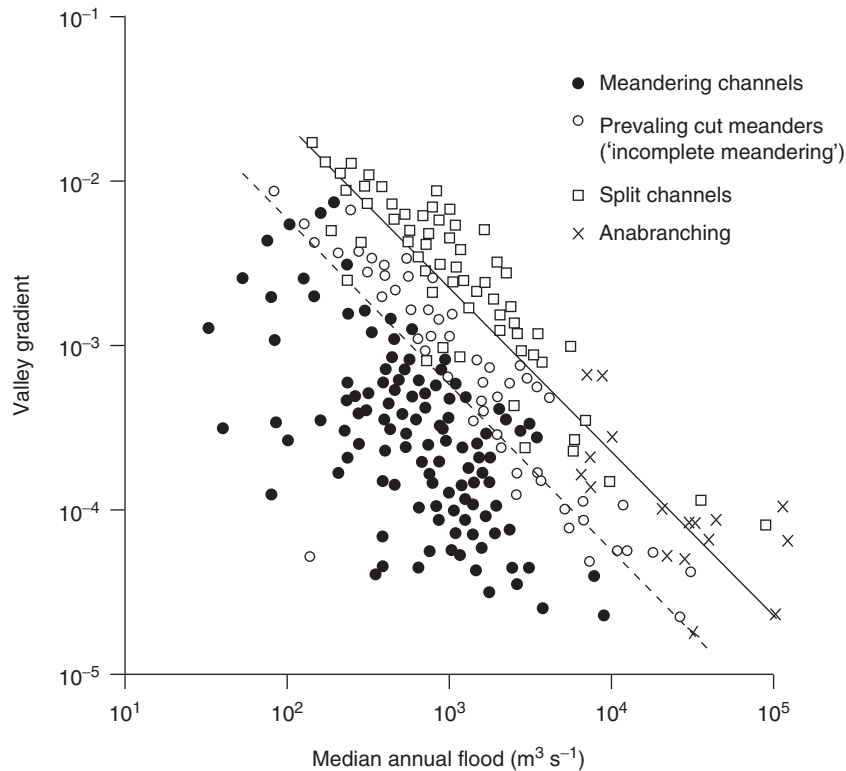


Figure 3 Relations between channel planforms, valley gradient, and mean annual flood. The term ‘incomplete meandering’ appears to relate to meanders prone to chute cutoff. The locations of individual data points were not specified. Reproduced from Alabyan, A.M., Chalov, R.S., 1998. Types of river channel patterns and their natural controls. *Earth Surface Processes and Landforms* 23, 467–474, with permission from Wiley.

as having an anabranching pattern. We will re-visit this uncertainty in a later section. It is unlikely that there will ever be definite metrics for discrimination of the various planforms of large rivers because they constitute a continuum of complex forms. The following text describes iconic examples of processes and landforms representing each of the fuzzily demarcated classes.

9.32.5 Floodplain Construction by Single-Thread Sinuous Rivers

Despite the frequency of the anabranching planform along large rivers, it is useful to begin analyzing processes that construct floodplain landforms by considering the case of the single-thread, sinuous planform, because such river reaches exhibit a set of processes that are fundamental to flow, erosion, and sedimentation in all alluvial rivers and that find expression to some degree in the other elements of the Nanson–Knighton scheme. After discussing this general situation, it is possible to add the extra processes and features found in the braided and anabranching cases.

9.32.5.1 Bar Accretion and Bank Erosion of Floodplains

Rivers create and re-mobilize floodplains most directly through the related processes of bar formation and bank erosion (Figure 4), both of which arise because the sinuosity

of a river channel drives asymmetries in the flow field and sedimentation. The relatively high shear stresses along the outer margins of bends can erode banks directly through fluid shear, or they can erode the pool or the foot of the bank, leaving the bank too high or steep for stability, especially when it is subject to seepage pressure from riparian groundwater flowing back into the channel during recessions of the water level (Figure 4(c)). Bank retreat along the outer margin makes the bend grow asymmetrically, with a tendency for the highest rates of erosion to occur immediately downstream of the bend apex (Furbish, 1988). Thus, the bend enlarges and migrates into the floodplain surface (Howard, 1992). If bars are sufficiently well developed, they may intensify the concentration of flow along the outer margins of bends and accelerate bank erosion and bend growth (Dunne et al., 2010; Legleiter et al., 2011). A bar may then be incorporated into the floodplain as the convex bank moves away from it, lowering the shear stress and sediment transport across it, and allowing the growth of vegetation and the accumulation of finer, suspended sediment to raise the bar surface and block any minor channels that have developed across it (Braudrick et al., 2009). This sedimentation process is often referred to as lateral accretion (Figures 4(a) and 4(b)). Sequences of arcuate bars with intervening depressions constitute scroll-bar topography, and the expression of their distinctive topography and sedimentology may be enhanced by later soil formation and plant colonization. Butzer (1976) referred to this simplest model of a floodplain generated by lateral accretion as a ‘flat’ floodplain



Figure 4 Photographs of bar formation (a, b) and bank collapse that occurred during hydrograph recession (c) along the middle Amazon River approximately 200 km upstream from Manaus, Brazil. The bar heights in (a) and (b) are approximately 4–5 m above low water at the time of the picture, and the bank height in (c) is approximately 10 m above low water (5–6 m at time of picture). The bars are formed from suspendible bed-material sand (median grain size 0.25 mm). The collapsed bank consists mainly of silt with 15% each of sand and clay. Photographs by T. Dunne.

(Figure 5), consisting mainly of bed-material deposits (not necessarily bedload; the bars of large lowland rivers are mainly constructed with suspendible sandy or silty bed material). An overlying layer of fine-grained washload may settle on the bed-material deposits (the ‘flood silts’ in Figure 5). Where this layer is thin or absent, the arcuate topography of the original point bars protrudes above the surface between intervening, poorly drained depressions.

By mapping channel positions on sequences of georeferenced aerial photographs or satellite images, measuring bank heights, and textures of both banks, it is possible to estimate the multi-year rates of exchange of sediment between channels and floodplains through bar development and bank erosion. Along the 2000 km-long Brazilian Amazon (drainage areas

$0.9\text{--}4.6 \times 10^6 \text{ km}^2$; gradients $4.3\text{--}1.3 \text{ cm km}^{-1}$), Dunne et al. (1998) measured large imbalances between the average annual amount of sediment returned to the channel through bank collapse (equivalent to 127% of the flux at tidewater), and the amount of sand deposited as bars (30% of the total export). However, the imbalance was more than compensated for by overbank deposition throughout the broader floodplain. The exchange rates reflected alongstream variations in channel migration rates, which in turn were controlled by the tectonically modulated degree (or lack) of confinement of the channel between cohesive terraces. Aalto et al. (2008) used a similar method on the Strickland River, Papua New Guinea (drainage area $18\,400 \text{ km}^2$; gradient $\sim 10 \text{ cm km}^{-1}$), and found that total bar-bank annual exchange of sediment was equivalent to

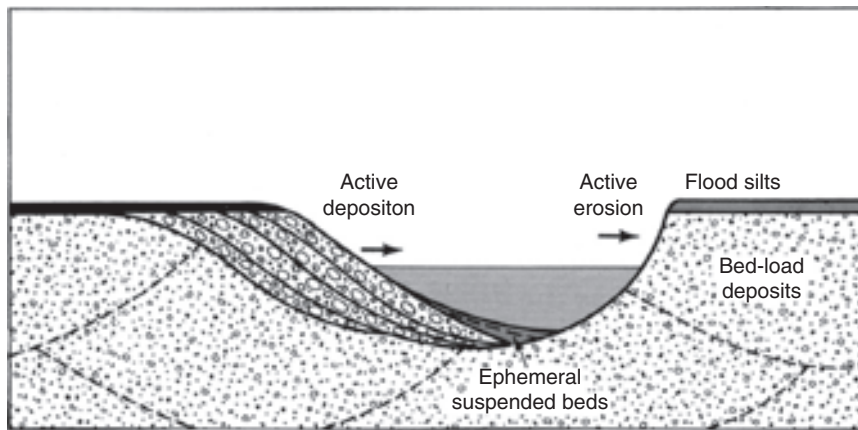


Figure 5 The ‘flat’ floodplain defined by Butzer (1976), constructed mainly through lateral accretion of bed-material load (not necessarily bedload; the bars of large lowland rivers are mainly constructed with suspendible sandy or silty bed material) in the form of point bars. Where the overlying layer of ‘flood silts’ is thin or absent, the arcuate topography of the original point bars protrudes above the surface between intervening, poorly drained depressions. Reproduced from Figure 8-5 of Butzer, K.W., 1976. *Geomorphology from the Earth*. Harper & Row Publishers, New York, 159 pp., with permission from LWW.

approximately 50% of the total load, but the net storage was within the uncertainties of the field measurements of the two components. Along the rapidly aggrading Beni River of eastern Bolivia (drainage areas 68 000–120 000 km²; gradients 12–2 cm km⁻¹), Aalto et al. (2002) also found the rates of bar accretion and bank undermining to be essentially in balance.

9.32.5.2 Floodplain Construction from Overbank Sedimentation

Rivers also construct floodplains by distributing suspended sediment (mainly channel washload) across the floodplain surface by diffuse and channelized flows, leading to various forms of vertical accretion. This component of the floodplain construction is generally finer (overwhelmingly silts and clay with some very fine sand in the case of large river floodplains) than that involved in lateral accretion, and it tends to distribute sediment into floodplain depressions and to reduce the amplitude of both positive topographic features such as scroll bars and negative topographic features such as channels and lakes. Mertes (1994) estimated instantaneous overbank transport rates at several sites along the middle Amazon River (drainage area $\sim 2.2 \times 10^6$ km²) from computations of flow and concentrations of suspended sediment measured from satellite images, both checked with field measurements. She estimated overbank transport rates at three mainstem discharges of 3–18 t d⁻¹ per meter length of channel bank, and also that almost all of the sediment settled out within a few hundred meters of the channel edge, depositing layers at rates of 0.3–3.3 cm day⁻¹. Asselman (1999) made direct measurements of sediment accumulation on small mats of artificial turf on a grassy floodplain of the River Waal, the largest tributary of the lower Rhine. The short-term measurements indicated that deposition rates increased with the magnitude of the overbank discharge at a faster rate for sand than for silt-clay, but that the trap efficiency of the floodplain

decreased with increasing flow rate. The relationship between deposition rates and overbank discharge, generalized with a mathematical model of sediment advection and settling, suggested that overbank flows of low magnitude and high frequency (1–2 yr) are the most effective contributors of vertical accretion to the floodplain.

Dunne et al. (1998) made lower-resolution estimates of overbank sedimentation based on measured sediment concentrations and flood-routing computations of overbank flow for ten ~ 200 km-long reaches of the Amazon (drainage areas 0.9–4.6 million km²; gradients 4.3–1.3 cm km⁻¹). The overbank transport varied over the year as main channel stage and sediment concentration varied with discharge. The average annual rates of transport over each bank for various reaches during a 16-year period ranged from 30 to 850 t m⁻¹ yr⁻¹, depending on the gradient, valley width and sinuosity of each reach (Figure 1). The resulting annual net accumulation for the entire 2000 km-long reach was estimated to be 1100 Mt yr⁻¹ of silt-clay (equivalent to 112% of the mainstem export to tidewater; drainage area 4.6 million km²) and 120 Mt yr⁻¹ of sand (equivalent to 50% of the export). Using direct measurements of isotopically dated sediments from 11 transects in a 318 km-long reach of the Strickland River in Papua New Guinea (drainage area 318 400 km²; gradient 10 cm km⁻¹), Aalto et al. (2008) showed that during the past 65 years, 17–27% of the suspended load of the river (50–70 t m⁻¹ yr⁻¹) had been deposited overbank, almost entirely within 1 km of the channel. Sedimentation rates were typically higher in sinuous reaches than in straight reaches and particularly high on the tops of point bars immediately downstream from the axes of bends where water flows overbank most abundantly (Constantine et al., 2009b) and levees have not developed. Sedimentation at locations of this type is analogous to the frequently inundated sites where Asselman (1999) measured accumulation.

As sediment-laden water leaves the channel, it encounters vegetation, which together with the suddenly reduced flow

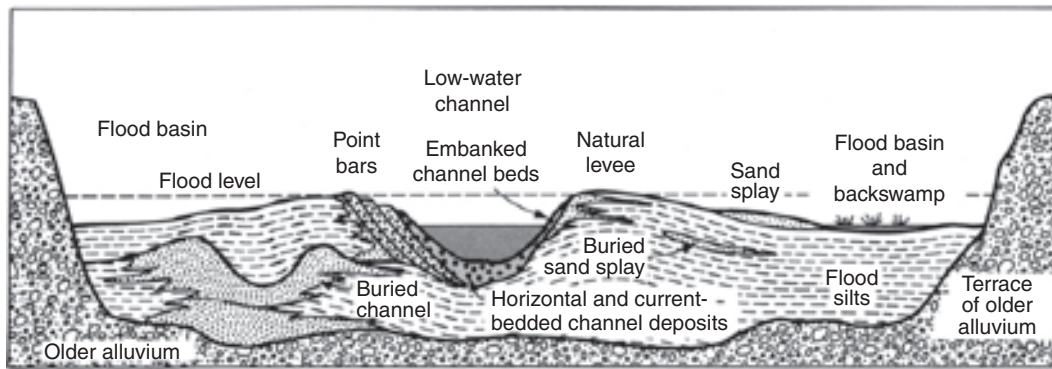


Figure 6 The 'convex' floodplain defined by Butzer (1976), constructed mainly by vertically accreted fine sediment carried by diffuse or channelized overbank flow. Note that the vertical scale of the diagram involves a potentially misleading degree of vertical exaggeration. The levee height above the basin is generally less than the channel's bankfull depth, bankfull width is generally less than 5% of the floodplain width, and transverse gradients on the floodplain are generally less than 10 cm km^{-1} . Point bars are not extensive opposite well-developed levees, the construction of which requires slow lateral migration. Reproduced from Figure 8-3 of Butzer, K.W., 1976. *Geomorphology from the Earth*. Harper & Row Publishers, New York, 155 pp., with permission from LWW.

depth, slows the water, causing deposition of sediment to begin almost immediately at the channel edge, and to accumulate there faster than it accumulates as the flow continues to spread sediment across the more distant floodplain surface. The result is a more or less continuous berm near the channel, gradually declining away from the channel with gradients between 100 and 1000 cm km^{-1} . The term levee is applied to the positive feature; the more distant, slowly rising parts of the floodplain receive smaller amounts of sediment and are called 'flood basins' (Figure 6). The process of short-term levee growth has been documented on large floodplains by Aalto et al. (2003) for the Beni and Mamore rivers in eastern Bolivia and by Aalto et al. (2008) on the Strickland river in Papua New Guinea (Figure 7). Field mapping of stratigraphy and interpretations of longer-term levee growth suggest that these alluvial ridges grow wider and higher with age and thus are generally somewhat higher on the cut bank side than on the point bar side of a migrating channel.

