The Planform Mobility of River Channel Confluences: Insights from Analysis of Remotely Sensed Imagery

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Abstract

River channel confluences are widely acknowledged as important geomorphological nodes that control the downstream routing of water and sediment, and which are locations for the preservation of thick fluvial deposits overlying a basal scour. Despite their importance, there has been little study of the stratigraphic characteristics of river junctions, or the role of confluence morphodynamics in influencing stratigraphic character and preservation potential. As a result, although it is known that confluences can migrate through time, models of confluence geomorphology and sedimentology are usually presented from the perspective that the confluence remains at a fixed location. This is problematic for a number of reasons, not least of which is the continuing debate over whether it is possible to discriminate between scour that has been generated by autocyclic processes (such as confluence scour) and that driven by allocyclic controls (such as sea-level change). This paper investigates the spatial mobility of river confluences by using the 40-year record of Landsat Imagery to elucidate the styles, rates of change and areal extent over which large river confluence scours may migrate. On the basis of these observations, a new classification of the types of confluence scour is proposed and applied to the Amazon and Ganges-Brahmaputra-Meghna (GBM) basins. This analysis demonstrates that the drivers of confluence mobility are broadly the same as those that drive channel change more generally. Thus in the GBM basin, a high sediment supply, large variability in monsoonal driven discharge and easily erodible bank materials result in a catchment where over 80 % of large confluences are mobile over this 40-year window; conversely this figure is less than 40 % for the Amazon basin. These results highlight that: i) the potential areal extent of confluence scours is much greater than previously assumed, with the location of

some confluences on the Jamuna (Brahmaputra) River migrating over a distance of 20 times the tributary channel width; ii) extensive migration in the confluence location is more common than currently assumed, and iii) confluence mobility is often tied to the lithological and hydrological characteristics of the drainage basins that determine sediment yield.

1. Introduction

River confluences are important nodal points in alluvial networks, often representing abrupt downstream changes in discharge, grain size and channel geometry, which in turn may exert a significant control on channel morphology, migration and avulsion (Mosley, 1976; Richards, 1980; Ashmore, 1991; Bridge, 1993; Ashmore and Gardner, 2008; Best and Rhoads, 2008). The morphology of the confluence zone also has many ramifications for understanding and managing aspects of river behaviour, such as the fact that the dynamic morphological adjustments at these sites may make managing land use and infrastructure difficult (Ettema, 2008). Meanwhile, the morphological and geochemical heterogeneity often present at confluence sites has led ecologists to conclude that they are 'hotspots' of high biodiversity (e.g. Benda et al., 2004), and/or may form sites of appreciable biological change (e.g. Rice et al., 2008). Even at confluences that possess a relatively stable planform location, the hydraulic processes at junctions are still highly complex, which makes understanding of pollutant pathways, for example, problematic (Biron and Lane, 2008). In the present paper, we focus on exploring the planform morphodynamics of large confluences and linking this to the subsurface sedimentology

River confluences have the potential to create some of the points of deepest incision into underlying sediments (Mosley, 1976; Best, 1988; Bristow et al., 1993; Salter, 1993; Siegenthaler and Huggenberger, 1993; Best and Ashworth, 1997; Miall and Jones, 2003; Ullah et al., 2015) and hence their subsequent fill has been argued to possess the highest preservation potential of fluvial channels (Huber and Huggenberger, 2015). Since the depth of junction scour and mobility of the confluence are determined by flow processes in the confluence hydrodynamic zone (Best and Rhoads, 2008), it can be argued that differing junction dynamics may produce a range of characteristic confluence zone sedimentology from sandy bar development to mud-filled scours. Furthermore, understanding the planform mobility of confluences, and thus the potential spatial extent of basal scour surfaces, particularly in large rivers, is key to interpreting alluvial stratigraphy and discriminating between autocyclic and allocyclic scour surfaces (Best and Ashworth, 1997; Fielding, 2008), reconstructing palaeohydraulics and channel sedimentary architecture (Bristow et al., 1993; Siegenthaler and Huggenberger, 1993; Miall and Jones, 2003), as well as identifying potential sites for hydrocarbon exploration (Ardies et al., 2002).

Despite the fact that the sedimentary fill of confluences may be preferentially preserved and that their large scale may lead to confusion in discriminating between autocyclic and allocyclic scour, to date there has been no comprehensive analysis of confluence mobility to resolve questions concerning the extent and ubiquity of migrating confluence locations. For example, Holbrook and Bhattacharya (2012) question whether confluences can migrate sufficiently to produce a scour large enough to resemble that of an incised valley, and hence be mistaken for a product of allocylic-driven erosion. However, some case studies, such as the confluence of the Ganges and Jamuna rivers, Bangladesh, show junction migration over distances of several kilometres in a year (Best and Ashworth, 1997). In addition, the course of the Jamuna River has also been shown to avulse on centennial to millennial timescales (Best et al., 2008; Pickering et al., 2014; Reitz et al., 2015), thus changing the location of its confluence with the Ganges River by hundreds of kilometres. High-angle confluences in meandering rivers have also been demonstrated to adjust their confluence planform over decadal timescales (Riley, 2013). Ettema (2008) discusses episodic bank erosion and changes in bar formation at confluences in response to flood events, particularly those driven by ice jams, whilst Best (1988) and (Best and Roy, 1991) document tributary bar migration as a response to changing discharge ratio between confluent channels. Several studies have also noted changes in confluence location and morphology in response to sediment deposition in the confluence zone. At a very small scale, Shit and Maiti (2013) attribute the up- and down- stream movement of confluences in small gully systems to the deposition of sediment wedges from sediment-laden tributaries. Zhang et al. (2015) also show the dynamic behaviour of sedimentation at tributaries of the Huang He River in China, which in some areas possesses tributaries that transport huge sediment loads into the main channel. Similarly, several studies have shown deposition at the junctions of high sediment load tributaries that are located downstream of recently constructed dams, leading to local bed aggradation that can cause lateral and longitudinal movement of the confluence location, as well as changes in confluence morphology (Graf, 1980; Petts, 1984; Allen et al., 1989; Grant et al., 2003; Gilvear, 2004; Petts and Gurnell, 2005; Phillips et al., 2005)

There is a broader theoretical basis for assuming confluence location and morphology may change substantially over time. Mosley (1976) showed that confluence morphology (Figure 1) is dynamic and responds and adjusts to upstream boundary conditions of flow and sediment supply in each tributary, and thus confluences may be expected to adjust to three broad factors. Firstly, upstream boundary conditions of discharge, or momentum, ratio between the tributaries, where momentum ratio exerts a control on scour morphology (Mosley, 1976; Best, 1986; Best, 1988; Best and Rhoads, 2008) and tributary bar morphology (Best, 1988; Biron et al., 1993; Rhoads, 1996; Biron et al., 2002; Boyer et al., 2006; Best and Rhoads, 2008). There is also some evidence that inter-event fluctuations in momentum ratio can lead to changes in bar morphology (Boyer et al., 2006), and where tributaries drain different lithological or climatic areas there could be annual or seasonal variations in momentum flux. Secondly, junction angle controls both scour morphology (Mosley, 1976; Best, 1988; Sambrook Smith et al., 2005) and tributary mouth bar morphology (Best, 1988). Where the channels upstream of the confluence are meandering, the junction angle could thus change over time in response to bend migration and channel cut-off. Finally, formation of a mid-channel bar in the post-confluence channel (Mosley, 1976; Best, 1988),can occur through convergence of sediment transport pathways (Best, 1988; Best and Rhoads, 2008) and declining flow velocities and turbulence intensities downstream of the zone of maximum flow acceleration (Best, 1987; Best, 1988; Sukhodolov and Rhoads, 2001; Rhoads and Sukhodolov, 2004).

Such bar formation can promote bank erosion and channel widening (Mosley, 1976), potentially driving changes in confluence morphology over time although this mid-channel bar formation is somewhat dependent on the first two factors. In many ways, the key characteristics that thus drive confluence mobility are the same as those that drive channel migration more generally; the discharge and sediment load within the channels (themselves linked to climatic/hydrologic regime and basin characteristics) and the rates of migration of the incoming tributaries (controlled by hydrological regime, floodplain composition, bank strength, planform character and geologic controls). The examples from large rivers presented in section 3 below are used to help identify these key controls (section 4) from which an overall classification is derived (section 5). The rationale for focusing on large rivers is briefly outlined below.