As the levee grows, it confines high flows in the channel, allowing them to rise above the surrounding floodplain, so that vertical accretion of the floodplain may eventually be shut down for decades until a sufficiently large flood overtops the levee. The lateral gradient on the outside of the levee favors scour of a breach, or crevasse, that allows large volumes of floodwater to suddenly enter the floodplain, creating extensive packages of fine-grained sedimentary layers, either in a single event or over a number of years of high flows before the breach is healed through some combination of deposition in minor floods and choking of the breach by vegetation and woody debris that slow the flow and encourage sedimentation. Aalto et al. (2003, 2008) documented silt-clay layers several decimeters thick, separated by multi-decadal non-erosive hiatuses in the sedimentation record of the Beni, Mamore, and Strickland rivers. Close to the crevasse itself, deposition is generally sandier than the more extensive deposits, and the term 'sand splay' is reserved for such features (Figure 6). Conditions under which a crevasse survives and develops into a long-lived channel diversion will be considered later; for now we consider only the case where the

crevasse heals and the channel remains single-threaded. Especially on the convex bank side, levees are commonly penetrated by stringers and fans of sand deposited in crevasse splays and then covered with finer sediment. These buried stringers of sand later provide avenues for percolation during extended periods of high water that can undermine the levee by seepage erosion, sometimes called 'piping' (Dunne, 1990).

There is generally a downstream decrease in levee height above the surrounding floodplain from $\sim 5 \text{ m}$ to less than a meter as the dominant texture decreases from silt-fine sand to silt-clay. Repetition of levee construction and crevasse sealing as the main channel migrates within its meander belt eventually creates a broad alluvial ridge, several kilometers wide on each side of the channel. The ridge diverts runoff generated on the floodplain or in adjacent catchments into a series of channels and lakes running parallel to the main channel until their water and sediment discharges, commonly combined with those of major tributaries, create the land surface elevation and water pressure gradient necessary for them to force entry to the main channel. In some large floodplains, these channels are tens of kilometers long (e.g., Figure 11).

Measurements of sedimentation of the kind illustrated in Figure 7, together with remote sensing (see Chapter 9.35) of surface sediment concentrations (Mertes, 1994, Figure 3; 2002, Figure 6(b)), and even calculations of settling rates of fine sediment, emphasize that diffuse overbank transport of fine-grained sediment extends no farther than a few kilometers from the channel on even the largest floodplains. In addition to the settling dynamics of fine-grained sediment (especially when it is flocculated in the presence of dissolved organic compounds), the advection of water as well as sediment into a large lowland floodplain is commonly resisted by the presence of meters of water that may have accumulated before the flood rise as a result of seasonal rains onto the floodplain and surrounding uplands (Mertes, 1997). The limitation on diffuse sedimentation far from the main channel allows morphological features of the distant floodplain to remain distinct for centuries to millennia (Dietrich et al., 1999; Aalto et al., 2008).

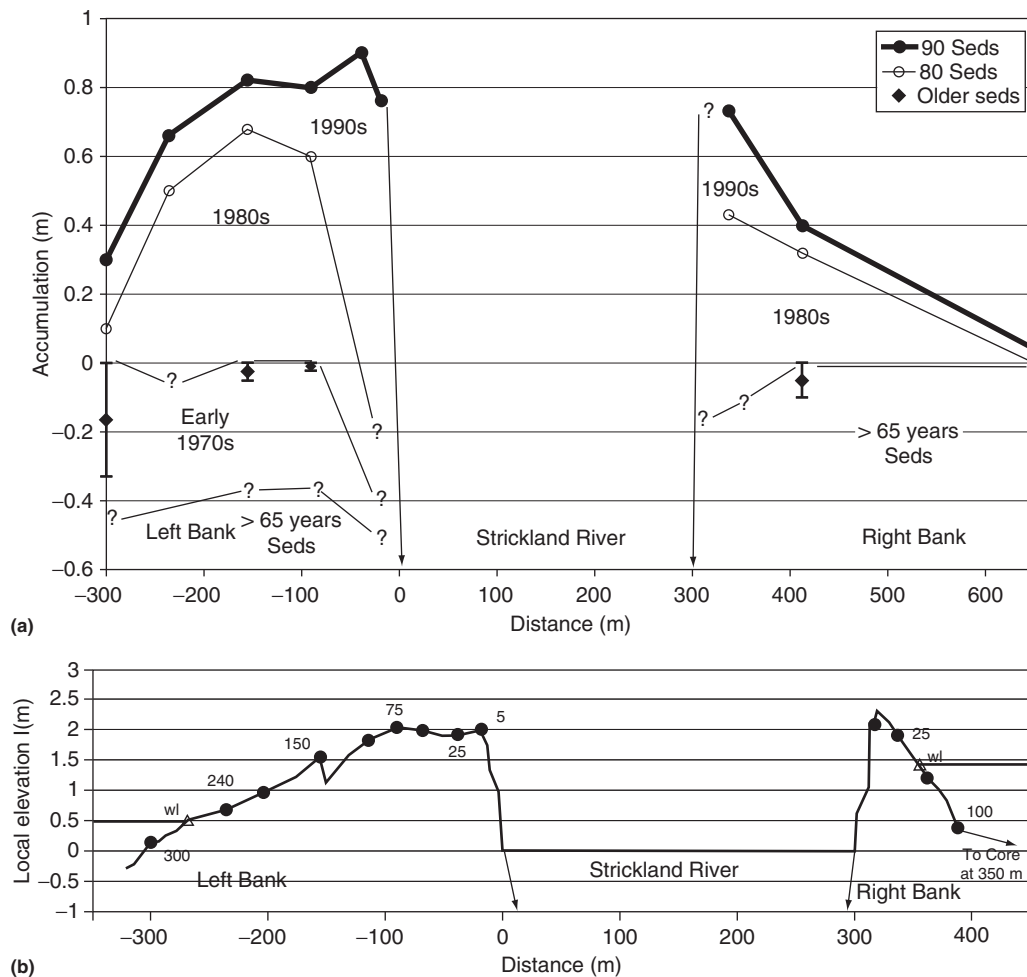


Figure 7 (a) Cross-section of depositional lenses emplaced across transects on both sides of the Strickland River, Papua New Guinea. The ages of the sedimentary packages were determined by dating sediment samples in cores with the isotope ^{210}Pb . Points above zero on the accumulation axis indicate the depth of post-1980 sediment (23 years, or one ^{210}Pb half-life). (b) Topographic cross-section for transect 2. All coring locations are marked with circles, with the distance noted for the core locations that were dated. Modified from Figure 6 of Aalto, R., Lauer, J.W., Dietrich, W.E., 2008. Spatial and temporal dynamics of sediment accumulation and exchange along Strickland River floodplains (Papua New Guinea) over decadal-to-centennial timescales. *Journal of Geophysical Research – Earth Surface* 113, F01S04, doi:10.1029/2006JF000627, with permission from Journal of Geophysical Research.

Sediment is also distributed into the floodplain by channelized flow in a complex set of distributaries with diverse origins (see Figure 20). Figures 8–12 provide examples of the diversity of form, orientation, and scale of such channels in the case of the Amazon floodplain. These channels may develop by levee breaching along the main channel; by maintenance of hydraulic connections between the main channel and a lake with seasonal alternations of sediment flushing; as tributaries from the fringing landscape; and as conduits kept open by runoff generated from a large, rainy floodplain. Mertes et al. (1996) conducted a statistical survey of scroll bars on the Amazon floodplain, and concluded that most of the floodplain channels recorded by the scroll bars were much smaller than the main channel. Dunne et al. (1998) measured the geometry of all major distributary channels along the Brazilian Amazon and computed that they trapped approximately 35% as much sediment as was exported by the river to tidewater (drainage area 4.64 million km^2). The amount of

sediment stored in this way involved a balance between export from the channel and the trap efficiency of each channel, both of which increased with the size of the distributing channel. Both the number and size of the channels and the sediment concentrations being decanted into them vary with the large-scale physiography of the valley and the hydrology of the river and floodplain.

Most of the large floodplain channels that decant sediment from the Amazon rejoin the main channel, while the smaller ones spread sediment into lakes and progressively smaller sloughs between scroll bars or levee complexes (Figures 8–12). Some, however, enter lakes formed by the inundation of extensive, low areas of the floodplain, including those where sedimentation has not yet fully responded to modern sea level. Examples occur ENE of the labels ‘Rio’ and ‘Amazonas’ in Figure 12, and particularly in the latter location they form a maze of leveed channels with intervening lake remnants. This appears to be a way of transporting suspended

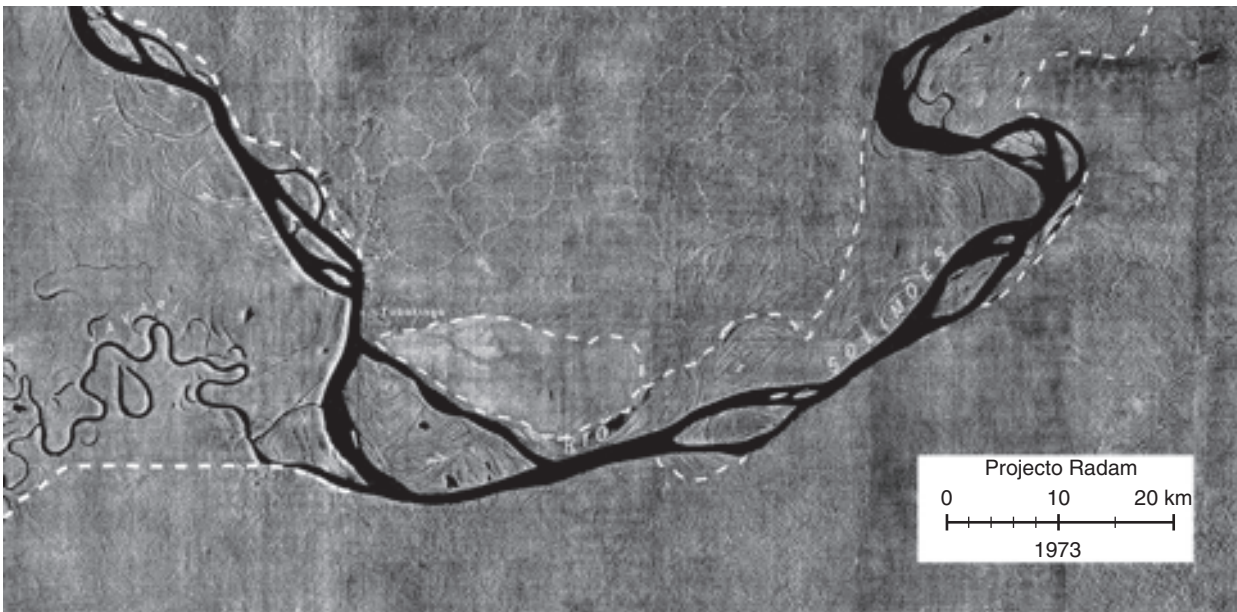


Figure 8 Low-flow image of the Solimões River reach, Brazil centered approximately at $69^{\circ}45'$ W where the river crosses the Jutai Arch, approximately at 550 km in **Figure 1(b)**. The floodplain with scroll bar topography is generally less than 10 km wide, and the channel impinges on cohesive terrace materials throughout most of the reach. The dashed white curves outline the boundary between the modern floodplain and the higher terrain that has not been alluviated probably since the late Tertiary and has been eroded by distinctive drainage networks. The closed dashed polygon north of the river in the central portion of the image is probably an older portion of the floodplain on which the scroll bars, channels, and narrow lakes that dominate the modern floodplain have been smoothed by either erosion or overbank sedimentation. Radar image from the Radambrasil Project. Source: Government of Brazil.

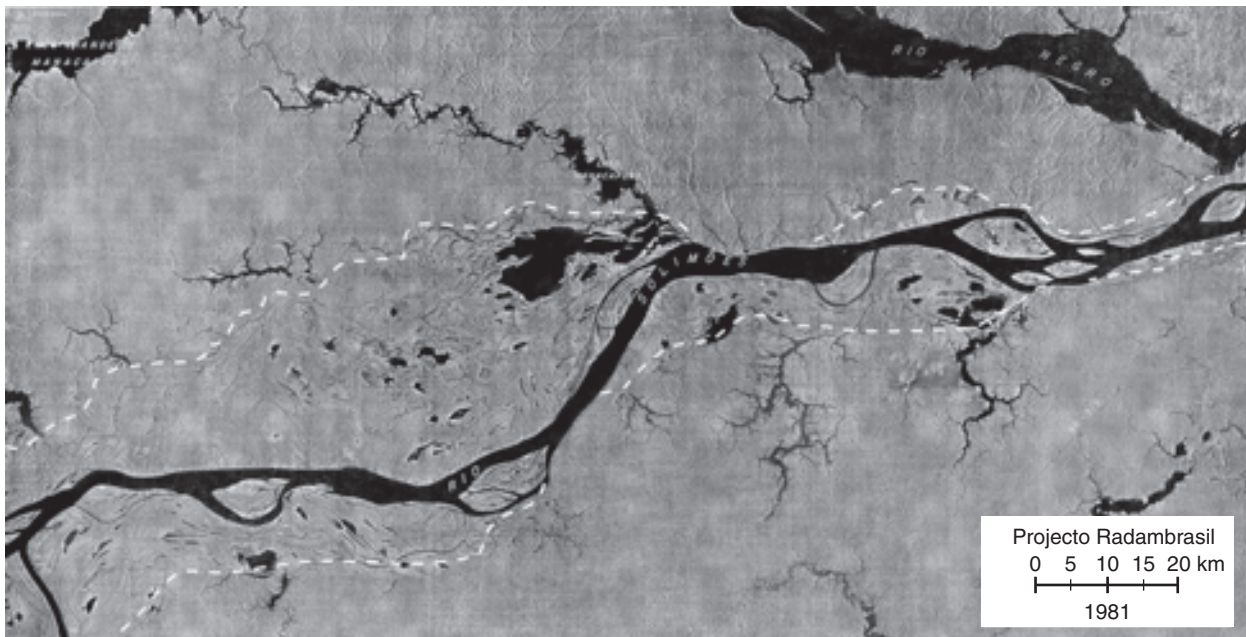


Figure 9 Low-flow image of the Solimões River reach between the Purús River (lower left corner) and Negro River (upper right corner) confluences, centered approximately at $60^{\circ}45'$ W near Manacapurú at 2030 km in **Figure 1(b)**. The dashed white curves outline the boundary between the modern floodplain and the higher terrain that has not been alluviated probably since the late Tertiary and has been eroded by distinctive drainage networks. Small, sediment-poor streams draining from the Tertiary sediments across the floodplain margins are dammed by tectonic tilting and the rapid alluviation of the mainstem floodplain. The Solimões–Amazon River is crossing the Purús Arch in the eastern half of the image, and the floodplain is narrow and the channel steep [around 2000 km in **Figure 1(b)**]. Radar image from the Radambrasil Project. Source: Government of Brazil.

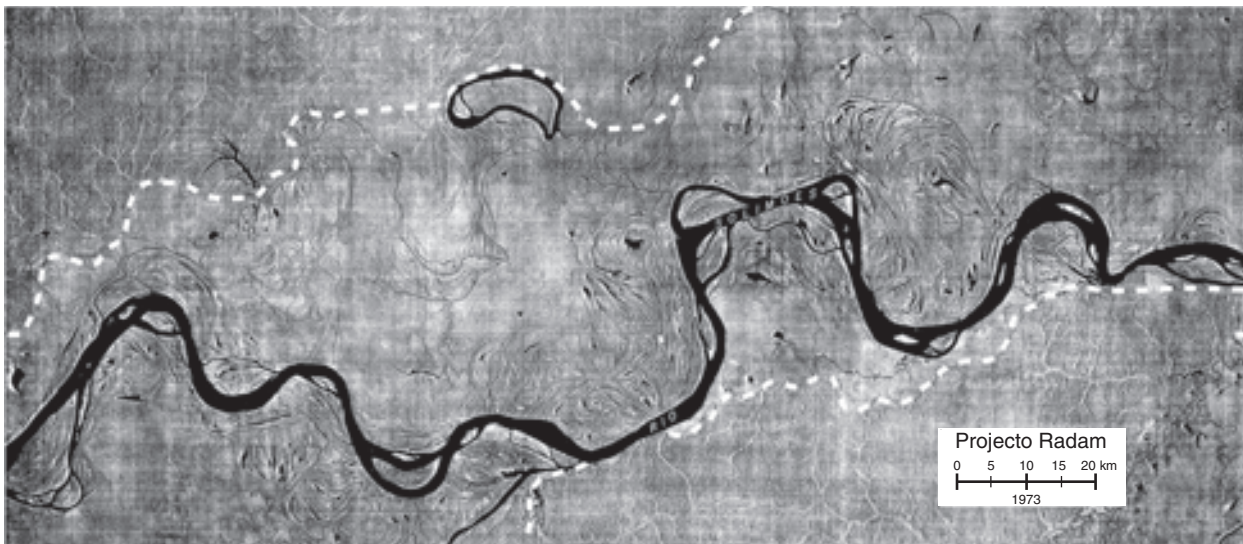


Figure 10 Low-flow image of the Solimões River reach centered on $66^{\circ}45'$ W downstream of the River Jutai confluence at 1100 km in **Figure 1(b)**. In the tilted fault block reach between the Jutai and Purús Arches in **Figure 1(b)**, the floodplain is wide, allowing the development of large meanders, extensive scroll bars, and an abandoned oxbow lake. The dashed white curves outline the boundary between the modern floodplain and the higher terrain that has not been alluviated probably since the late Tertiary and has been eroded by dendritic drainage networks. The ages of the various surfaces within the Quaternary floodplain are unknown. Radar image from the Radambrasil Project. Source: Government of Brazil.

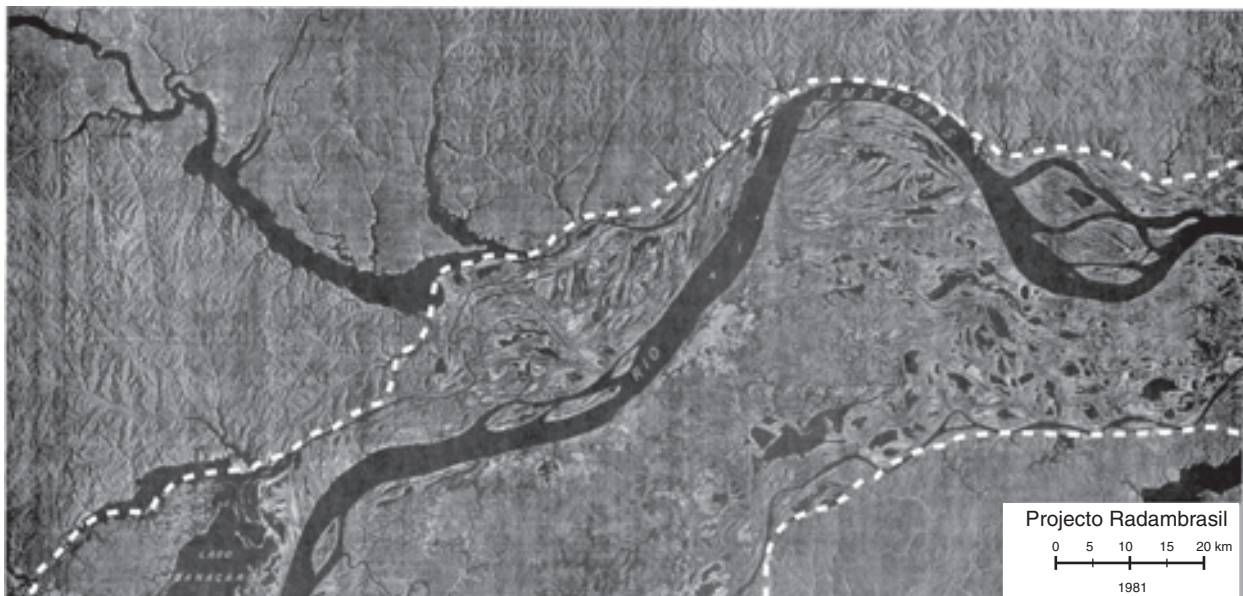


Figure 11 Low-flow image of the Amazon River reach centered at $57^{\circ}45'$ W approximately at 2450 km in **Figure 1(b)**, ~150 km downstream of the Madeira River confluence. The floodplain is 40–50 km wide and includes scroll bar topography near the river and irregular lake networks farther from the channel. The dashed white curves outline the boundary between the modern floodplain and the higher terrain that has not been alluviated probably since the late Tertiary and has been eroded by distinctive drainage networks. Sediment-poor tributaries draining from the Guiana Shield and Tertiary sediments across the floodplain margins are dammed by the rapid alluviation of the mainstem floodplain. Radar image from the Radambrasil Project. Source: Government of Brazil.

sediment into the inundated floodplain in the face of the aforementioned pressure gradient that limits the penetration of diffuse overbank sediment transport. Morphologically, these channels appear to be broadly similar to ‘tie channels’ documented by Blake and Ollier (1971), Gagliano and

Howard (1984, **Figure 3**) on the lower Mississippi, and Rowland et al. (2009) along the Fly River, Papua New Guinea (drainage area $\sim 18\,400\text{ km}^2$), and other large rivers. Rowland et al. (2009) interpreted these channels as resulting from the maintenance of a flow connection from the main channel

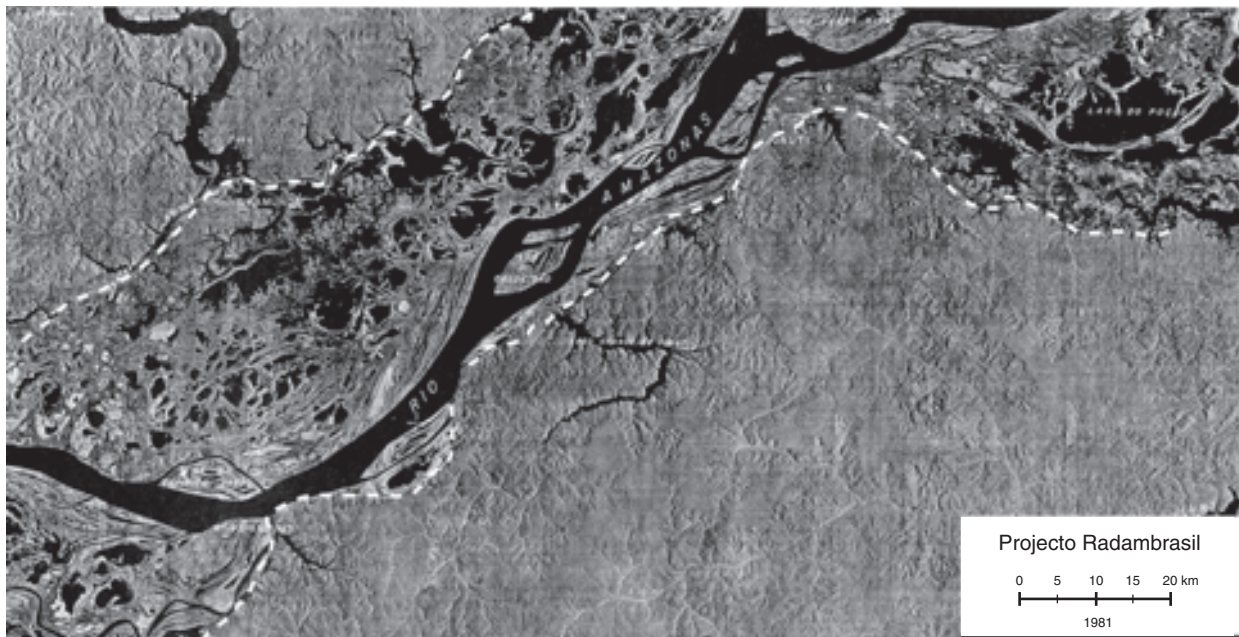


Figure 12 Low-flow image of the Amazon River reach centered at $56^{\circ}15'$ W approximately at 2650 km in **Figure 1(b)**. The Óbidos gauging station, at the head of tidewater, is immediately north of the NE corner of the map. The floodplain appears to be 'underfilled,' with a large area of lakes separated from the channel by narrow scroll bars and levees that are almost straight. Small channels entering these lakes from the main channel or from tributaries build leveed channels and small deltas into the lakes. The dashed white curves outline the boundary between the modern floodplain and the higher terrain that has not been alluviated probably since the late Tertiary and has been eroded by distinctive drainage networks. Sediment-poor tributaries draining from the Guiana Shield and Tertiary sediments across the floodplain margins are dammed by the rapid alluviation of the mainstem flood plain. Radar image from the Radambrasil Project. Source: Government of Brazil.

through the partially sealed plug at the end of an oxbow lake. The invading water generates a sediment-laden jet, and sedimentation along the margins of the jet builds subaqueous levees, which reduce the spreading of the jet. The process of subaqueous levee construction was investigated quantitatively in laboratory experiments by Rowland et al. (2010). The subaqueous levees are extended and raised to the surface, where they are stabilized and augmented with sediment trapped by colonizing vegetation so that they also grow laterally in the manner described earlier for levees along the main channel.

The channels extend into open lake waters, with no measurable lateral migration, at rates of meters to tens of meters per year, depending on the sediment concentrations in the water emerging from the main channel (Figure 13). The channels remain open as long as they can be scoured by clear water returning to the main channel from the lake in the low-flow season. The channel morphology appears to result from a dynamic balance between levee sedimentation and channel scour and mass failure of the banks. The leveed channels in the Amazon floodplain (Figure 12) have major similarities with the tie channels studied by Rowland et al. (2009) in the sense that they appear to be self-formed leveed channels that have prograded across inundated portions of the floodplain. However, their morphology is more complex in that some of them bifurcate, some arise from tributaries, and they are not entering oxbow lakes through a partially sealed sediment plug. An opportunity arose to document the influence of channelized flows in exporting sediment to a lowland floodplain when a catastrophic sediment release, traceable by its distinctive copper content, increased the suspended sediment

concentration of the Fly River approximately fivefold. Day et al. (2008) mapped the spread of this sediment into the floodplain over the succeeding decade, finding that tie and other floodplain channels decanted and trapped more than 40% of the total suspended load in the middle Fly River.

9.32.5.3 Sedimentation in the Distal Floodplain

More than a kilometer from most main channels, but close to the main channel in cases where the floodplain has remained incompletely filled since the beginning of the Holocene sea-level rise (e.g., Figure 12), sedimentation may be exceedingly slow. This is because neither diffuse nor channelized overbank flow can transport sediment that far against the resistance of vegetation or the pressure of water stored in the floodplain, or because high natural levees prevent overbank sedimentation near the channel. These parts of floodplain surfaces are ~ 1 – 10 m lower than the general elevation of the plain, and form shallow dish-shaped depressions, oriented roughly downvalley, and occupied by lakes or swamps, in some places with irregular shorelines that suggest continuing subsidence. In the lower Amazon, which occupies a graben, tectonic subsidence, coupled with continuing eustatic sea-level rise, appears to be favoring the continual production of new flooded accommodation space, and lakes are widespread (Figure 12). Even along large rivers, such as the lower Mississippi, which aggraded their valley floors rapidly during the Holocene transgression, or rivers such as the middle Sacramento River in the Central Valley of California, which was



Figure 13 (a) False-color aerial photograph of a tie channel connecting the Raccourci Old River oxbow lake to the Mississippi River (top) approximately 65 km north of Baton Rouge, Louisiana, USA. An * marks the channel junction with the river and the # sign indicates the channel terminus in the lake. (b) Enlarged view of a sediment-laden jet entering the lake at the Raccourci Old River channel. (c) A 95 m-wide section of the tie channel one kilometer from its junction with the Mississippi River. The vertical scar in the foreground and the back-rotated tree stumps in the channel mark failure blocks. Reproduced from Figures 1(a), 1(b), and 13 of Rowland, J.C., Dietrich, W.E., Day, G., Parker, G., 2009. Formation and maintenance of single-thread tie channels entering floodplain lakes: observations from three diverse river systems. *Journal of Geophysical Research* 114, F02013. doi:10.1029/2008JF001073, with permission from *Journal of Geophysical Research*.

only slightly affected by sea-level rise, sedimentation more than a few kilometers from the channel is very slow, and topographic lows, or ‘flood basins,’ are semi-permanent landscape features. Lakes in these environments are typically shallow, and some are seasonal. Other flood basins in drier climates are centrally drained to a seasonal lake by irregular, low-gradient streams, heavily impacted by riparian vegetation. The typical sediments of flood basins are massively bedded clays and peats, which drain very slowly, although occasional intrusions by sand-transporting water from levee breaks or floodplain channels can leave strings of coarser sediment. Flood basins may also receive fans of sediment from small tributaries, although a significant sediment source would replace all but the largest flood basins with an alluvial fan.

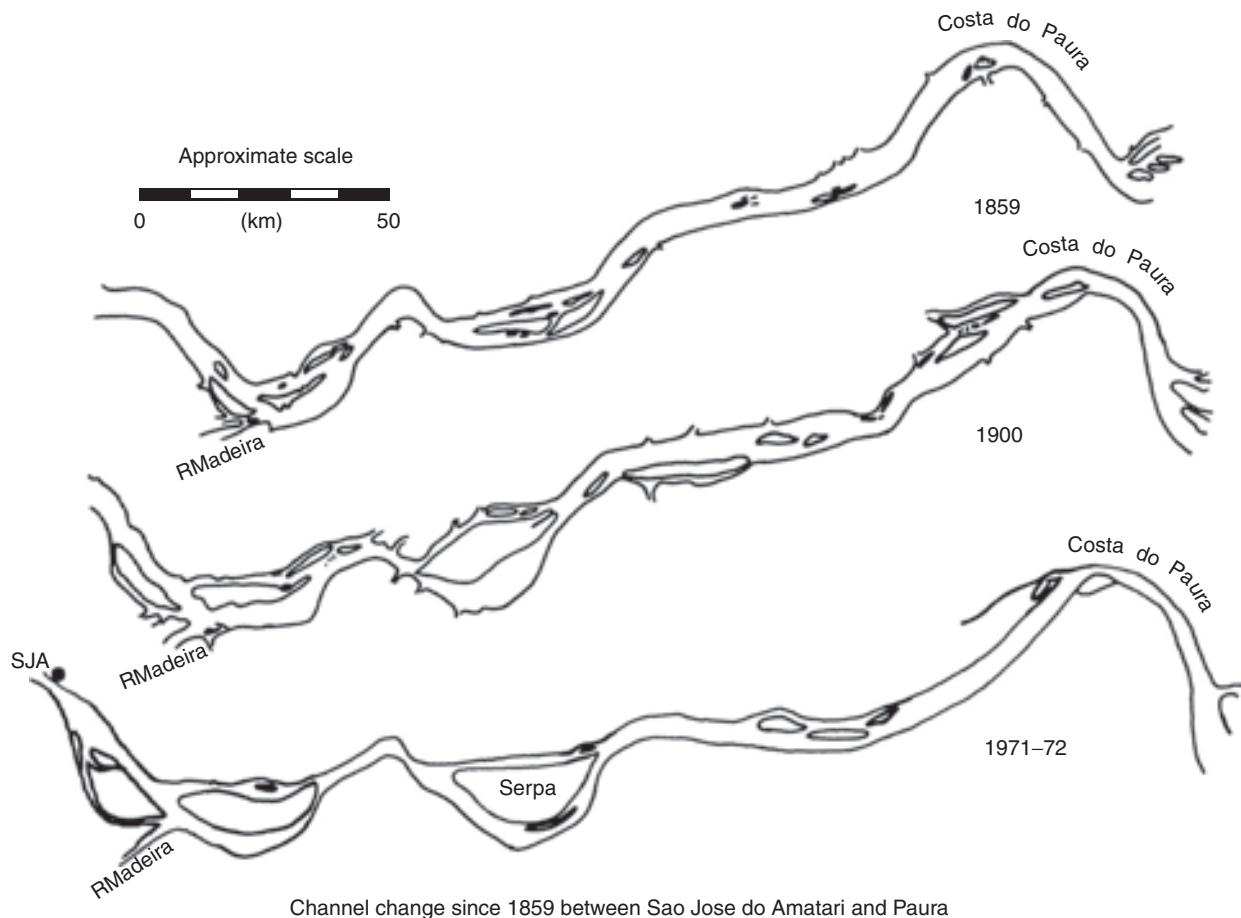
Figures 9, 11, and 12 also indicate that some floodplains contain marginal lakes, produced by the blockage of runoff from surrounding terrain. The blockage may be due to aggradation (Figures 11 and 12) or tectonic tilting (Figure 9). Where the size and erodibility of the tributary landscape are low, the lakes have persisted throughout the Holocene. Figure 11 also demonstrates that in a wet region where the quantity of runoff is high, the low floodplain margins

commonly provide avenues for channels of considerable size that collect runoff from the floodplain, the marginal landscape, and even some main-channel water, eventually conveying to the main channel far downstream of its origin.