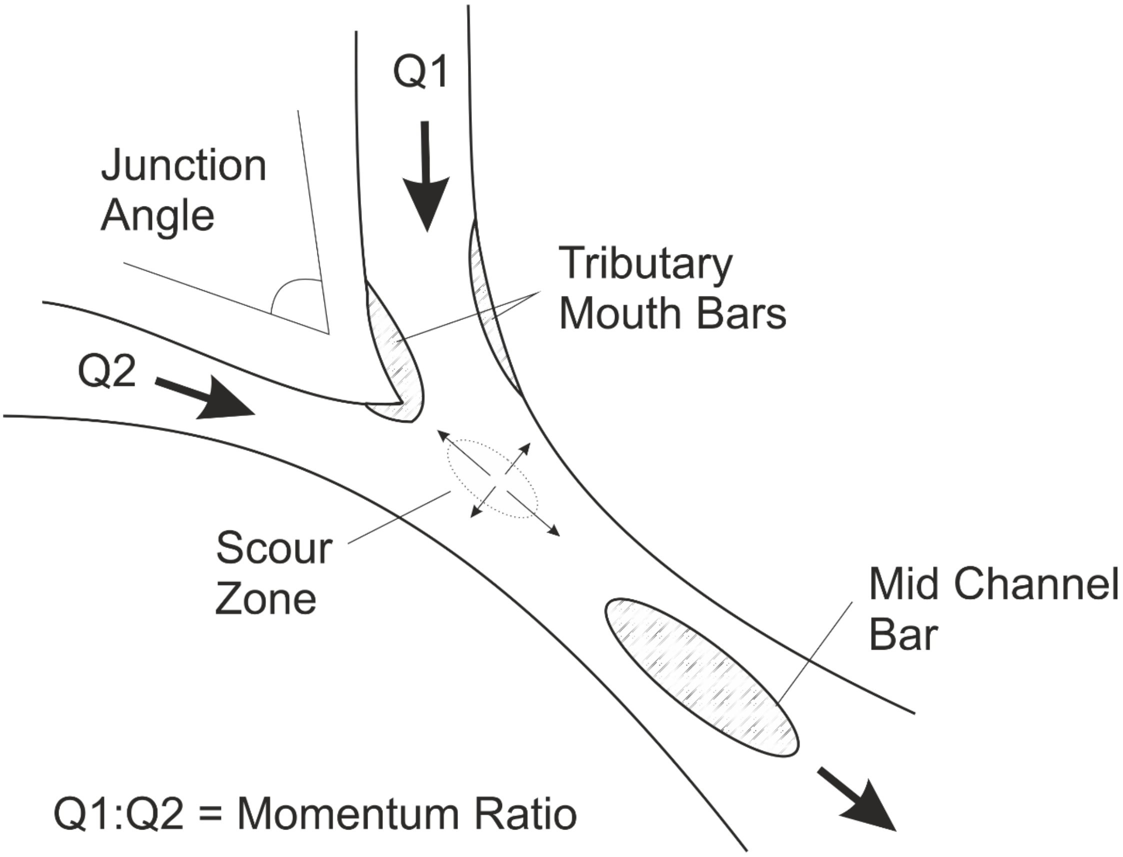

Figure 1 – Cartoon showing the major morphological features of a channel confluence as referred to in the text.

Current understanding of the morphodynamics of river confluences has largely been dominated by examples of experimental and small fluvial channels (e.g. Mosley, 1976; Best, 1988; Roy and Bergeron, 1990; Best and Roy, 1991; Biron et al., 1993; Kenworthy and Rhoads, 1995; Rhoads and Kenworthy, 1995; Rhoads, 1996; Rhoads and Kenworthy, 1998; De Serres et al., 1999; Rhoads and Sukhodolov, 2001; Biron et al., 2002; Boyer et al., 2006; Leite Ribeiro et al., 2012), and it is only with recent advances in technology that the direct field investigation of large river confluences has been possible (e.g. McLelland et al., 1999; Ashworth et al., 2000; Richardson and Thorne, 2001; Parsons et al., 2005; Parsons et al., 2007; Lane et al., 2008; Parsons et al., 2008; Sambrook Smith et al., 2009). There is therefore a need to critically examine, describe and quantify the decadal morphodynamics of large river junctions in order to better understand the extent to which river confluences are mobile, how mobility is expressed and the rates of change. With recent advances in remote sensing, the planform characteristics and decadal evolution of large rivers can be described in greater detail (Ashworth and Lewin, 2012; Trigg et al., 2012; Lewin and Ashworth, 2014a), and the temporal morphodynamics of large rivers can be quantified (e.g. Mount et al., 2013). With over four decades of global imagery now available from programmes such as NASA's Landsat, there is thus a great opportunity to study the morphodynamics of large river confluences over decadal timescales.

Herein, we use Landsat satellite image sequences to examine the planform morphodynamics of large river confluences over decadal timescales. Our aims are to:

1. Illustrate the range in behaviour of the planform confluence morphodynamics in large rivers
2. Quantify the potential spatial extent and mobility of the confluence planform over decadal timescales
3. Detail the spatial distribution of different morphodynamic types of junctions within large rivers and examine the potential controls on confluence mobility, and
4. Discuss the implications of confluence mobility for the interpretation of ancient sedimentary sequences.

2. Methods

Georeferenced Landsat imagery (30 megapixel resolution) spanning the period 1972-2014 was analysed to quantify the planform dynamics of large river confluences. Although there is no universal definition of large river channels (Gupta, 2008), a channel width of 100 m is commonly used (e.g. Miall, 2006; Latrubesse, 2008; Ashworth and Lewin, 2012; Lewin and Ashworth, 2014b). However, herein large river confluences are classified as those where both confluent channel widths are 250 m or greater. This 250 m width criteria is used to allow morphological changes to be more easily identified and quantified in the Landsat imagery; a single pixel in a 250 m wide channel represents a maximum of ~12% of the channel width, whereas a 100 m wide channel is only three pixels wide. Variations in global Landsat coverage over the period (Goward et al., 2006) together with the need for low cloud cover (<10%) in images, limits image availability. Landsat imagery for all confluences was selected from low flow stage, which minimised errors in misclassifying morphological features, such as bars, which may be emergent or submerged at different river stages. Low flow stage was defined seasonally, based on reference to existing literature on the climate of the study basins, and a further check was applied to images to identify the presence of low flow features such as exposed point and mid-channel bars in order to exclude any images during unseasonal high flow events. Fourteen confluences were studied in detail, across a range of climatic and physiographic regions, and these are presented in section 3 below. The objective in this initial analysis was to understand the range of behaviours displayed by large river confluences. This is then used to present a conceptual model of confluence types in section 5 based on this analysis. This analysis of confluences was then performed on all confluences within the Amazon and Ganges-Brahmaputra-Meghna basins to examine spatial distribution and quantify the morphodynamics of different confluence types.

The extent of channel migration in braided rivers was classified as either "within braidplain" or "braidplain migration" based on a classification of land cover types. This classification is based on the assumption that vegetated areas have been morphologically stable for at least the length of time that dense vegetation takes to become established; conversely, it is assumed that bare sediment has been disturbed by channel processes within a time frame that is not greater than that required for the establishment of vegetation. Therefore, "within braidplain" migration is defined as the reworking of exposed sedimentary material assumed to be within the active braidplain, whilst "braidplain migration" is given as erosion into vegetated surfaces that is older and not recently active. Both natural and false colour composite images were used to determine the edge of the active channel belt, by identifying land cover types as either exposed sediment or vegetation. The use of false colour composite images allows coarse discrimination between vegetation (chlorophyll) intensity, and it is therefore possible to discriminate areas of sparser vegetation (pioneer vegetation on bars for example) from denser vegetated areas (e.g. riparian forest). This does introduce a potential source of error in terms of timescales of adjustment and the broad definition of what constitutes the braidplain of a river. The present definitions and methods differentiate between a river that is reworking deposits less than ~30 years old, and one that is eroding into older materials. However, this distinction is partly a function of the short time scales over which these rivers are examined, and may be capturing the same process operating at different rates. These differences for individual examples are discussed in section 3, but all braided river migration is treated as one type of adjustment in the quantification (section 5) to eliminate any potential error from the analysis.

Where confluence angle (see Figure 1) is reported, this was measured using the approach of Hackney and Carling (2011). River centre lines were drawn to a distance of three channel widths from the confluence for the upstream tributaries and downstream confluent channel, and the angle at the intersection of these centrelines was measured. Where confluence locations are reported and included on figures herein, these mark the point at which the centrelines of the upstream tributaries intersect at the junction.

Confluent Channels	Country	Type	Channel Width (km)[a]	Migration length (km)	Dimensionless migration length[b]	Number of Images Studied	Junction Angle Range
Orinoco/Meta	Columbia	Bar Migration	1.0-2.0	1	0.5-1.0	7	60°-100°
Lena/Aldan	Russia	Bar Migration	7.0	N/A	N/A	6	N/A
Jamuna/Ganges	Bangladesh	Tributary Channel Migration	2.0	14	7.0	20	70°-100°
Jamuna/Gangadhar	India	Tributary Channel Migration	1.0	20	20.0	6	30°-80°
Jamuna/Dud Kumar	India	Tributary Channel Migration	1.0	25	25.0	6	30°-70°
Jamuna/Dharla	India	Tributary Channel Migration	1.0	7	7.0	6	40°-120°
Paraguay/Bermejo	Argentina	Meander Neck Cut Off	0.8	0.6	0.8	7	15°-110°
Mississippi/Arkansas	USA	Meander Neck Cut Off	1.3	5	4.0	31	40°-90°
Sardar/Ganghara	India	Channel Belt Avulsion	1.9	23	12.0	8	35°-90°
Meghna/Padma	Bangladesh	Pinned	4.0	17	4.2	20	45°-90°
Yangtze/Dongting Lake	China	Pinned	1.5	0.8	0.5	6	70° -110°
Solimões/Negro	Brazil	Fixed	4.0	0	0	7	N/A
Congo/Kasai	DRC	Fixed	1.5	0	0	6	N/A
Murray/Darling	Australia	Fixed	0.1	0	0	6	N/A

Table 1 – Confluences studied, with type of morphodynamic behaviour and range of movement. [a] – channel width of the post-confluence channel, [b] - Migration lengths for mobile confluences defined as migration distance divided by confluent channel width.

3. Styles of confluence evolution

This section presents data on 14 large confluences (summarised in Table 1) that cover a broad range of channel size, geological setting and geomorphological style. This overview allows different styles of confluence evolution to be characterised and compared, from which major confluence types can then be identified. This analysis is then used to propose a conceptual model of confluence types and quantify their prevalence within two example river basins in section 5. Presentation of the examples below is broadly themed to cover: i) those confluences in which evolution may be related to bar migration, ii) where bank erosion or bend migration are key controls on confluence behaviour, iii) where channel avulsion may be dominant, and iv) those cases that possess a stability in confluence over the 40-year time period examined (Table 1).

Bar Migration in Tributary Channels

The confluence of the smaller, braided Meta River with the Orinoco River in Venezuela provides an example of the migration of confluence location in relation to the dynamics of the bars (Figure 2). The high sediment yield and large seasonal flux in water discharge of the Meta River leads to deposition of abundant bars and islands that become emergent at low flow (Nordin and Perez-Hernandez, 1989). The sequence of images (Figure 2) shows that bars both upstream of the junction, and at its mouth within the Meta River, form and are eroded over the

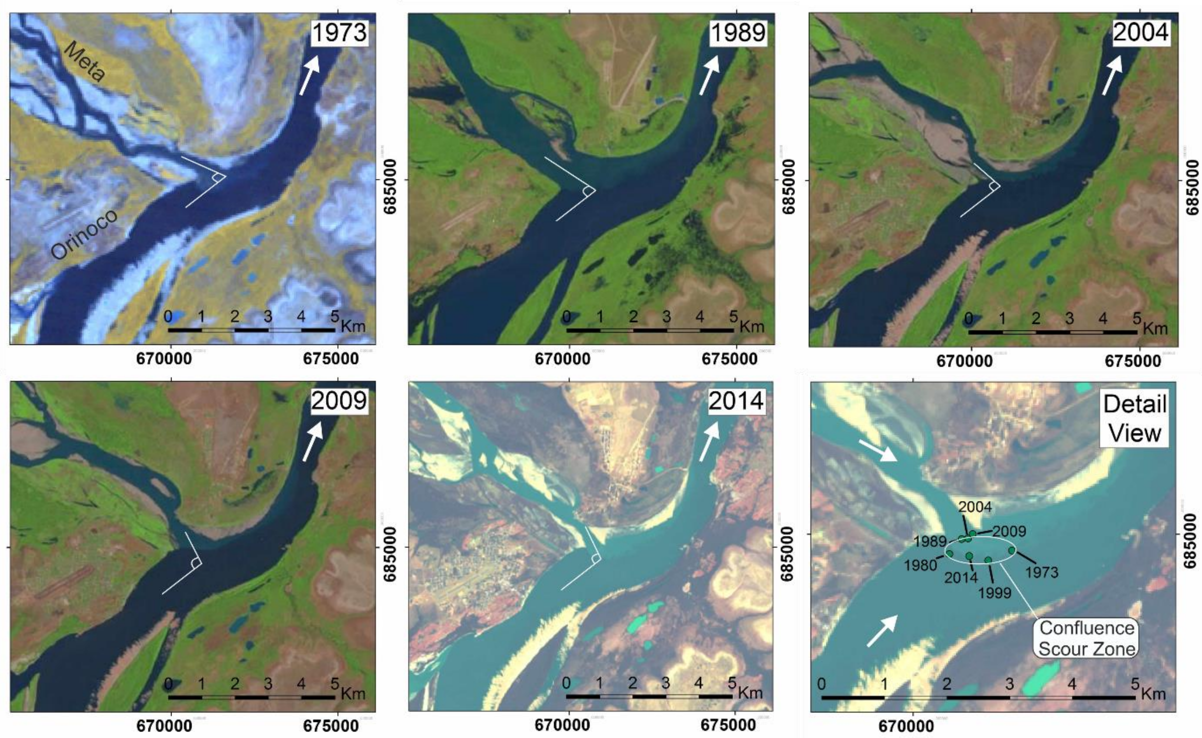

Figure 2 – Landsat image sequence showing planform changes at the junction of the River Orinoco and River Meta. The confluence position and angle shift subtly over time with formation and erosion of bars at the mouth of the Meta River. The morphological response to this bar movement is migration of the confluence within a narrow zone, shown in the detail view, approximately equal in length to the width of the Meta River channel. Note that due to paucity of cloud free images during 1973-2000, the 1989 image is at a higher river stage than the other years.

period 1973-2014. The net result of this bar formation and migration is that the flow from the Meta River migrates between the left and right edges of the wider river channel, and thus the location of the confluence migrates up- and down-stream by ~1km (~0.5-1 channel widths) with respect to the larger Orinoco River. In addition, the junction angle changes subtly over time from a minimum of ~60° up to a maximum of ~90°-100°. Past research (Mosley, 1976; Best, 1988) would suggest this change in confluence angle would increase the maximum

scour depth. Although there is ample evidence of planform change within the Meta River upstream of the confluence over the time period 1973-2014, the location of the tributary channel at the confluence does not show any migration or avulsion over this period, and thus the movement in confluence location is within a narrow zone of ~1 km, which is approximately equal to the overall channel width of the Meta River (Figure 2).

In large braided rivers, bars may also alter the direction of flow in the tributary channels and migrate into the confluence zone, thus changing the position and character of the confluence. The confluence of the anastomosing Lena River with the smaller Aldan River, Russia (Figure 3) shows limited morphological change over the period 1972-2014 that is driven by island and bar migration. Bank erosion along these rivers is relatively low due to the presence of permafrost, with lateral channel migration rates of 2-4 m yr^{-1} (Are, 1983; Costard et al., 2007), whereas downstream island migration is an order of magnitude greater (Costard and Gautier, 2007), with rates up to 40 m yr^{-1} (Costard et al., 2007; Costard et al., 2014). The junction between these two rivers is occupied by many braid bars and thus the confluence zone consists of multiple smaller junctions rather than one single confluence. In this case, it is likely that a series of smaller, mobile, confluence scours may yield a more complex pattern of intersecting scour surfaces and scour fills linked to the migration of these smaller junctions.

Tributary Channel Migration

In a multi-channel river, the migration, bifurcation or avulsion of tributary channels within a braid belt will cause corresponding migration and/or avulsion of the confluence location, and thus drive channel mobility at a greater spatial scale relative to active river width than that mediated by bar dynamics within the confluence zone. The width of the active channel belt of a multi-channel tributary therefore sets the potential migration length of the confluence location. An outstanding example of a confluence driven by channel migration is that described by Best and Ashworth (1997) of the Jamuna and Ganges Rivers in Bangladesh. Figure 4 illustrates that the Ganges-Jamuna confluence is highly dynamic, with the net result of these morphodynamic processes being the migration of the confluence location ~14 km southwards over the period 1973-2014. It can be seen that the orientation and position of the widest channel in the Jamuna River (flowing north to south) shifts over time. Initially, the widest channel occupies the right bank of the braidplain before migrating laterally, and later periodically switching around a large island that becomes vegetated, and thus stabilised. The meandering Ganges River also shows a gradual southerly lateral migration, with bars migrating into the confluence zone.