9.32.5.4 Consequences of Single-Thread Channel Mobility for Floodplain Construction

The foregoing text presumes that an immobile, single-thread channel and its local floodplain hydrology create the hydrodynamic and sedimentation processes constructing a floodplain. It is now possible to build on this simple model by engaging the Nanson–Knighton classification scheme portrayed in Figure 2 and the processes which it implies to examine divergences from the simplest case. In this section, we will continue to focus on the single-thread case in the upper left of Figure 2.

Since no large river remains straight for a long distance, our application of the Nanson–Knighton classification begins with rivers, such as reaches of the Amazon, which have sinuosities of 1.0–1.1. It is not clear why an almost-straight large river would not develop greater sinuosity through the processes



Channel change since 1859 between Sao Jose do Amajari and Paura

Figure 14 History of channel migration and floodplain formation in a reach of the Lower Amazon River, including the reach shown in **Figure 11**, with a modern sinuosity of 1.3. The channel gradient varies seasonally between 0.4 cm km^{-1} at low flow and 3.0 cm km^{-1} at high flow (valley gradient of $\sim 2 \text{ cm km}^{-1}$). The river bends encounter the cohesive edges of terraces (also outlined by white dashes in **Figure 11**), which constrain the development of sinuosity. The river is steepening as it approaches the Monte Alegre and Gurupá structural highs (**Figure 1**), which are probably driven by upward flexuring of the continental crust by the load of the Amazon Fan (Driscoll and Karner, 1994). **Figure 9** shows similar constraints on bend formation as the river flows across the Purús Arch. The maps are not accurately georeferenced. The 1859 and 1900 maps were traced from river-level surveys provided by Professor H.O. Sternberg, and the 1971–1972 map was traced from radar aerial photography supplied by Radambrasil.

driven by flow asymmetry referred to in Section 9.32.5.1. Possibilities include: confinement by cohesive terraces or bedrock valley walls where a large river begins to develop bends scaled to its width and discharge (**Figures 8, 9, 11**); a dearth of bed material able to accumulate as point bars (also true of the lower Amazon); and a low channel gradient that keeps the shear stresses on the bed and outer banks of bends low, possibly even below some threshold value required to scour the banks or pools. Dietrich et al. (1999) applied Howard's (1992) suggestion of a threshold to explain the immeasurably slow rate of migration of the middle Fly River. Gagliano and Howard (1984, p. 148) also suggested that an abrupt reduction of valley gradient in the lowermost 240 km of the Mississippi River explained how the river "loses its tendency to meander," whereas in the 885 km upstream, with a valley gradient of 15 cm km^{-1} , it created neck cutoffs at the rate of 13–15 per century. US Geological Survey stage records spanning the lowermost reach indicate water-surface gradients

of $\sim 3 \text{ cm km}^{-1}$ at high flow and $\sim 0.15 \text{ cm km}^{-1}$ at low flow, suggesting an averaged valley slope of $\sim 1.5 \text{ cm km}^{-1}$. **Figure 14** and its caption illustrate the history of channel migration along a reach of the lower Amazon, which has a low sinuosity and migrated very slowly throughout the twentieth century on a valley gradient of $\sim 2 \text{ cm km}^{-1}$. The low sinuosity and migration rate appear to result at least in part from confinement of the river planform by cohesive terraces. In this reach, one can see a basis for Latrubesse (2008) to classify the planform as anabranching, but the channel also has a definite meandering habit with a main channel sinuosity of 1.3.

The second element of the Nanson–Knighton classification is the stable-sinuuous channel. Again, it is difficult to understand from a geometric or a fluid mechanical point of view how a sinuous channel could always be immobile, so presumably a formerly meandering channel generated the bends, and either they continue to evolve but at rates that are not

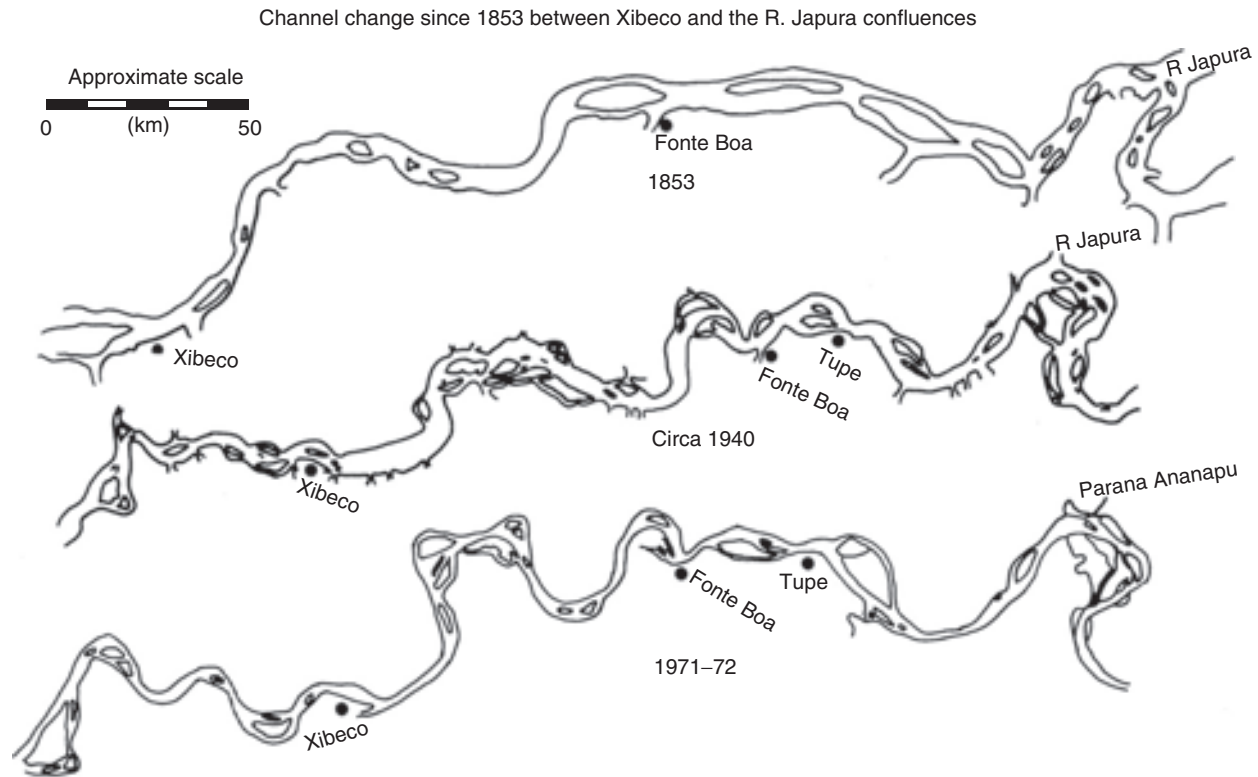


Figure 15 History of channel migration and floodplain formation in a reach of the Solimões River (middle Amazon River) centered on the reach in [Figure 10](#), with a sinuosity of ~ 1.6 . The channel gradient is $3\text{--}3.5\text{ cm km}^{-1}$. The maps are not accurately georeferenced. The 1853 map was surveyed from river level, the 1940 map from aerial photography, and the 1972 map was traced from aerial radar photography by Radambrasil. More details about the surveys are provided by [Mertes et al. \(1996, Figure 6\)](#).

measurable with the techniques applied so far, or the river has recently been rendered immobile through a reduction of gradient or bed-material supply or an increase in bank strength. [Dietrich et al. \(1999\)](#) suggested that a reduction of gradient to $\sim 2\text{ cm km}^{-1}$ on the middle Fly River, caused by downstream sedimentation, might account for the very slow rates of channel migration and the freshness of evidence for earlier channel migration in the floodplain.

The freely meandering component of the Nanson-Knighton classification can be recognized on a wide range of large rivers, even if one allows [Latrubesse's \(2008\)](#) point that the largest rivers also tend to develop a sufficient number and size of side channels to be considered multi-threaded. For example, in [Figure 10](#), the middle Amazon (drainage area 1.2 million km^2 ; valley gradient $\sim 3\text{ cm km}^{-1}$) has a strong meandering planform with a sinuosity of ~ 1.5 and both morphological and mapped evidence for channel migration rates of up to $\sim 25\text{ m yr}^{-1}$ over the previous 150 years ([Figure 15](#)). Similarly, [Gautier et al. \(2007\)](#) documented rapid meander migration patterns in the Beni River as it drains the foreland of eastern Bolivia (drainage area 67 500–282 500 km^2 ; gradient $100\text{--}10\text{ cm km}^{-1}$).

[Dunne et al. \(2010\)](#) proposed that there is a fundamental difference in river behavior and floodplain form between valley floors in which the river can incise its floodplain and those in which it can never or only very rarely do so. On floodplains of smaller rivers, upstream migrating cutoffs have

been documented, resulting from perturbations such as ice jams or log jams that force water out of the channel lowering the downstream stage and inducing upstream migration (e.g., [Gay et al., 1998](#)), but such blockages seem to be rare on large rivers. The original proposal was based on the analysis by [Constantine et al. \(2009b\)](#), whose conceptual model and calculations suggested that the incision of a chute cutoff channel across the floodplain requires a combination of valley slope and vegetation density that will allow sufficient excess flow energy and shear stress to scour sediment from the floodplain surface where water spills from the channel downstream of the bend axis. Of course, the precise location and trajectory followed by a chute cutoff channel after the floodplain surface is breached would be affected by swales between scroll bars and former channels, but the calculations illustrating this principle were made for a flat floodplain surface.

In floodplains where the valley gradient is low and the lower-storey vegetation is dense (and possibly where the floodplain sediment is cohesive), the probability of chute cutoff is very low. In this case, all floodplain erosion would be expected to occur through lateral bank erosion in the manner described in Section 9.32.5.1, and modeled by [Ikeda et al. \(1981\)](#), [Howard and Knutson \(1984\)](#), and [Johannesson and Parker \(1989\)](#), until the sinuosity of the channel increases sufficiently to cause neck cutoff. Based on this conceptual model, [Stølum \(1998\)](#) used simulations of the long-term

evolution of trains of river bends and a rule for neck cutoff development to propose that the monotonic increase in sinuosity and asymmetry of bends is eventually balanced by censoring of the bends through neck cutoff, producing stable populations of bend and oxbow lake lengths. Constantine and Dunne (2008) expanded on this principle with a survey of 30 large, lowland rivers on various continents showing that the cutoff process produces a characteristic and predictable size-frequency distribution of oxbow lakes the mean of which depends on the sinuosity of the river. Assumption that the average sinuosity remains constant over time then allows a calculation of the frequency of cutoff from a prediction of bend lengthening with a modification of the Johannesson and Parker (1989) method.

In other words, there are characteristic rates and forms of channel cutoff and oxbow lake production that depend on valley gradient, type of floodplain vegetation, and the erodibility of the floodplain surface sediments. Where lateral floodplain erosion is limited to undermining of banks and neck cutoff is favored, the rivers have irregular, high-sinuosity planforms and the floodplain contains a relatively high frequency of long, sinuous oxbow lakes, developed through neck cutoff, and therefore having high angles of divergence between the arms of the oxbow and the shortened channel. Figure 16(a) shows an example of this kind of floodplain, developed in the central Amazon basin under conditions of low gradient, thickly vegetated floodplain, and clay-rich alluvium. Stølum's (1998) simulations of river planforms and oxbow lakes were supported by a survey of the characteristics of floodplains in the central Amazon basin for these reasons.

Furthermore, the analysis by Constantine et al. (2010) of how the divergence angles of cutoff channels affect patterns of bed-material accumulation predicts that high-angle cutoffs, common at the entrances and exits of oxbows produced by neck cutoff, should shoal rapidly with relatively little penetration of bed material far along the oxbow (Figure 17(a)). A sedimentary plug typically forms at the ends of such oxbows, as documented through the field investigations summarized in the conceptual model of neck cutoff evolution by Gagliano and Howard (1984) and Saucier (1994), shown in Figure 18, and confirmed by other field studies (e.g., Piégay et al., 2002; Rowland et al., 2009). Under the sediment transport conditions on most low-gradient, thickly vegetated floodplains, transportation of washload into these neck cutoffs is also slow and the lakes are likely to survive for long periods of time, sometimes being filled by the tie channels studied by Rowland et al. (2009) and illustrated in Figure 13. Saucier (1994) also documented that a sediment-rich river such as the Mississippi can develop sinuosity and build levees quickly along the shortened channel, causing the levee to once again approach or even cover the oxbow lake (Figure 18).

In floodplains that are sufficiently steep, thinly vegetated, and surfaced with relatively erodible sediment, Constantine et al. (2009b) and Dunne et al. (2010) proposed that before the bend growth process can create a neck cutoff, a sufficiently large overbank discharge would scour an embayment into the floodplain and extend it into a chute cutoff. In the cases they studied along the Sacramento and Missouri rivers, the initial embayments developed a short distance downstream of the

bend apex, approximately where the calculated superelevation of the water surface and the velocity of water leaving the channel were greatest. Bank erosion contributes to this process by progressively increasing the channel curvature. However, before the sinuosity attains a value of more than ~ 1.5 , chute cutoff occurs. Figure 16(b) illustrates results of the chute cutoff process on channel alignment and oxbow lakes for the Sacramento River, California, a sand- and gravel-bed river approximately 10 times steeper than the Purús, shown in Figure 16(a). The sequence of events by which high-velocity overbank flow extends a trough across the floodplain to create a chute is illustrated by the sequence of images in Figure 19. At these locations, the uppermost increment of the channel flow is no longer steered by the riverbank but instead enters the floodplain, flowing in a direction that closely parallels the channel immediately upstream of the overbanking location as well as the valley slope.