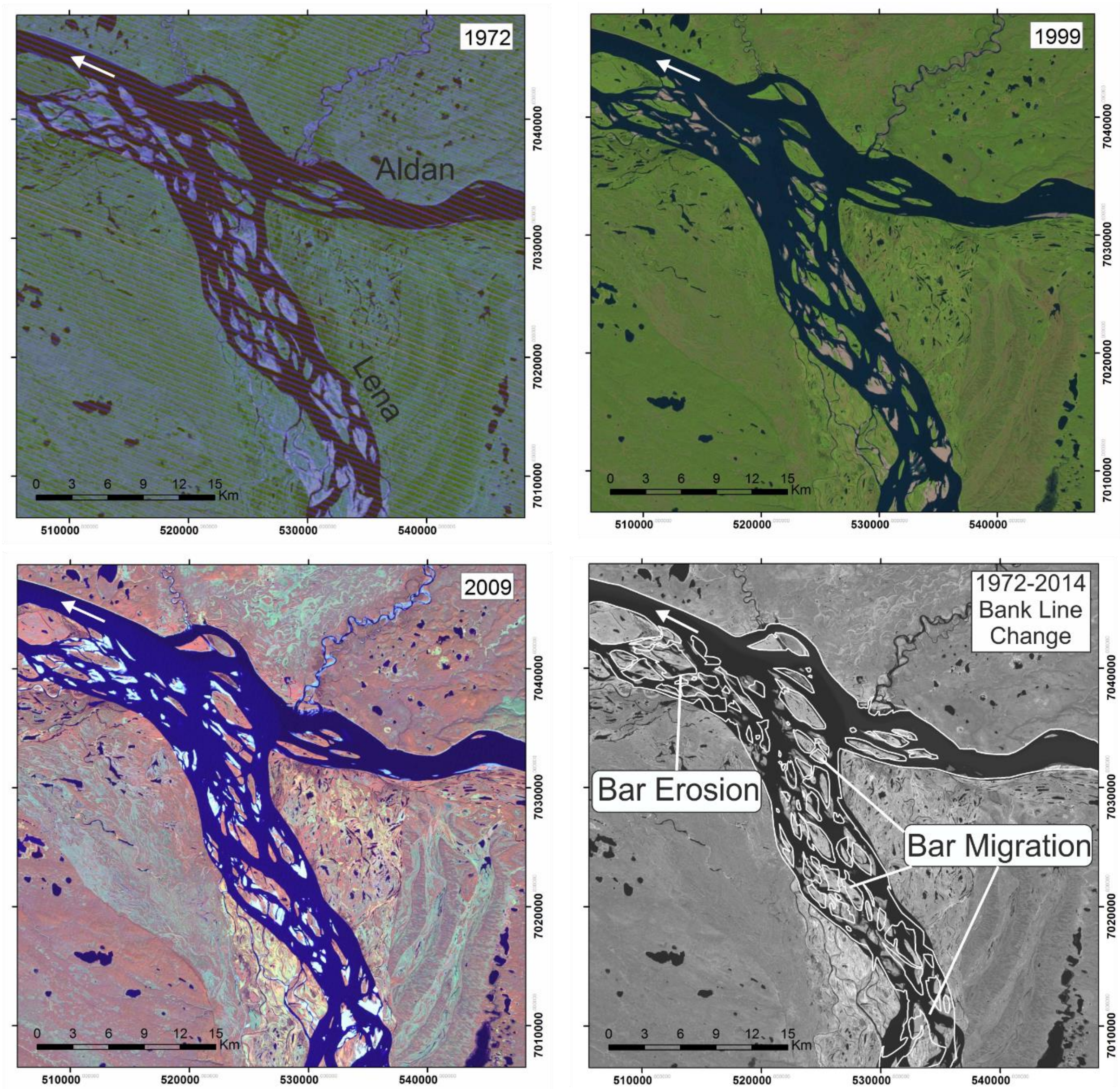

Figure 3 – Landsat images showing planform change at the confluence of Lena and Aldan rivers, Siberia, Russia from 1972 to 2014. Erosion at bar heads leads to very slow downstream migration of bars into the confluence zone; there is also gradual bar/bank erosion in the zone downstream of the confluence.

An example of braided river confluences moving over a greater scale relative to the channel width is shown by three tributaries of the Jamuna River in the Kurigram District of Northern Bangladesh (Figure 5; from north to south: Gangadhar, Dud Kumar and Dharla Rivers) that drain the Himalayas, and that possesses wandering planforms. The sequence of images (Figure 5) shows that the main flow of the Jamuna River moves towards the Western edge of its braidplain over time, resulting in the lateral and longitudinal migration of confluence locations. The northern most tributary, the Gangadhar River, initially flows into a smaller anabranch channel of the Jamuna River in 1973 (marked by “1” in Figure 5), with the Dud Kumar also flowing into this anabranch approximately 5 km downstream.

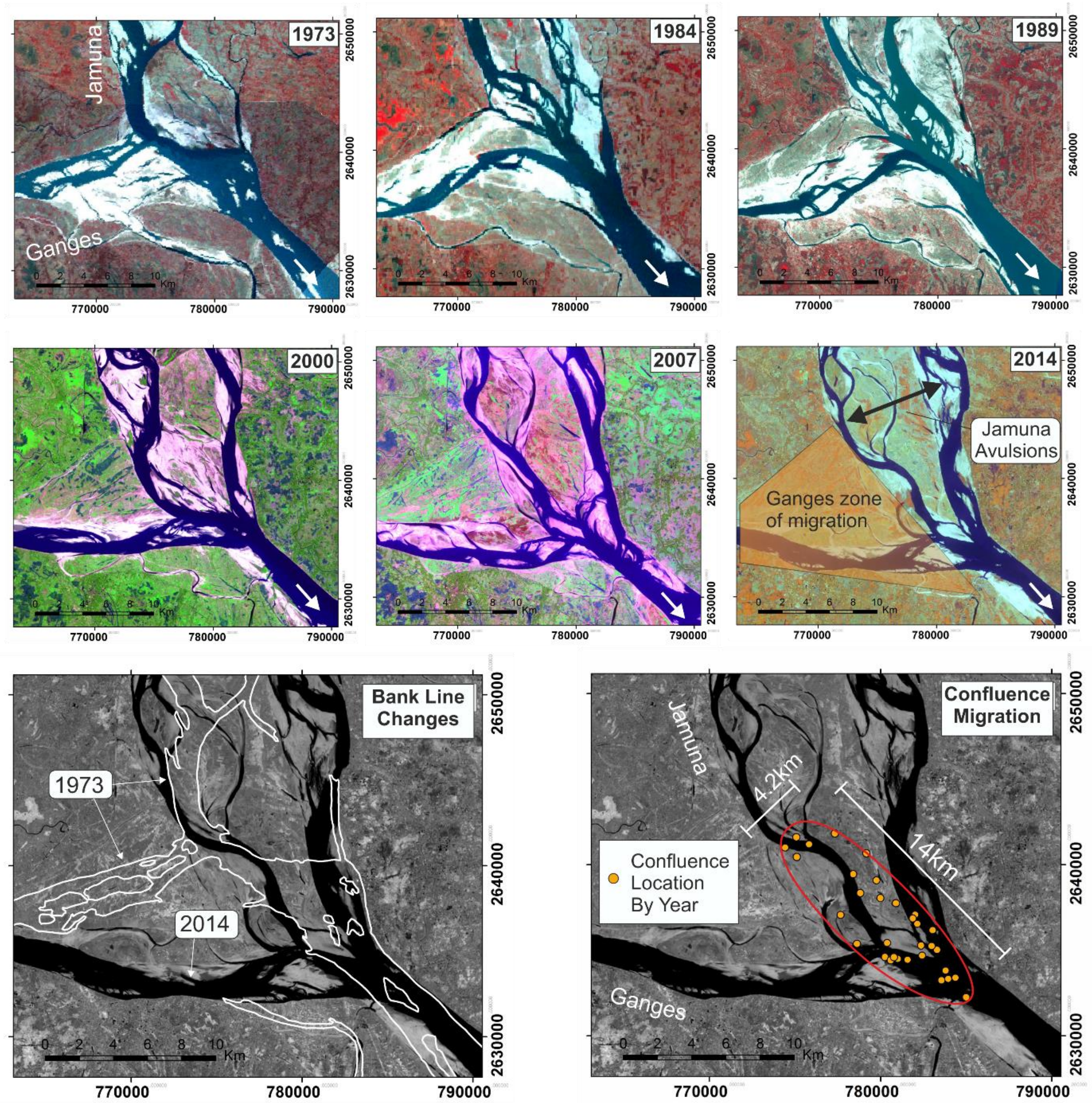

Figure 4 – Sequence of six Landsat images of the junction of the Ganges and Jamuna rivers, Bangladesh, over the period 1973-2014, with additional panels comparing banklines between 1973 and 2014 and the overall confluence migration by year. The Ganges River has migrated in a southerly direction over the image sequence, which appears to be part of a cyclical north-south migration of this channel downstream of a nodal point (see text); a proposed zone for this migration is shown on the 2014 panel. In addition, periodic changes in orientation and position of dominant flow in the Jamuna River are evident, with the extent of this variation being indicated by the black arrow on the 2014 panel. The combined result of these two modes of tributary movement at the junction results in extensive changes in confluence position over time, which over 40 years encompasses a zone 14 km long and 4.2 km wide.