The chute may cut across the point bar farther downstream than indicated in Figure 19 if water flows overbank through a swale between scroll bars (Figure 20), enlarging the swale until it conveys most of the main channel flow (Saucier, 1994, p. 113, reporting on observations by Fisk). Some of the chute cutoffs on the Fly River appear to be of this type. Slow vertical accretion that leaves swales open for long periods would favor this process. The long duration of overbank flow along large rivers, referred to in Section 9.32.3, would also favor the process, particularly where peak suspended sediment concentrations (see Chapter 9.9) occur on the rising limb of the hydrograph and decline during the flow peak and lengthy recession. In this situation, the increased gradient along the shorter path would compensate for the extra drag caused by entering the smaller channel, and if the swale is vegetated, the same conditions of flow depth, gradient, sediment erodibility, and plant density described above would have to prevail.

In order to formalize these relationships between overbank flow depth, flow path gradient, sediment erodibility, and plant density, Constantine et al. (2009b) used a method developed by Smith (2004) for flow through uniformly spaced cylinders penetrating the water surface in order to calculate flow velocity and the boundary shear stress on the underlying floodplain surface. The results suggest, for example, that overbank flow entering a sandy floodplain with a gradient like that of the Sacramento ($\sim 3.3 \times 10^{-4}$ in one of the reaches for which computations were made) decreases its velocity because of the reduction in flow depth and the increase in frictional energy loss due to the vegetation. Extraction of momentum from the flow decreases the boundary shear stress available for transporting sediment on the underlying floodplain surface. Constantine et al. (2009a) measured *in situ* the critical value of the shear stress required to initiate erosion and sediment transport on such a sandy surface and on other floodplain sediments along the Sacramento River. The critical values varied from 0.01 to 0.03 Pa for clay-rich soils, to 0.01–0.1 Pa for sand, to 1.6–2.8 Pa for sandy gravel, and 3.9 Pa for weathered terrace gravel, indicating another important control of sediment transport and sedimentation on the channel cutoff process.

However, the dominant control of floodplain surface erodibility appeared to be vegetation type and density.



(a)



(b)

Figure 16 (a) Google Earth™ image of the Purús River floodplain, a tributary of the central Amazon River, with a sinuosity of 2.75 and abundant evidence of recent and imminent oxbow lake generation by neck cutoff. Most of the divergence angles between cutoff entrances and the residual channel are high. (b) Aerial photo mosaic of the floodplain of the middle Sacramento River in the Central Valley of California with a sinuosity of 1.35 with oxbow lakes produced mainly by chute cutoff, which generates a wide range of diversion angles between the cutoff entrance and the residual channel. Image courtesy of the California Department of Water Resources.

The Smith (2004) model predicts that where the riparian vegetation consists of shrubs (with a stem diameter of ~ 0.5 cm), flow is only competent to transport sand if the ratio of plant stem spacing to stem diameter exceeds 35–40. Greater densities of shrub stems would protect against incision of a chute. Similar calculations for a floodplain covered with trees with a trunk diameter of 0.35 m showed that an average trunk spacing denser than 1.75 m would be required to resist chute incision (Constantine et al., 2009b, Figure 14). Such a density is not widely observed for mature floodplain trees with large canopies. However, a floodplain with a gradient of 5×10^{-5} (similar to Amazon lowland tributaries) would be

protected by shrubs stems spaced only one-third as densely as the Sacramento case.

The results imply that sandy floodplains with gradients like that of the Sacramento with mature forest canopies would frequently be incised by chute cutoffs if it were not for the stabilizing effect of dense covers of small plants and possibly other small woody fragments such as fallen branches. Thus, the penetration of light to the forest floor, aided by disruption of the forest canopy by overbank flooding, frequent collapse of large branches, and plant strategies such as shade tolerance or early sprouting before deciduous canopies have leafed out would all contribute to the growth of dense shrub layers and

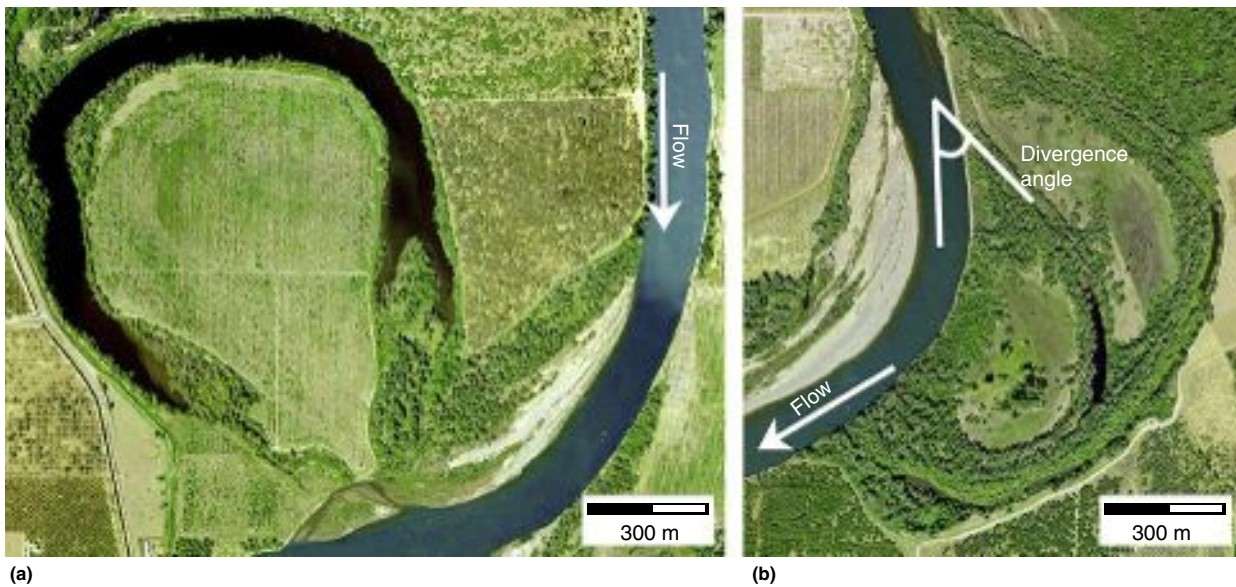


Figure 17 (a) A Sacramento River oxbow lake formed by neck cutoff (and therefore producing two large divergence angles) 134 years before the aerial photo was taken. (b) An oxbow lake formed by a chute cutoff (and therefore with a lower divergence angle) 18 years before the date of the aerial photo. An aerial photo taken 15 years after this cutoff occurred shows active sedimentation on bars along the concave bank throughout the length of the cutoff channel. Reproduced from Constantine, J.A., Dunne, T., Piégay, H., Kondolf, G.M., 2010. Controls on the alluviation of oxbow lakes by bed-material load along the Sacramento River, California. *Sedimentology* 57, 389–407. doi: 10.1111/j.1365–3091.2009.01084.

floodplain resistance. On the other hand, if the critical shear stress values measured by Constantine et al. (2009a) for sandy gravel are used in the calculation, they indicate that even sparse vegetation covers are sufficient to stabilize steep gravelly floodplains against channelized incision.

Another implication of the chute cutoff process, visible in Figure 16(b), is that the chute cutoff process generates a generally lower but wider range of cutoff diversion angles than does the neck cutoff process. Constantine et al. (2010) modeled how lower diversion angles promote the washing of bed material farther along the oxbow lake and faster, more extensive transition of the lake into swamp and then plain morphology (Figure 17).

Slingerland and Smith (1998, 2004) proposed a set of required conditions for cutoff channels to remain open after a sufficiently high overbank flood has scoured a crevasse channel down the outer margin of a levee. The lateral gradient of the levee or the meander belt would favor this process, though the potential effect of vegetation would have to be considered. The process is relevant to channels which develop significant levees (unlike the Sacramento reach in Figure 16(b)). Slingerland and Smith computed the conditions that would lead suspended sediment from the breach to settle out and fill the cutoff channel or be transported out of the cutoff, keeping it open. They proposed that the depth of the initial incision, together with the grain size and concentration of the incoming sediment, the bed-material grain size of the chute channel, and the ratio of crevasse slope to main channel slope, would determine whether the crevasse heals, erodes to the depth of the main channel, or evolves to a stable intermediate depth. Smith et al. (1989) documented and interpreted a large-scale case of avulsion by

the sediment-rich Saskatchewan River (drainage area $\sim 390\,000\text{ km}^2$) into a low-gradient reach of floodplain. The avulsion initially created a complex of sand splays with multiple channels, the number of which gradually declined to a single-thread, meandering channel on an alluvial ridge as the floodplain was built up, gradient increased, and riparian vegetation provided flow resistance and bank reinforcement that confined flows.

The range of locations for chute cutoff channels – across the point bar, near the axis of the bend, or randomly at a levee breach (in this case filled by a sand splay deposit) – is captured in Figure 21 by Holbrook et al. (2006) in their conceptual model of the sinuous meandering reaches of the Missouri River. However, since the Missouri is generally a wide, shallow river with considerable sandy bed-material load, even its meandering reaches are close to the development of braiding (see later).

In each of the above cases, single cutoffs or splays are envisioned, and it is taken for granted that the frequency with which they occur is sufficiently low to allow the time required for the new cutoff to grow and gradually consume the entire flow of the main channel, allowing the main channel to remain single-threaded. Sequences of maps and aerial photographs and ^{14}C dating of sediments indicate that the time required for complete diversion of the main channel flow and the isolation of the old channel varies from years to decades, and the time required for conversion of the oxbow lake to a plain coincident with the rest of the floodplain surface varies from decades to thousands of years (possibly, for example, the large oxbow lake on the north side of the Amazon floodplain in Figure 10), depending on the original orientation of the diversion angles, and the flow regime and suspended sediment load of the main channel.

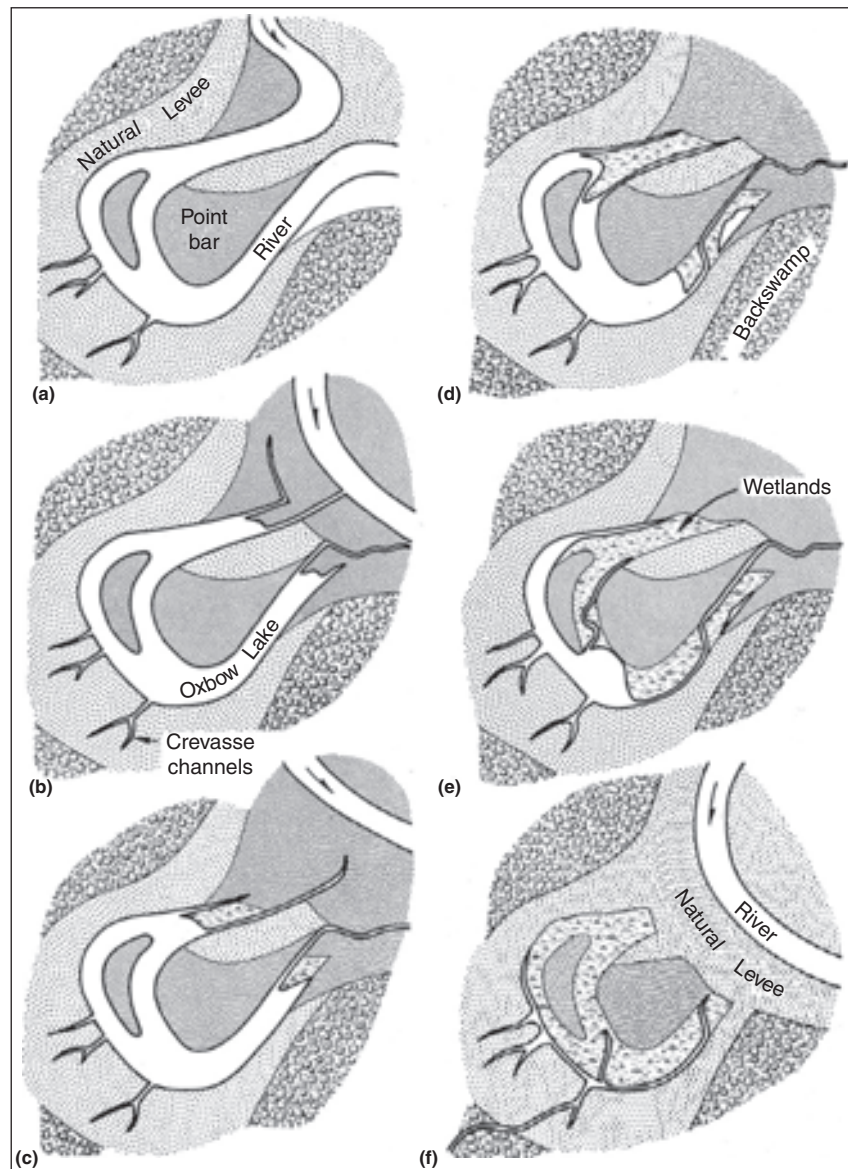


Figure 18 Conceptual model of the life cycle of an oxbow lake produced by neck cutoff and filled by tie-channel incursion, diffuse settling, and main-channel levee encroachment. Reproduced from Saucier, R.T., 1994. *Geomorphology and Quaternary geologic history of the lower Mississippi Valley*. Mississippi River Commission, Vicksburg, 364 pp.

9.32.6 Floodplain Construction by Single-Thread Braided Rivers

Discussion of floodplain formation by large braided rivers is complicated by the lack of agreement on where it is possible, or useful, to establish a clear separation in the field between an active braided channel with well-defined banks, encompassing a complex of bars, multiple thalwegs, and a more stable floodplain consisting of sedimentary landforms that become isolated from, and evolve independently of, the channel for some significant period of time. We recognize the difference between the three reaches shown in [Figures 22](#) and [23](#), the former consisting only of active channel environments and the latter two showing various degrees of distinction

between a frequently altered braid plain with channel and bar environments, but with some vegetated islands reflecting periods of relative stability, and a longer-lived surface which is subject to inundation and sedimentation in floods with decadal-scale recurrence intervals, but is no longer being molded by the channel. Increased availability of remote sensing techniques should allow sufficiently frequent monitoring of topographic change and inundation patterns to resolve the differences between subaqueous bars that are molded by each high flow and more stable islands that eventually accrete to an extensive floodplain. However, much remains to be investigated about the mechanics of braiding and anabranch development before it can be determined whether it is more revealing to conceive of large braided rivers

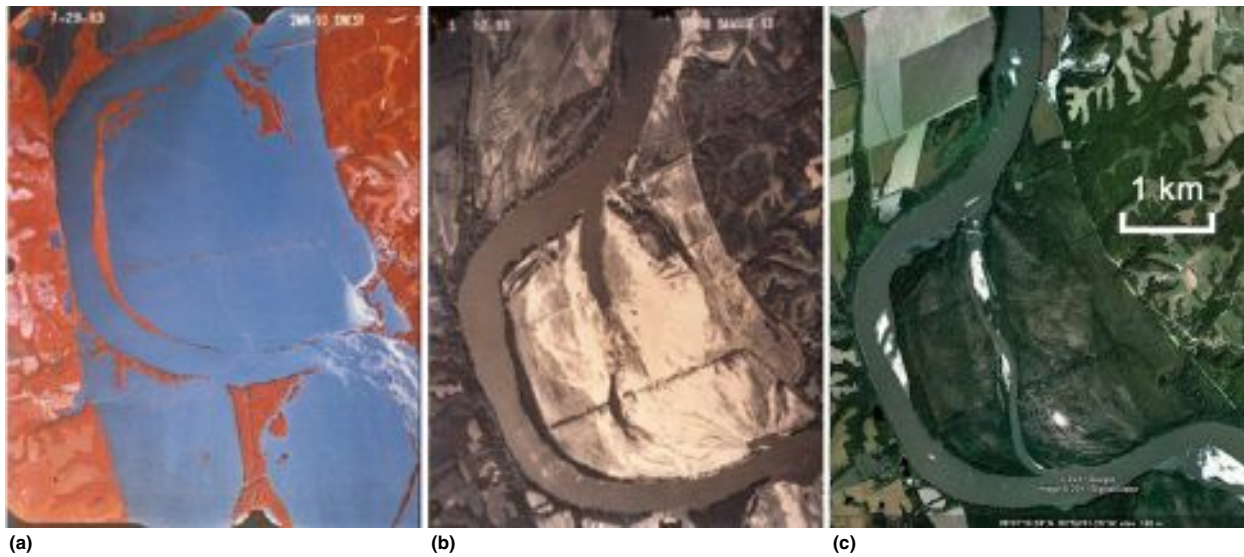


Figure 19 Sequence of events in the development of a chute cutoff channel on the Missouri River from (a) the overbank flood of July 1993 to (b) the embayment incised into the concave bank and floodplain that was visible by October 1993, and (c) to the fully developed chute cutoff shown in the Google Earth™ image from September 2006 at lat. 39.115° N, long. 92.925° W. The chute had been modified by dredging and flow training structures since its formation.



Figure 20 Overbank flow in channels between scroll bars on the middle Amazon floodplain. Photo by T. Dunne.

as maintaining anabranches in the same way that Huang and Nanson (2007) propose, namely that they result from the river narrowing its width and increasing unit stream power to transport its load over very low gradients. In the following text, we will concentrate on knowledge of sedimentation processes and the degree to which there is evidence for a separation between channel and a coherent floodplain surface along large braided rivers.

Single-thread, braided channels of large rivers consist of wide depressions or corridors with bankfull width–depth ratios up to several hundred, in which networks of flow successively converge and diverge around bars that are formed beneath the water during floods but become distinctive subaerial features at low flow (Figure 22). The bars and intervening flow concentrations (which we will distinguish from the entire channel by calling them ‘braid channels’) are usually, but not always, highly mobile, migrating laterally at 10s–100s of meters per year. The bed material comprising the bars moves as bedload and suspended load (McLelland et al., 1999). Because parts of

many braid channels have a least a small degree of curvature, they may be slightly asymmetric in cross-section, and each channel participates in lateral bar accretion and bank undermining as outlined in Section 9.32.5.1 for single-thread sinuous channels to the extent that the braid channel is sinuous. However, many braid channels have low sinuosity, which tends to make them symmetrical in cross-section, and causes bed material to arrive from directly upstream and to be deposited along the upper and lateral surfaces of the bars in the form of trains of dunes. Coleman (1969) reported low-flow active dune heights in the braided channels of the Jamuna–Brahmaputra River (Figure 23(a)) of ~1 m, rising to 2–6 m in frequent floods, and sand waves that rise to 17 m in height during extreme floods. Scouring of the upstream faces of bars by flow concentrations and extension of the bar tails cause downstream movement of the bars at rates that are much faster than the migration of alternate bars or point bars in single-thread, sinuous channels. The lateral accretion of bars creates a braid plain of channel-margin sediments with an irregular surface and thin, discontinuous, vertically accreted sedimentary covers in depressions and former channels (Figure 24). The braid plain is essentially analogous to the channel belt of a sinuous river. Most of the bars are diamond-shaped, rounded to varying degrees, depending on whether they have recently been molded by bank undercutting or by smoothing through flow and deposition.

The banks of the braid channels are commonly indistinct because of the abundance of accreting bars, but the edges of the braid plain are defined either by valley walls (Figure 22) or by abrupt bluffs of older sediment which has become stabilized to varying degrees by overbank fines and vegetation. The development of a distinct edge between an active, channel-dominated braid plain and a less active sedimentary accumulation that is not being turned over frequently and is developing some mechanical strength through weathering and

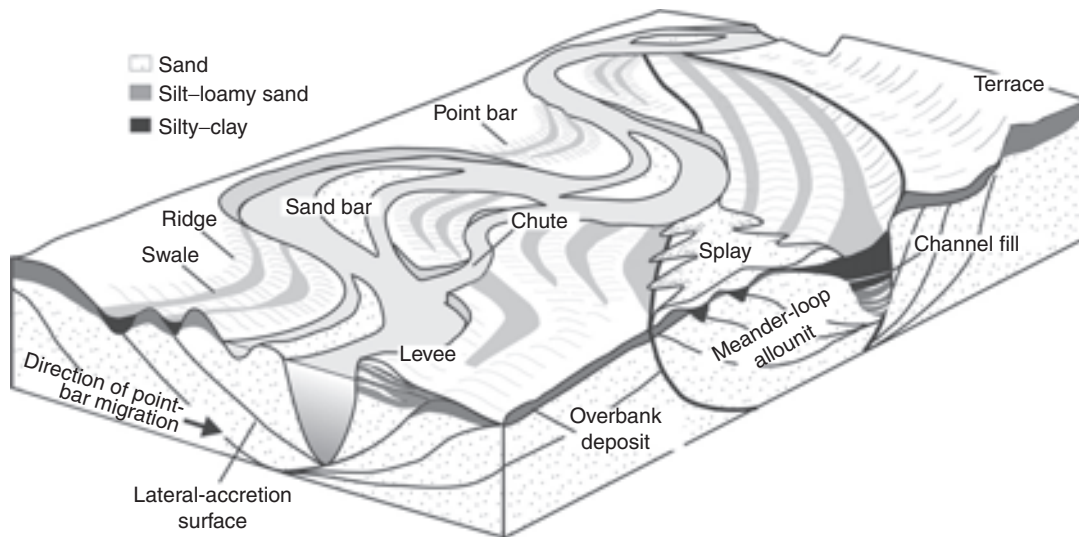


Figure 21 Idealized diagram of a large, sinuous-river floodplain, such as the Missouri River before regulation. In other reaches, the river had a straighter or braided character before regulation. Reproduced from Figure 2 in Holbrook, J., Kliem, G., Nzewunwah, C., Jobe, Z., Goble, R., 2006. Surficial alluvium and topography of the Overton Bottoms North Unit, Big Muddy National Fish and Wildlife Refuge in the Missouri River Valley and its potential influence on environmental management. In: Jacobson, R.B. (Ed.), *Science to Support Adaptive Habitat Management—Overton Bottoms North Unit, Big Muddy National Fish and Wildlife Refuge*, US Geological Survey, Missouri. Scientific Investigations Report 2006-5086, pp. 17–31.

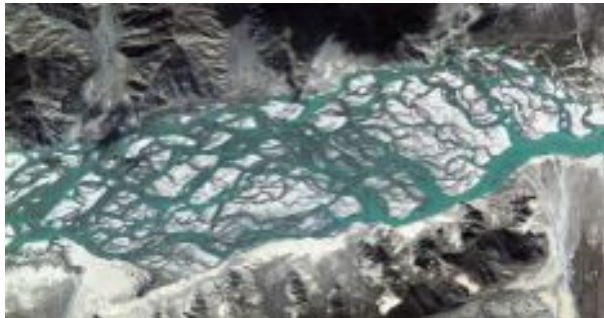


Figure 22 The Lhasa River, approximately 50 km east of Lhasa, Tibet, showing the pervasive molding of the river bed into bars and channels across the entire valley floor. The channel margin is provided by the valley walls. NASA, photo taken from the International Space Station. A scale was not given at the original source, rst.gsfc.nasa.gov/Sect17/Sect17_4.html, but the valley floor is approximately 2–3 km wide.

reinforcement by plant roots probably depends on the magnitude and frequency of floods, but no principle has yet been recognized as a basis for understanding mechanically and predicting the width of the braid plain. The edges of the braided plain are also abrupt where the corridor is being widened or is moving laterally (**Figure 23(a)**), as these rivers often do for decades (see Dunne and Leopold, 1978, Figures 1–14 and 1–15, for an example from the Yakima River, Washington). The edges of the braid plain are much less distinct, however, if the braided river is aggrading a foreland basin.

Braided channels develop where (a) flows are not strongly confined – i.e., in wide, and therefore generally shallow,

channels with banks that can be rapidly eroded; and (b) there is copious transport of sediment along or near the bed that can be molded into bars. For these reasons, braided channels tend to develop where the supply of coarse sediment is high and therefore the channel gradient is high, or where flow is diverging and becoming shallower, or the gradient is declining. Along large rivers, these conditions are most commonly encountered at mountain fronts in foreland basins, at junctions with large sediment-rich tributaries, at tectonically induced reductions of valley gradient, and near tidewater.

Under circumstances (a) and (b), perturbations of the flow field, caused by slight channel widening or local increase in flow resistance through concentration of coarse material or large woody debris (see **Chapter 9.11**), can cause local reduction in flow velocity and bed shear stress, thereby creating a patch of aggradation which becomes the nucleus of a bar. The formation of this proto-bar forces some of the flow to diverge around it, causing further reduction of velocity and shear stress, and augmenting the aggradation. The diverted flow converges with neighboring flow, causing acceleration and increase in bed shear stress, and thus the scouring of proto-channels around the bar. The wider is the entire river, and the more rapidly its banks can be eroded, the greater are the number and rate of growth of these nuclear bars and associated braid channels. A channel that has become scoured by diverted flow may widen immediately downstream of the bar, allowing velocity reduction and a new bar accumulation. **Coleman (1969)** observed that in the Jamuna–Brahmaputra channels the most significant changes of flow direction and channel migration occurred during falling river stage, when sediment accumulated most rapidly on the bars. This is also a time, after the bed at the base of concave banks has been scoured during high flow and riparian pore-pressure gradients

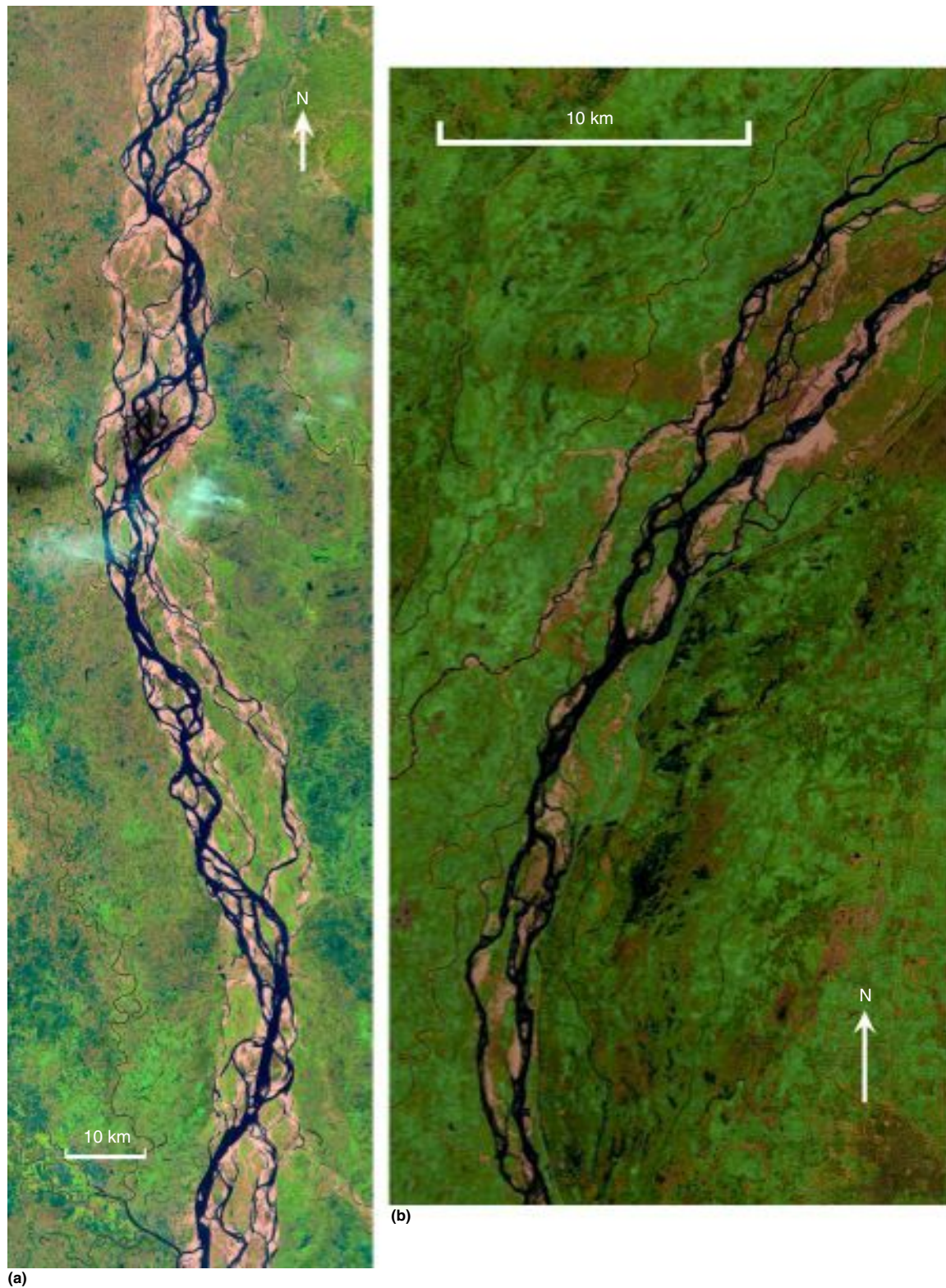


Figure 23 (a) The braided floodplain of the Jamuna–Brahmaputra Bangladesh – the north–south sand-bedded reach of the river that was formed by river capture and avulsion of an earlier south-eastward flowing river in the late eighteenth century. (b) The braided Kosi River, Bihar, India ($25^{\circ}57' \text{ N}$, $86^{\circ}26' \text{ E}$). Landsat image from www.usgs.glovis.org



Figure 24 SPOT image of a part of the Jamuna–Brahmaputra floodplain, showing the domination of the braid-plain topography by bar and channel deposits. The short-lived nature of much of the floodplain surface is reflected in the sparse vegetation, some of which has been cleared for cultivation (http://rst.gsfc.nasa.gov/Sect17/Sect17_4.html).

develop as the river stage declines, when bank collapse occurs by subaqueous sand flows in low-cohesion sediments or block failures in cohesive sediments. Coleman (1969) studied this process of bank slumping extensively on the Jamuna–Brahmaputra.

The long-term intensity at which these coupled processes operate depends on the ratio between some measure of the river's energy dissipation, such as its stream power, and the texture and supply rate of its bed material (roughly summarized by $(Q*S)/(Q_b*D_{50})$, where Q is water discharge, S is water-surface gradient, Q_b is the supply rate of bed-material sediment, and D_{50} is the median bed-material diameter). This principle assumes the constraint mentioned above that much of the bed material must travel along or near the bed so that it can be repeatedly or continually molded into the braid-bar and braid-channel form. The result is a low-sinuosity, single-thread channel comprising multiple thalwegs with interdependent hydraulics. If most of the bed material is suspendible in high flows, as is the case in most large lowland rivers, the longer scale of particle excursion pathways during floods allows a larger scale of organization into single, alternating point bars associated with river bends that are partially stabilized and confined by stronger banks, generating the sinuous, single-thread channels described in an earlier section.