In 1973, several other anabranch channels of the Jamuna River also meet this right hand anabranch, with the effect that as the channels are funnelled towards the geological control at the Garo-Rajmahal Gap (approximately 5km south of image sequence in Figure 5), the belt narrows and there is a confluence between the main flow of the Jamuna River and the combined Gangadhar/Dud Kumar/Jamuna anabranch (labelled '2' in Figure 5). The anabranch is then abandoned by the Jamuna River and occupied by the Gangadhar River, whose confluence moves around 7 km south-west by 1978, with the confluence of the Dud Kumar moving around 1 km south, and the confluence unit at point "2" (Figure 5) moving around 1 km upstream. The Gangadhar River then forms a distinct, separate, confluence with the Dud Kumar River by 2000 where this combined tributary flows into the Jamuna River some 20 km south of the original confluence of the Gangadhar and Jamuna rivers in the vicinity

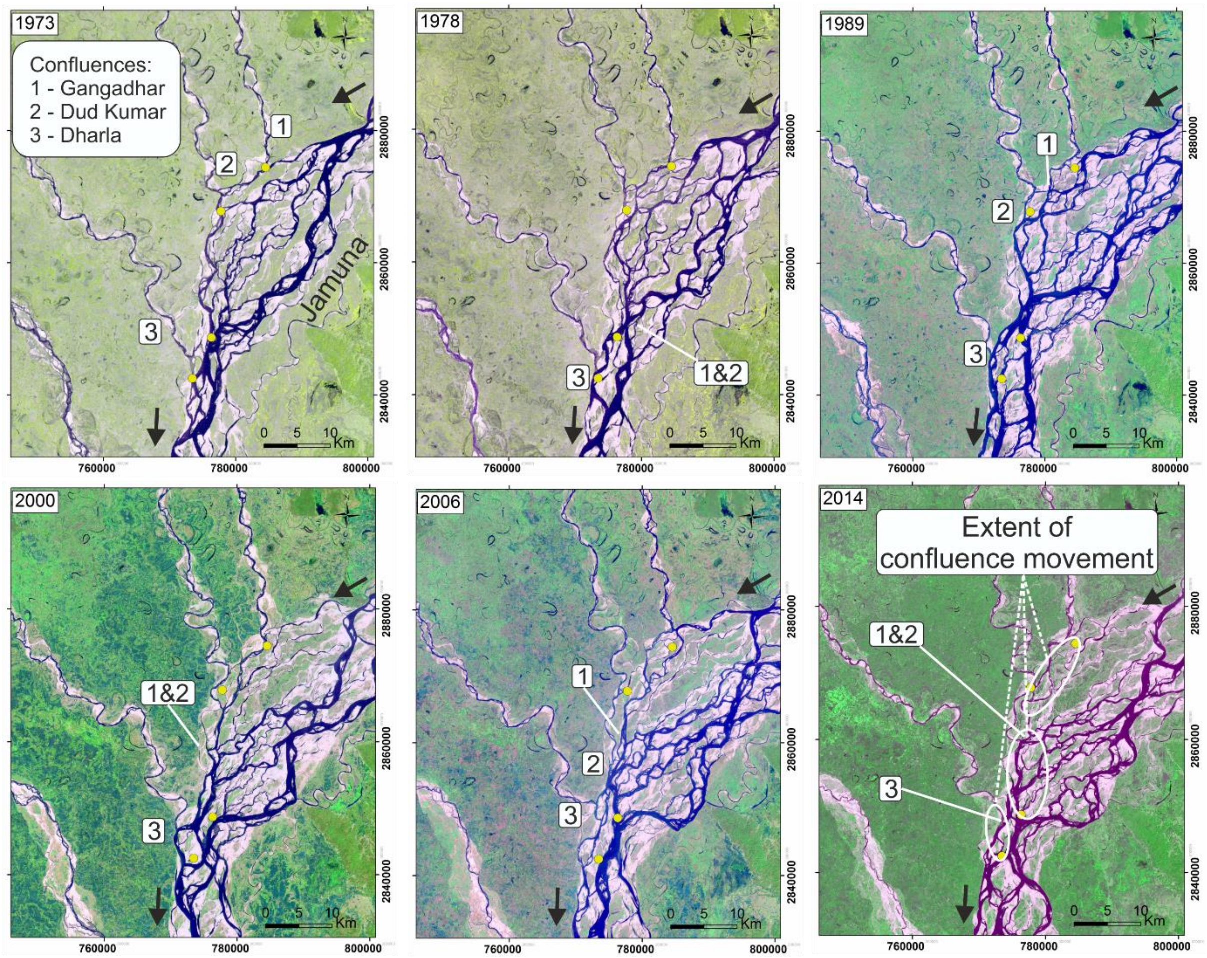

Figure 5 – Confluence of the Jamuna (Brahmaputra) River with its tributaries, from north to south: Gangadhar River (1), Dud Kumar River (2) and Dharla River (3), in the Krigram District of Northern Bangladesh. Original 1973 confluence locations marked as dark yellow points in all images. Migration of the main thalweg of the Jamuna River within its braid plain over time leads to migration and avulsion in the position of the confluences. The 2014 image is annotated with white ellipses to show the zones over which the confluences moved during the 40-year image sequence.

of "2" (Figure 5). In the mid-2000's, the Jamuna River briefly reoccupies an abandoned channel towards the southeast edge of the braid belt and the confluence reverts to near its 1973 location, with a major confluence around 1 km downstream of point "2". At this point, the lower Dud Kumar River has avulsed away from its nascent confluence with the Gangadhar River and occupied an abandoned anabranch of the Jamuna River, briefly having a distinct confluence with the Jamuna River around 25 km south of its 1973 confluence location. By 2014, the main flow of the Jamuna River again abandons the anabranch and a combined Gangadhar/Dud Kumar tributary meets the Jamuna River around 15 km south of point 1 (Figure 5). The southernmost confluence in Figure 5, between the Dharla and Jamuna rivers, is less complex, as there appears less lateral space for the Jamuna River to migrate. The position of the confluence marked as "3" (Figure 5) can be seen to migrate steadily towards the right edge of the Jamuna River braid belt from 1973 to 2000, before moving upstream with the abandonment of an anabranch of the Jamuna River in 2006. Most importantly, in this river the reworking of deposits at these wandering junctions may be extensive enough to encompass the entire 20 km wide braid plain over a period of 40 years. Within this zone of reworking, the associated confluence scours are each likely to occupy zones up to 8-10km long and up to 5km wide. Over longer time periods, these are likely to form continuous composite scour surfaces, perhaps similar to the Lower Cretaceous tributary scour surfaces reconstructed by Ardies et al. (2002).

Confluence evolution in response to channel movement can also be seen in meandering rivers, as illustrated by the junction of the Paraguay and Bermejo rivers in Argentina (Figure 6). The Paraguay River at this location is relatively stable, but meander migration in the Bermejo River, upstream of the confluence, drives changes in the confluence location. Between 1985 and 1993, the Bermejo River cuts through and abandons a meander

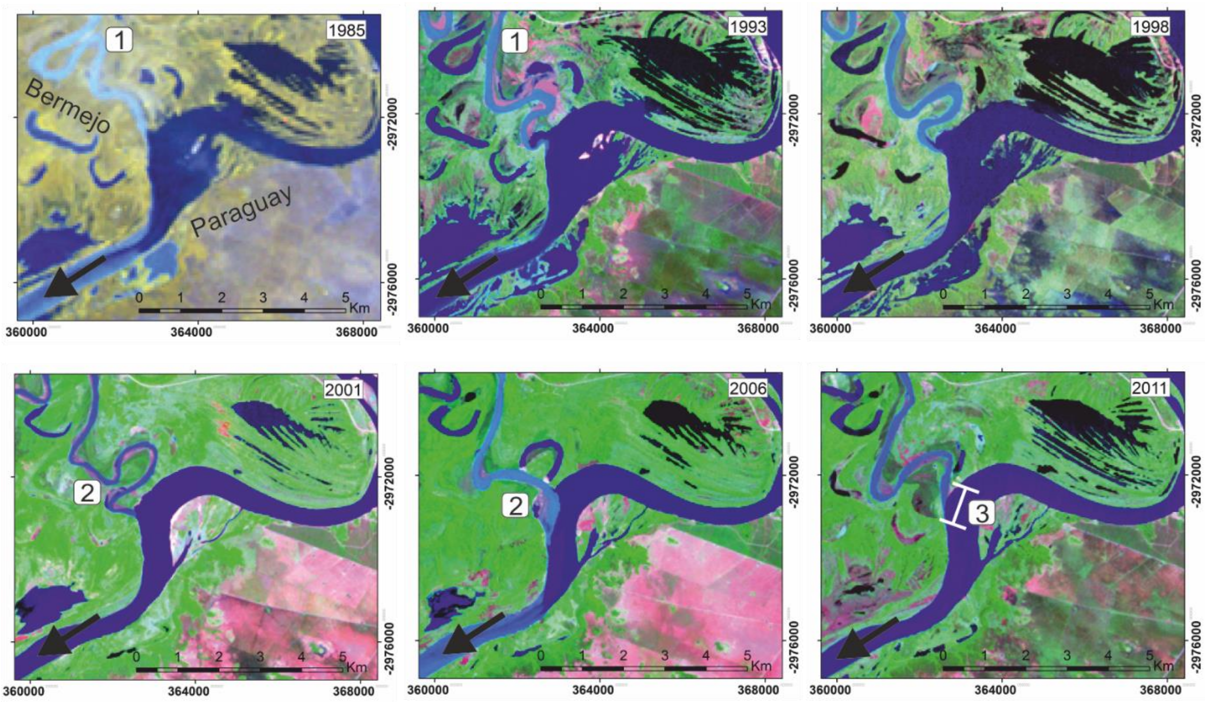

Figure 6 – Landsat images from 1985 to 2011 showing confluence morphodynamics of the Paraguay and Bermejo Rivers, Argentina. Between 1985 and 1993 a meander cut-off (1) upstream in the Bermejo River, coupled with meander loop extension in the vicinity of the confluence, causes an increase in confluence angle and downstream migration. A second cut-off between 2001 and 2006 (2) leads to an upstream shift in confluence location and a decrease in confluence angle. The maximum extent of confluence location change, just over 1 km, is illustrated by label 3, and is equivalent to approximately one post-confluence channel width.