The morphological consequences of these interactions were elegantly captured by Murray and Paola (1994) in a simple rule-based simulation of the bed-elevation changes to be expected if an initially random, wide, granular bed is subjected to a water flow that transports the bed material at rates proportional to local flow rate or stream power raised to a power greater than 1.0. (Some other detailed conditions were imposed to simulate very local effects, but they are less

significant than the fundamental principle stated above.) This simple rule accounted for the required behavior described above, namely that lateral diversion and convergence of the flow change the flow speed and shear stress, allowing either accumulation or scour, which then imposes a feedback on the flow that augments the accumulation and scour, creating bars and channels. Murray and Paola were able to demonstrate that allowing a wide sediment-transporting flow to operate in this way would produce the basic features of a braided channel with the habit of continually forming and reconnecting channels and creating a spectrum of bar and channel sizes, typically with a small number of larger channels and bars and a larger number of smaller ones. Figure 22 provides a field example.

Live or dead vegetation (large woody debris) can have important influences on this set of interactions, even in large rivers and especially in very humid regions that produce large trees. Large woody debris masses may accumulate and become anchored on a mid-channel braid bar and promote flow deceleration and sedimentation. Dead or living vegetation colonizing a bar can reduce the probability of its being scoured away, and there appears to be a rough correspondence between the extent and reinforcement potential of plant colonization on bars and their size and longevity. Trees of sufficient size and root penetration can reduce the rate at which channels a few meters deep are widened by bank undermining, but are unlikely to be effective along channels that can scour tens of meters deep in a single flood. Both live and dead vegetation can also colonize smaller channels between large floods, and promote their filling and excision from the braided channel; even if they do not narrow the corridor formed by extremely high flows, they can convert active bars into the braid plain. The degree to which vegetation can survive on mid-channel braid bars for long enough to favor sedimentation up to the level of the braid plain, creating an island, affects whether the river is functioning entirely as a single-thread braided river or as an anabranching river (Latrubesse, 2008). However, in very large, active braid plains (Figure 22 and parts of Figure 23), vegetation seems to have little influence on bar formation.

Because of the lateral activity and sparse vegetation along braided rivers (Figure 24), levees develop only to heights of about a meter, but they are present along some channels because sediment concentrations in overbank flow are high and the overbank reduction in flow depth rapidly diminishes the transport capacity. Since the levees are also easily erodible, however, they are crevassed in many places, and sand splays are a significant form of floodplain construction, both within the braid plain and along its margins (see several lighter margins adjacent to the channel in Figure 24). Settling of fine-grained sediment into depressions is limited within most braid plains, but outside of the corridor large floods inundate extensive floodplain surfaces (Brammer, 1990), where clays and organic sediments accumulate over the near-channel sediments that have been deposited through lateral migration of the whole corridor. As in the case of sinuous-channel floodplains, avulsing channels are much more efficient than diffuse inundation at transporting even clays into flood basins.

In addition to the subaqueous formation of bars and channels, new channels can form across the braid plain

through vertical erosion of chute cutoffs in the manner described above along sinuous channels. The results of Constantine et al. (2009b) suggest that avulsions of this kind across the braid plain would be relatively common because braided rivers and braid plains have relatively steep gradients, floodplain vegetation is absent or sparse due to frequent disturbances and droughty soils in the coarse-textured braid plain, and the wide, shallow channels within the main river corridor are commonly overtopped. However, the results of Slingerland and Smith (1998, 2004) predict that these channels can also be rapidly filled if the suspended sediment concentrations in the main channel are high. Migrations of bars and channels also create new flow concentrations that scour channels across former bars or accreted parts of the braid plain. But to retain the single-thread braided classification (Nanson and Knighton, 1996), any avulsion that creates an entirely new channel would have to be compensated by the abandonment and filling of an original channel. The lateral migration of the braid-plain corridor then constructs the extensive floodplain dominated by channel and near-channel deposits with only a thin cover of overbank deposits.

Braiding on a large scale is more restricted in its distribution than are sinuous channels because it requires large bed and near-bed sediment fluxes to continually re-mold mid-channel bars and flow conduits. Many large rivers expose mid-channel bars at low flows, but are not classified as braided because during floods they typically have a single, more organized flow channel with a dominant thalweg and varying degrees of sinuosity. Braided rivers can completely inundate their corridors in large floods, but larger bars or islands, generally reinforced to varying degrees by vegetation, tend to survive and divide the flow and sediment transport, even during such floods. However, some large single-thread rivers appear to operate close to the regime required for braiding because there is widespread evidence that they have braided during earlier conditions of flow, sediment supply, and geometrical boundary conditions. The relict sediments from these previous regimes have left significant imprints on the modern floodplain and its surrounding surfaces. Geomorphic surfaces on the Ganga Plain in northeast India record a transition from braiding to meandering in the last 25 ka, accompanied by decreases in grain size and discharge that resulted from climate change (Singh et al., 1990). In the lower Mississippi floodplain, there are buried and outcropping deposits of braided river sediments resulting from the supply of sandy glacial outwash from Wisconsinan glacial retreats (Saucier, 1994), when profile rejuvenation had increased the valley gradient to approximately 20 cm km^{-1} (Blum et al., 2008). Figure 25 and the northeast corner of Figure 16(b) show the distribution of braid plains and the modern sinuous floodplain of the Sacramento River, a shift which probably resulted from changes of runoff and sediment supply during the Pleistocene–Holocene transition (Robertson, 1987).

9.32.7 Floodplain Construction by Anabranching Rivers

Latrubesse (2008) illustrated how the lowermost reaches of the nine largest rivers on Earth have anabranching planforms.

An informal survey via Google Earth™ of a more extensive sample of large rivers, including those for which coordinates were given above, supports Latrubesse's assertion that the world's largest rivers tend toward an anabranching habit. Furthermore, there seems to be a tendency (although we do not have statistical data to support this suggestion) that rivers with a higher ratio of sediment load to discharge (such as the Ganga River) have a more common occurrence of anabranching around mid-channel bars, whereas anabranching rivers with a lower ratio of sediment load to discharge (such as the Amazon River) separate more commonly around stable, vegetated islands excised from their floodplains.

Along these large anabranching rivers, sinuosity is typically < 1.3 for main channels and major anabranches. The number of anabranches in a reach is typically 2–3, although it is sometimes arbitrary how one limits the scale of channels chosen for this designation (Figure 9; Latrubesse, 2008). Mertes et al. (1996, Figure 13) measured the widths and seasonally varying depth of channels diverging from the main channel of the Amazon; the dimensions and discharges of the few channels that re-joined the main channel were much larger than most of the sample, and their trap efficiencies for sediment decanted from the river were correspondingly smaller (Dunne et al., 1998).

The stability of anabranching requires that repeated channel separation around mid-channel bars and the fretting of the floodplain into multiple channels must be resisted, but not prevented, by the channel banks or the floodplain surface. If the channel banks have some degree of cohesive resistance to shearing or collapse, the rapid channel widening that favors braiding will not occur; instead, the separated arms will be scoured deeper, and the width/depth ratio of even the divided channel will be low. Similarly, dense vegetation, low valley gradient, and cohesive soils will resist the repeated incision of the floodplain by small channels (see Chapter 9.29). On the other hand, certain features of large rivers referred to in the second section of this chapter appear to favor the keeping open of a small number of large anabranches once they are formed. The extensive drainage areas, great depths, and fine sediment loads of large rivers cause long periods of overbank flow to leave the main channels, carrying relatively low concentrations of fine-grained sediment, especially after the early-rising period of the seasonal hydrograph. Thus, the trap efficiency of these large distributary channels tends to be low (Dunne et al., 1998) and the channels can be kept open for long periods of time. It is also possible that the sustained flows and relatively high groundwater tables in fine-grained sediments of large rivers may favor the aggressive growth of riparian vegetation that stabilizes both mid-channel bars and the floodplain surface. These conditions suggest that although the recurrence interval of anabranch formation on large lowland rivers may be low, the average lifespan of large anabranches is probably high.

The lowermost energy range of large-river anabranching in the two upper right panels of Figure 2 is represented by the lower Negro River, a tributary of the Brazilian Amazon River with a low gradient and sediment supply, which since at least the Last Glacial Maximum has been extending a floodplain downstream in a wide structural valley, the lower end of which is a graben that was flooded tens of meters deep during the

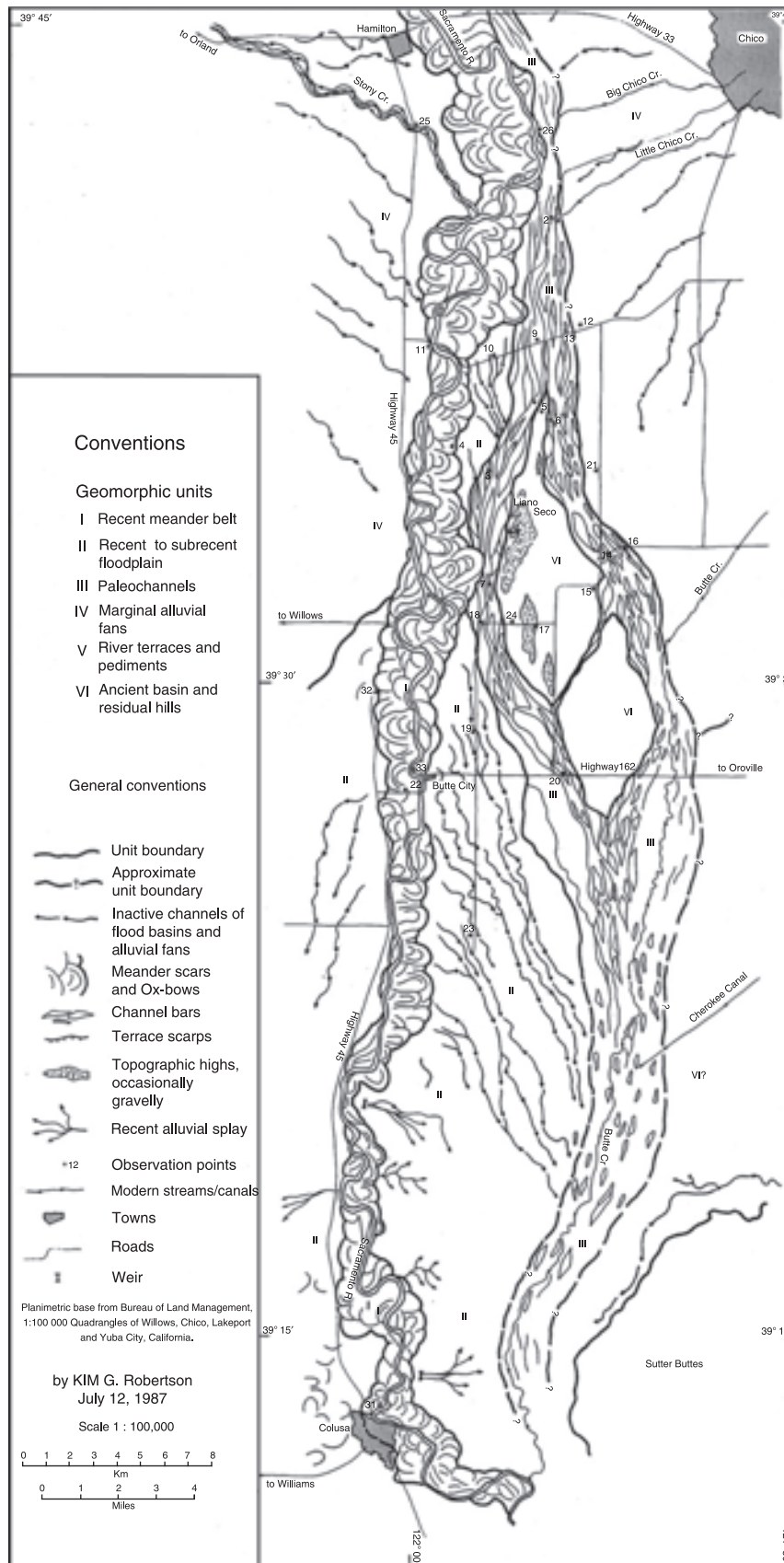


Figure 25 Sacramento River valley showing the channel belt deposits of the modern sinuous channel off-lapping deposits of the late Pleistocene braid plain (labeled 'paleochannels'). Reproduced from Robertson, K.G., 1987. Paleochannels and recent evolution of the Sacramento River, California. MS thesis, University of California Davis, Davis, CA.

Holocene sea-level rise (Latrubesse and Franzinelli, 2005). In the upstream reach in **Figure 26(a)**, the Negro floodplain occupies the entire 10–15 km-wide valley floor with ~4 large anabranches and many smaller ones between extensive bars

stabilized by brush and forest vegetation. Smaller channels also dissect the vegetated floodplain. The sequence from upstream to downstream was interpreted by Latrubesse and Franzinelli (2005) as illustrating how vertically accreting