bend (labelled 1 in Figure 6), whilst the bends in the immediate vicinity of the confluence extend, increasing the junction angle from 30° to 110°. Over the period 1993 to 2001, the Bermejo River gradually increases in sinuosity (from 1.72 to 2.37) as the individual meander bends extend and translate downvalley with respect to the tributary, and this has the effect of moving the confluence location gradually downstream relative to the Paraguay River, whilst the junction angle remains

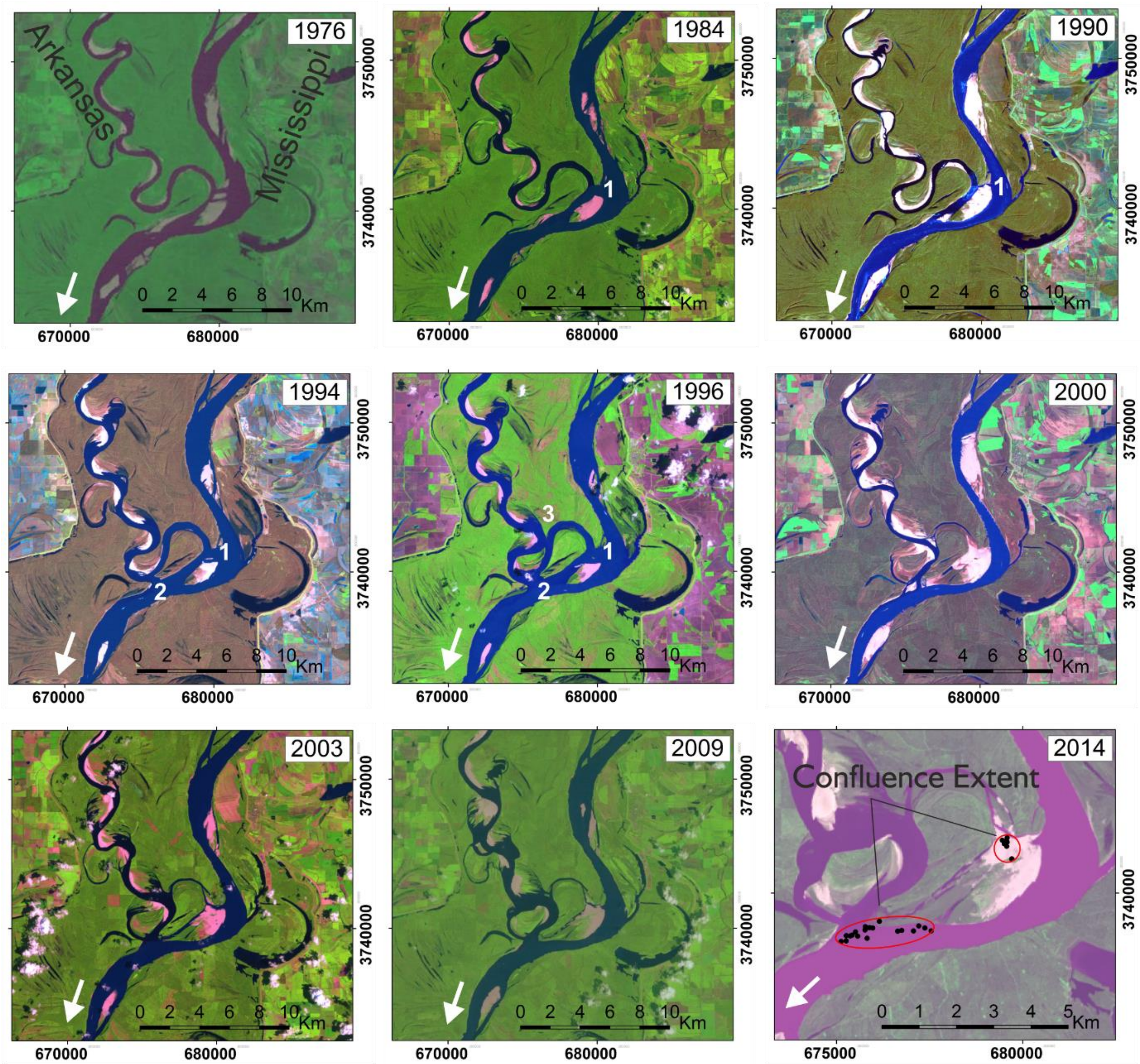

Figure 7 – Landsat images showing the confluence of the Mississippi and Arkansas rivers, USA. Downvalley migration of meander bends in the Arkansas River, coupled with extension and cut-off of individual bends, leads to rapid, avulsive switching of the confluence location on annual timescales. The point bar labelled (1) becomes attached and detached, thus shifting confluence location by ~3km between 1976-1992. In 1994, the gradual downvalley migration of meander bends in the preceding years leads to a neck cut-off (2) and shift of confluence location. A further cut-off upstream in the Arkansas River (3) promotes abandonment of the original channel and rapid infilling. The 2014 image shows confluence locations for every year from 1976-2014 for which an image is available, and highlights the spatial extent of confluence influence over this period.

high angle or obtuse (70-110°). A meander bend neck cut-off in the Bermejo River immediately upstream of the junction occurs between 2001 and 2006 (labelled 2, Figure 6), reducing sinuosity (from 2.37 to 1.44) and junction angle (95° to 45°), before rapid extension of a new meander loop between 2006 to 2011 once again increases sinuosity from 1.44 to 2.06. Over this temporal sequence, the location of the Bermejo-Paraguay confluence migrated over a distance of ~600 m, or approximately 0.8 times the post-confluence channel width; however, based on the position of abandoned meander loops in the floodplain, the confluence location may have repeatedly migrated over as much as 2 km through meander neck cut-offs. Given the confluence angle has also varied between 15° and 110°, it is likely there has also been an associated spatially-variable pattern in maximum scour depth.

The junction of the Mississippi and Arkansas rivers (Figure 7) is another example of a highly mobile confluence in a meandering river. The sequence of images (Figure 7) shows that the position of the confluence is driven by downvalley meander migration and resulting neck cut-off in the smaller Arkansas River, coupled with deposition, attachment and erosion of a large point bar in the Mississippi River (labelled 1, Figure 7). The result of these morphodynamic changes at the junction is a switching of confluence location up and downstream with respect to the Mississippi River over a total distance of around 5 km (4 channel widths; Figure 7). The presence of meander scars in the valley of the Arkansas River also suggests that the maximum extent of this confluence migration could be as much as 10 km.

Avulsion of the Channel Belt

In contrast to the examples given above, the position of a confluence can also adjust through migration, or avulsion, of the entire channel belt, representing the largest relative scale of adjustment in confluence location. The confluence of the Sarda and Ghaghara rivers (the Ghaghara River is a tributary of the Ganges River) in Uttar Pradesh, North India (Figure 8), is an example of a confluence that shifts position in response to channel belt migration in its tributaries. Both tributaries drain the Himalayas and possess a wandering braided planform. The change in confluence location appears to be primarily avulsive in nature, driven by movements in the lower course of the Ghaghara River (flowing north to south). The sequence of images from 1977 to 1986 (Figure 8) shows the presence of a very small northerly off-shoot of the Ghaghara River in 1977 that progressively received more of the flow over time, until by 1986 the original channel had been abandoned by the Ghaghara River (moving the confluence location ~5.2 km from “1” to “2”, Figure 8). The Ghaghara River again changed course in the 1990s and developed a bifurcated channel, so that by 2003 the confluence had moved around 8 km to the south (points 3, Figure 8). During the late 2000’s, the Ghaghara River abandoned the southern branch, and the confluence of the northern branch migrated ~2 km to point 4 (Figure 8). By 2014, the Sarda River migrated towards the west and a bifurcation formed in the Ghaghara River just upstream of the location of the twin 2003 confluences (points 3); a new confluence formed close to point 3 (labelled as point 4) with a second new confluence approximately 12.1 km south of point 4 (point 5, Figure 8). The confluence location over the 40 years of images thus moved over a distance of 22.7 km, for two channels that have a maximum braidplain width of 2 km during the image sequence. This illustrates the potential for confluences of morphodynamically-active tributaries to move over distances around an order of magnitude greater than their channel width on decadal timescales.

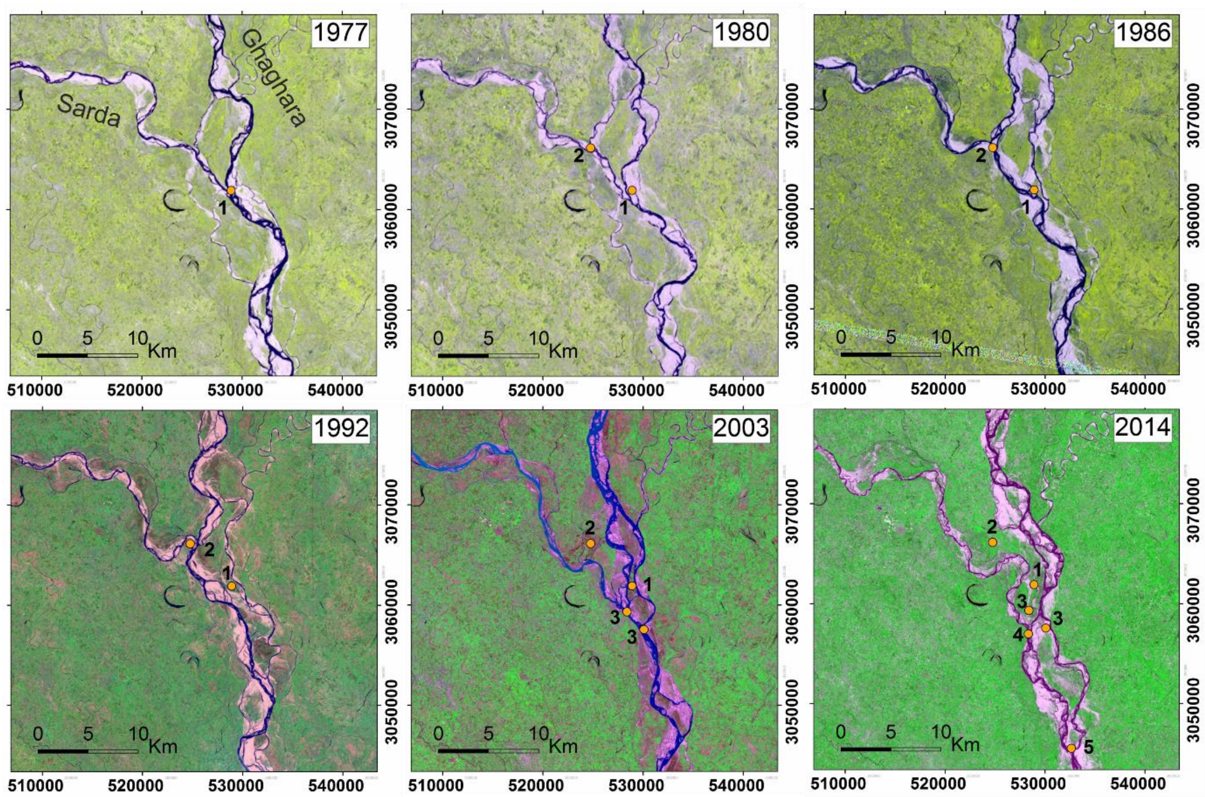

Figure 8 – Landsat images showing confluence of the Ghaghara River (flowing north to south) and Sarda River (flowing broadly west-east), Uttar Pradesh, India. Migration and avulsion of the lower Ghaghara channel drives the movement of the confluence location from (1) in 1977 to (2) in 1986 where a dual junction is present, to (3) in 2003 and finally two separate confluences (4 & 5) around 12 km apart in 2014. The 2014 image shows the extent of confluence movement is 23 km from (2) to (5). Note that confluence location also migrates approximately 1km during the intra-avulsion periods (1) between 1977-1980 and (2) between 1986-1992.

The imagery also demonstrates that the rate of confluence migration can change significantly over time, and previously mobile confluences may become much more stable. This can occur where, as a result of either a natural geological hard point or anthropogenic bank reinforcement, the confluence becomes constrained against a less easily erodible substrate and becomes "pinned" in place. Depending on the extent of the hard point, this confluence stability may be a temporary phenomenon, ending when the hard point is eventually eroded, or the morphodynamics are such that the channel avulses away from, or around, the location. Two examples are shown in Figures 9 and 10. In the case of the junction of the Padma and Meghna rivers, Bangladesh (Figure 9), the Padma River has migrated in a southerly direction from the early 1970's to the mid-2000's, when the confluence location is near the town of Chandpur (marked "1"; Figure 9), where there is extensive anthropogenic bank reinforcement (a 'hard point') to protect the town and harbour, and thus the southerly migration of the junction has been arrested at this point. The subsequent images (Figure 9, 2007 and 2013) show an increasingly concave embayment forming upstream of the pinned confluence, coupled with increased bank erosion downstream. It is important to note that although the location of the confluence is pinned against the hard point in 2014, there has been substantial planform adjustment up- and down- stream of the confluence from 2003 to 2014, demonstrating that the channel is highly mobile.

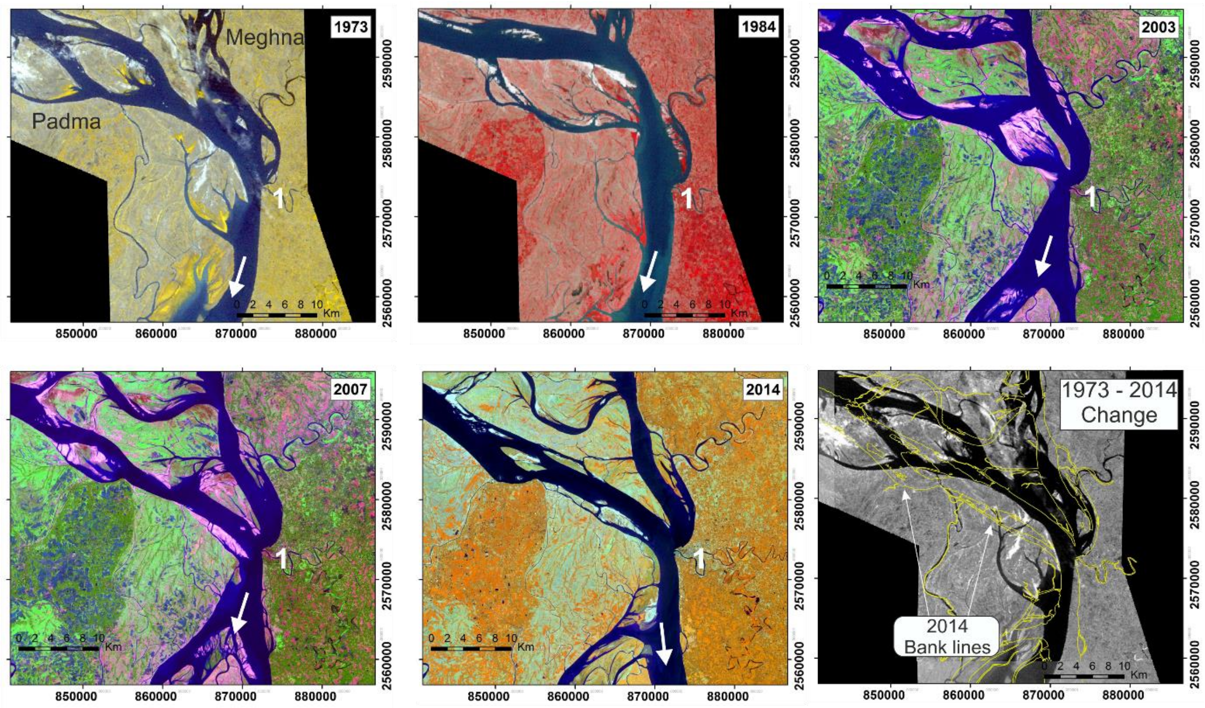

Figure 9 – Confluence of the Padma and Meghna Rivers near Chandpur, Bangladesh. The confluence location migrates in a southerly direction from 1973-2003 before reaching the anthropogenic hard point at Chandpur (point 1). In the 2007 and 2013 images there is increasing erosion up and downstream of point 1. The 1973-2014 change panel shows the 2014 banklines superimposed onto a grayscale image of the 1973 river.

Another similar example is from the Yangtze River, China, at Yueyang (Figure 10) where the outflow from Dongting Lake (itself receiving the waters of the Li, Yuan, Zi and Xiang Rivers) meets the Yangtze River at the port of Chenglingji. The right hand bank of the Yangtze River has been extensively reinforced, whilst the Yangtze River upstream of the confluence shows adjustments in its meander bends. The meander bends in the Yangtze River are translating downstream and extending at the hard point of the confluence, and this has the effect of increasing the junction angle, with the possibility that the junction angle may become obtuse in the future.