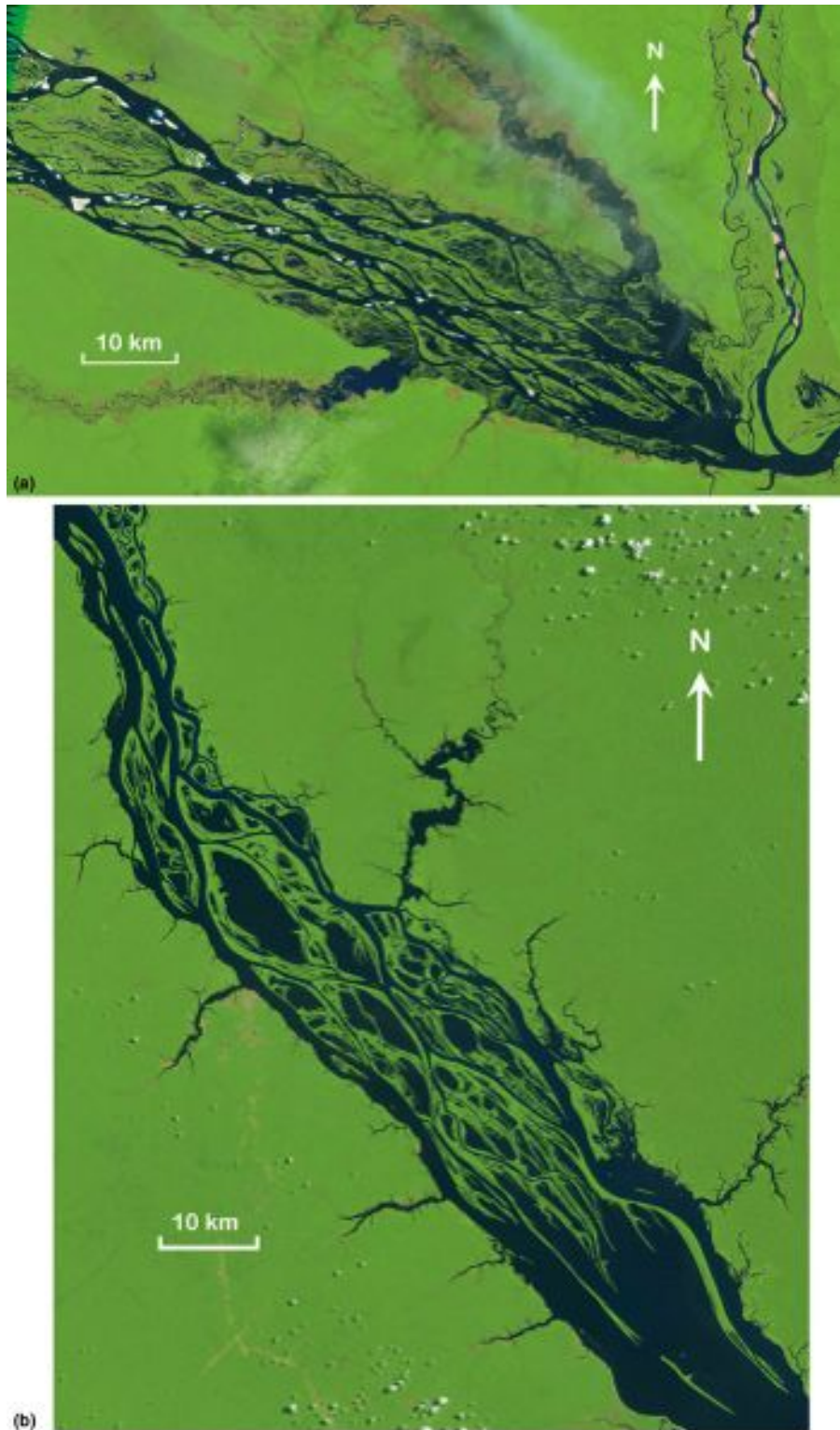


Figure 26 (a) The upper River Negro floodplain in Amazonas, Brazil ($1^{\circ}11' S$ $62^{\circ}18' W$). (b) Lower Negro River floodplain, near Manaus, Brazil ($2^{\circ}43' S$ $60^{\circ}44' W$; drainage area $691\,000\text{ km}^2$). Landsat image from www.usgs.glovis.org

floodplain sedimentation has spread gradually downstream. At the present time there is a sequence (**Figure 26(a)**) from a filled valley floor, formed through the coalescence of sandy islands with forested, silt–clay superstructures and a few, relatively large, sinuous anabranching channels, passing downstream into a larger number of silt–clay islands separated by more numerous, smaller anabranches. At the downstream end, there are fewer mid-channel sandy bars becoming colonized by vegetation, and the islands show evidence of accreting as narrow lateral levees, which accumulate under the influence of the drag of vegetated margins, and possibly because clays are flocculated by the high dissolved organic carbon in channel and floodplain waters (Stallard and Martin, 1989). Many island centers contain lakes surrounded by levees (east side of **Figure 26(a)**). Avulsions form new channels in the growing floodplain, presumably while it still has a low elevation. Low parts of the floodplain retain lakes and swamps, and lateral accretion also extends the floodplain from the valley sides. The eastward downstream progradation of the multi-channel system gradually converts more of the valley floor into floodplain with fewer channels.

After flowing through a narrow, structurally controlled reach with rapids, the river again forms anabranches that debouch into the deep waters of the graben of the lowermost Negro (**Figure 26(b)**). Each channel is extended between a pair of intertwined, steep-sided, straight or gently curving, silty-clay ridges. The ridges initially develop below water level and eventually emerge as pairs of tree-covered, parallel islands, ~100 m wide and tens of kilometers long, separated by narrow water bodies which gradually fill from their upstream ends and extend between the downstream-growing islands. The ridges do not shift laterally, and appear to replicate the lake-crossing channels in **Figure 11** and, more loosely, the jet-driven subaqueous levee formation along the tie-channels described by Rowland et al. (2009). These leveed channels probably increase the efficiency of sediment transport into the water body as a result of confined jet-like hydrodynamic conditions and kaolinite flocculation along the margins of the jet due to dissolved organic carbon in the Negro River. Franzinelli and Igreja (2002) described both the resulting archipelago of islands and a narrow floodplain accumulating on fault blocks at the base of the fringing bluffs. They interpreted the existence and narrow geometry of the islands as resulting from their establishment on up-faulted ridges of bedrock within the graben and their stabilization by trees and brushy vegetation. However, such narrow spacing (~2 km) is not common among faulted blocks in grabens, so it seems more likely that a distinctive hydrodynamic process is at work, similar to that described above.

The Amazon River and floodplain form an example of the stable to meandering sinuous anabranching systems in **Figure 2**. Stable, vegetated islands have originated both as mid-channel bars (downstream end of **Figure 8** reach, and throughout **Figure 10**) and by incision of the floodplain (**Figure 8** and throughout **Figure 9**). Although the rate of energy expenditure ($10\text{--}20\text{ W m}^{-2}$ at bankfull stage) lies in the low-energy range proposed by Nanson and Knighton (1996) for sinuous anabranching rivers, the Amazon cases occur over a four-fold range of gradient (**Figure 1(b)**), rather than being forced to narrow their channels to compensate for not being

able to adjust their slope to transport load, as Nanson and Knighton (1996) and Huang and Nanson (2007) propose. However, the sinuous anabranching form is compatible with an interpretation based on: (1) mid-channel sand deposition where gradients decline; (2) scouring of deep channels around the bars because of the resistance of cohesive floodplain and terrace materials; (3) aggressive plant colonization and stabilization of both mid-channel and point bars; (4) channel shifting through widespread lateral bank erosion driven mainly by channel curvature; (5) occasional incision of the floodplain by overbank flow, with or without exploitation of existing floodplain channels; and (6) the long-term flushing of these avulsion channels by enduring low-turbidity flow into the floodplain. Rather than reflecting an extremal principle of channel adjustment (Huang and Nanson, 2007), this view of sinuous anabranching presents the channel and near-field floodplain as the product of a set of interacting, and even competing, processes, the hydrodynamics of which are the same as those occurring in the single-thread channels described above in this chapter, but favored by certain characteristics common along large rivers. The remainder of the floodplain far from the main channel also develops by processes described for the large single-channel case, although the limited curvatures and low floodplain gradients of large river channels probably limit the rates of channel migration across the wide valley floors. These slow migration rates allow long periods of time for the floodplain surface (rather than the bulk of the sedimentary package) to be modified by other agents, such as small rivers supplied by runoff from the floodplain surface and the surrounding landscape (Mertes et al., 1996), major tributaries, alluvial fans (see **Chapter 9.23**), and the hydrodynamics of flow into and out of lakes (Rowland et al., 2009).

Braided anabranching patterns of the kind portrayed in the lower right of **Figure 2** appear to be rare among the largest rivers on the planet. Thorne et al. (1993) and Latrubesse (2008) classified the Jamuna–Brahmaputra (**Figure 23(a)**) as anabranching, but other investigators treat the river as a single, intensely braided channel (e.g., Coleman, 1969). Floodplain development by an anabranching braided river depends on how extensively the river can create enduring islands at or slightly above bankfull stage, filling marginal anabranches and allowing some islands to attach to the floodplain, and also the extent to which large floodplain fragments, isolated by chute cutoff, can survive the intensive scouring capacity of the shifting braid channels. In the case of the Jamuna–Brahmaputra, Thorne et al. (1993) describe the difference between braid bars, which are highly unstable, changing their size and position between flood seasons, and islands, which survive for several decades with perennial vegetation, cultivation, and human settlements. The islands form through the amalgamation of braid bars that attain elevations close to that of the flanking, currently unchanneled floodplain. Colonization by vegetation then forces silt deposition on top of the bars, raising their elevations another 1–2 m, equaling the height of the floodplain. The vigor of woody plant colonization plays an important role in this stabilization and growth process. The anabranches change their relative sizes, and flow switching causes some of them to fill with sediment and attach islands to the floodplain.

An island may be locally aggraded or scoured, and even dissected during its lifetime (Figure 24), and avulsion creates marginal channels along the anabranches. Large floods, such as the largest discharge of record in 1988, can inundate the floodplain outside of the braid plain for up to 25 km on either side of the river (Brammer, 1990), but Thorne et al. (1993) calculated that these large floods transport only small amounts of fine sediment overbank.

Development of a large, strongly anabranching braided channel, separated by stable islands and long-lived fragments of floodplain surface, seems to require energetic conditions that are rarely encountered. First, the valley floor or alluvial plain must be wide to accommodate both the width of multiple braided corridors and one or more intervening floodplain surfaces. Secondly, the energy dissipation rate required to maintain long-term bedload transport across several braided channels and braid plains must be high because of the shallow flow depths (relative to the discharge), large width, and the high form drag of the bars. Thus, the high discharge and valley gradient, together with the necessary grain size to ensure that significant transport occurs along and close to the bed, are found in very few large rivers. On the other hand, as we noted in Section 9.32.2 on distinctive characteristics of large rivers, a large river can build bars that are so voluminous that they are likely to survive for longer periods of time, both because their re-shaping or removal requires a long time, and because during persistent runs of lower-flood years they may be colonized by stabilizing vegetation (see Dunne and Mertes (2007, Figure 5.4) for an example of runs of high and low annual floods on the Paraguay River). Also, the wider the braided channel and braid plain become, the lower the cross-section-averaged shear stress and stream power become, increasing the probability of sediment accumulation in

coalescing bar complexes, marginal anabranches, and islands, and also favoring the attachment of islands to the floodplain.

A candidate braided anabranching river appears to be the Kosi River at the northern end of the reach shown in Figure 23(b). The reach, which can be viewed at higher resolution upstream of 26°04' N 86°28' E in Google Earth™, comprises three major anabranches and several minor ones, separated by islands up to 8 km long and ~2 km wide that have been stable for long enough to allow well-organized land subdivision and cultivation. Farther downstream in Figure 23(a), where the gradient is lower, the vegetated islands are smaller and apparently less stable, but the number of anabranches decreases from three to two, and immediately south of the image, the river forms a single-thread channel that builds the floodplain by lateral accretion of mid-channel and lateral bars. The Jamuna–Brahmaputra is clearly near the boundary of the proposed braided anabranching class, and formation of large islands that divert the flow for decades contributes to the high rates of lateral migration and accretion that Coleman (1969) documented.

Some large rivers and floodplains smaller than the Brahmaputra exemplify form and behavior that qualify as anabranching in certain reaches of their valley floors. These are the 'wandering rivers' described by Desloges and Church (1989) on the basis of their own and others' investigations of coarse-bedded, sediment-rich rivers draining recently deglaciated regions of the Cordillera of western North America. They refer to the gravel-bed lower Fraser River upstream of Mission, British Columbia, as an example (Figure 27). Wandering rivers are described as intermediate in form and behavior between braided and meandering cases, and to consist of alternating reaches of sinuous and braided channels. The slightly sinuous, single-threaded reaches are deep and irregular



Figure 27 Google Earth™ image of the wandering channel of the lower Fraser River, British Columbia, described by Desloges and Church (1989).

but remain stable for decades, passing sediment with little change of form. In the intervening reaches, the channel is shallower and is split by bars and vegetated islands, and multiple minor side channels thread the floodplain. Avulsion at high flows is common and the largest anabranches may alternate between several flood channels in the floodplain. The lower Fraser River reach, which has a drainage area of $\sim 230\,000\text{ km}^2$ and a mean annual flood of $\sim 8750\text{ m}^3\text{ s}^{-1}$ (Ham, 2005), plots near to both 'split' and anabranching channels on **Figure 3**. Both the islands and the floodplain (some of which is now isolated from the river by engineered levees) show signs of aggressive channel activity, former bar forms, and relatively little vertical accretion.

Another feature of the Fraser and smaller wandering-river floodplains of North America is the vigor of forest colonization that stabilizes islands so that they do not respond to every annual peak flow, as bars tend to do. Instead, bars of gravel become colonized by forest vegetation when they rise to the elevation of most annual flood peak stages, and after that point, the vegetation filters sandy sediment out of the flow to rise one to several meters higher. The islands and floodplains of the multi-threaded reaches respond to persistent runs of high-flood years, either by lateral accretion or loss. Although the main channel anabranches may alternate between side channels across the floodplain, the resulting reduction of flow strength in the original channel leads to its blockage by bars of bed material and large woody debris, thereby limiting the degree to which entirely new large anabranches can be cut and maintained. However, the generality and energetics of wandering channels and the floodplains they form remain to be documented systematically, so it is not yet clear whether they shed light on the environmental conditions under which an unequivocally anabranching braided river could exist and construct a complex floodplain.

9.32.8 Summary

The size and complexity of large-river floodplains introduces some scale-dependent processes and effects that do not occur in small floodplains. These result from the hydroclimatic and tectonic settings required to produce large rivers with copious sediment supplies and adequate accommodation space, and also from a few scale-dependent features of large rivers. The hydrology, hydraulics, and mechanics of sediment exchange between channels and floodplains determine the way that floodplain sedimentation occurs, creating a set of landforms that includes: bars, levees, crevasses, splays, oxbows, extensive plains, flood basins, residual lakes and swamps, alluvial fans, channels in lakes, channels maintained by local floodplain runoff, and various other landforms that are probably too complex for easy labeling. The intensity of plant colonization and stabilization, as well as physical and chemical changes to the accumulated sediment, can play important roles in stabilizing the sediment that has entered the floodplain, and therefore in controlling its residence time and geomorphology.

The behavior of the main channel as a mobile boundary condition and as a source of water and sediment, reflected in the river planform, controls some processes of floodplain

construction directly and leaves other parts of the floodplain to be altered by processes that are controlled indirectly by the sedimentation and inundation hydraulics originating in the channel. The range of river planforms and behavior is currently expressed through classification schemes, association with environmental conditions (mainly valley gradient and the supply of bed-material sediment), and interpretations of energy expenditure principles. There remains considerable opportunity to interpret the hydrologic and fluid mechanical behavior of processes originating in channels, the floodplain, and marginal landscapes in constructing and molding the floodplains of large rivers. There is no reason to believe that these processes are obeying a single principle but may be in competition with one another. The outcome of the competition (say, between the increase in sinuosity and chute cutoff, or the rate of oxbow production and the rate of channel margin and overbank sedimentation, or between subsidence and the sediment supplies from upstream and lateral sources) depend on large-scale tectonic and hydroclimatic features of the river's drainage basin. These features, together with the time available for adjustment to geologically recent tectonic, climatic, or eustatic changes, affect the geometry and behavior of modern large rivers and their floodplains.

Acknowledgments

In a review of this kind, the authors' gratitude must go first to all the contributors of literature that we have assimilated and have tried to shape into a coherent picture that includes examples outside of our own experience. However, we have avoided extending our discussion too far from our own field investigations. We avoided, for example, the impressive floodplains of large rivers that flow to the Arctic Ocean from both the sediment-poor cratons of Siberia (e.g., Costard and Gautier, 2007) and Canada and the sediment-rich orogenic belt of northwestern Canada and Alaska, with inundation regimes dominated by ice blockages in downstream reaches and earlier snowmelt upstream, and floodplain topography and hydrography affected by thermokarst (Uvarkin and Shamanova, 1978). Our understanding of the geologic and hydrologic processes at various scales that construct floodplains along large rivers have been developed through collaborative fieldwork and extensive discussions with a number of colleagues. Foremost among these colleagues are Leal Mertes, Robert Meade, Jose Constantine, and Michael Singer. At various times, our research on this topic has been funded by the following organizations: the US National Science Foundation, NASA, the California Delta Stewardship Council, Delta Science Program (#U-05-SC-058), and the Geological Society of America Easterbrook Award.

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