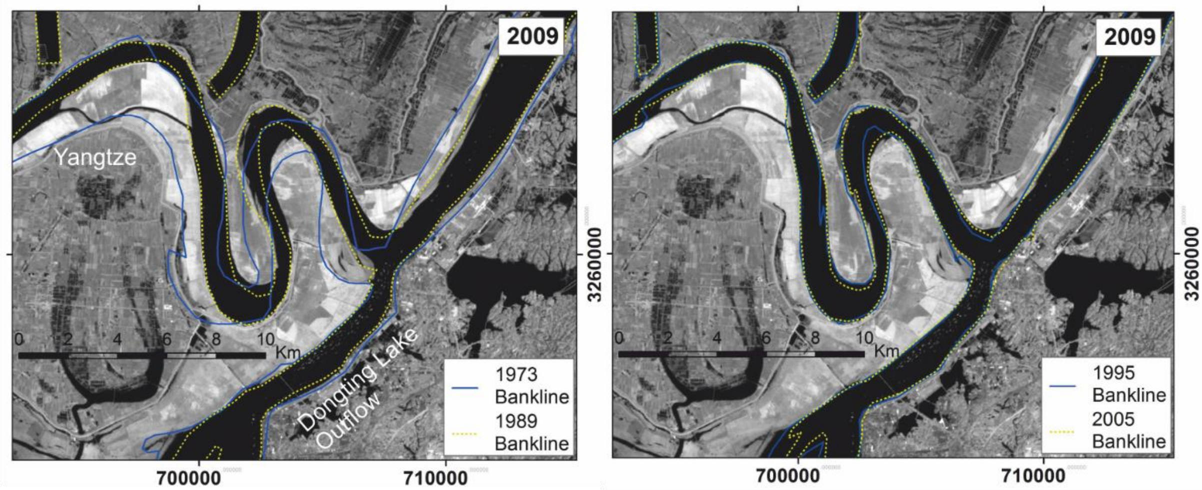

Figure 10 – Confluence of the Yangtze River and outflow from Dongting Lake, Yueyang, China. Digitised banklines from 1973, 1989, 1995 and 2005 are superimposed onto two images of the confluence planform from 2009. This sequence shows the translation and extension of meanders upstream of the pinned confluence.

Fixed Confluences

Finally, in contrast to the examples of mobile confluences discussed above, there are many large river confluences that remain fixed over decadal timescales, such as the junctions of the Solimões and Negro Rivers (Figure 11) in Brazil, or the Congo and Kasai Rivers at Kwamouth in the Democratic Republic of Congo (Figure 12). The confluence of the Murray and Darling rivers in New South Wales, Australia, is now also fixed (Figure 13), but this imagery indicates that confluence mobility can

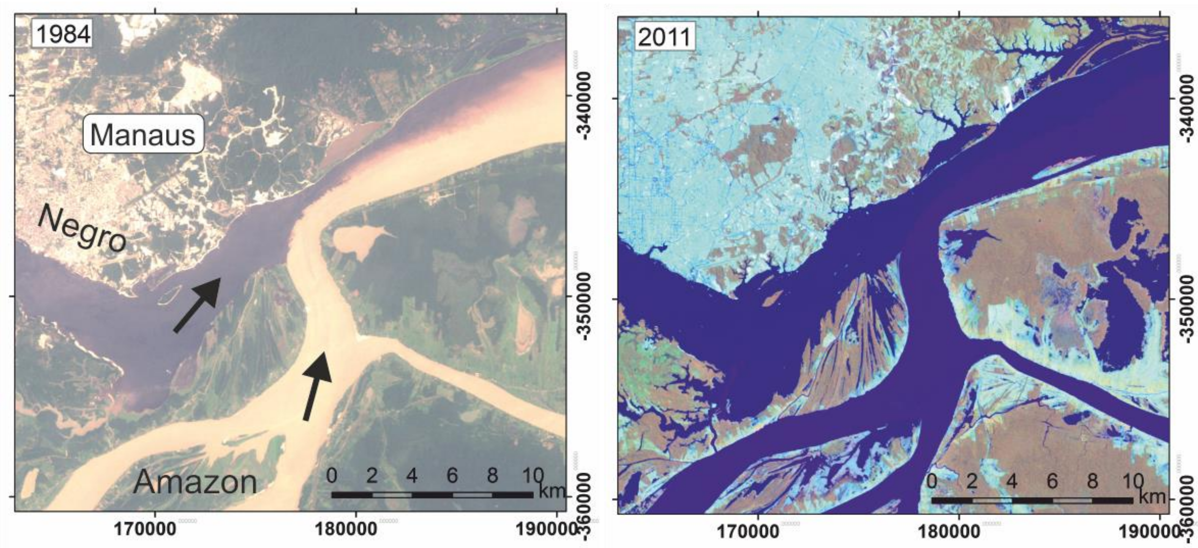

Figure 11 – Confluence of the Solimões and Negro rivers, Brazil. Despite evidence of accretional features in the floodplain associated with channel migration, and slight movement of the entrance point of the Solimões River into the junction, the confluence has remained essentially fixed over decadal timescales. Note growth of city of Manaus (light blue) in the 2011 false colour image with associated bank development/reinforcement.

change significantly through time. For example, the abandoned meander loops and scars in the floodplain (Figure 13) suggest that at some point in the past the river was morphodynamically active and confluence evolution may have been more similar to the example of the Mississippi and Arkansas rivers presented above. It is important to note that these junctions can only be viewed as fixed over the 40 year period of observation, and that they may display either much slower timescales of adjustment, or the period of observation may have coincided with a hiatus in a more episodic type of mobility. Further work is required to quantify the abundance of fixed confluences over much longer timescales as these are likely to represent discrete scour features in the rock record, compared to more extensive scour surfaces produced by mobile confluences. In order to understand more about fixed confluences and timescales of adjustment, it is thus necessary to understand the broader controls on confluence mobility.

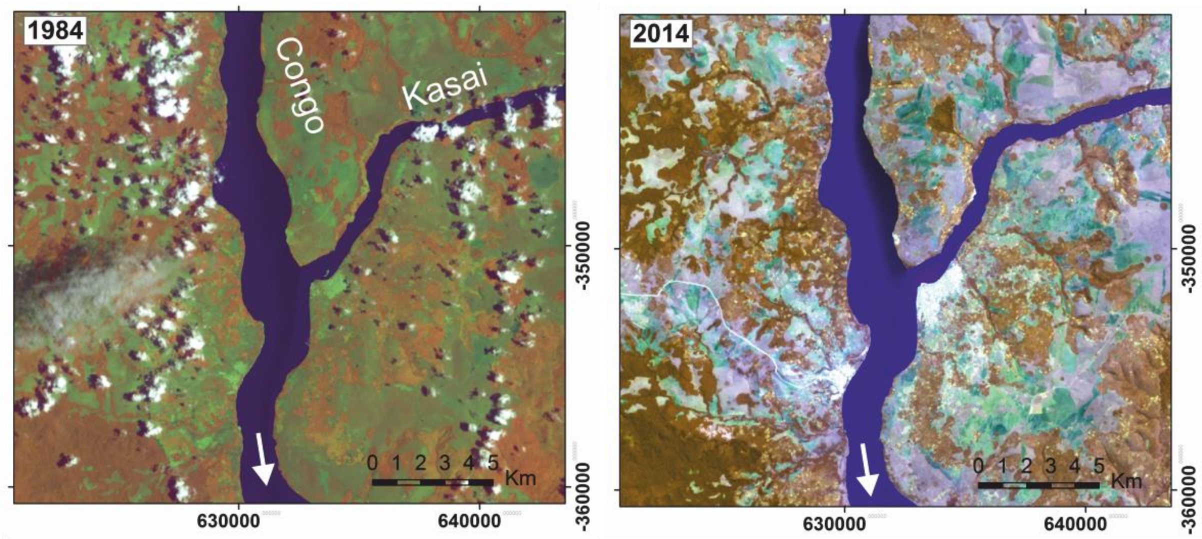

Figure 12 – Landsat images showing the confluence of the Congo and Kasai Rivers in the Democratic Republic of Congo. The rivers are heavily incised into surrounding bedrock that prevents lateral channel migration and results in a fixed confluence.

4. Controls on confluence evolution

The preceding examples illustrate that confluences can adjust their planform position over a range of relative spatio-temporal scales and that such changes can occur in a broad range of river planform types. Some inferences concerning the processes that may be driving the style and rate of change observed at these confluences are now discussed briefly, focusing on the role of discharge, sediment supply, tectonics, climate, bank material and human influence.

In broad terms, it would appear that the same drivers of channel planform change are also responsible for controlling confluence evolution. Thus it might be expected that confluences in areas with high rates of sediment supply, high water discharges and easily erodible banks would be highly mobile, due to bar migration driving changes in channel orientation and location, thus resulting in

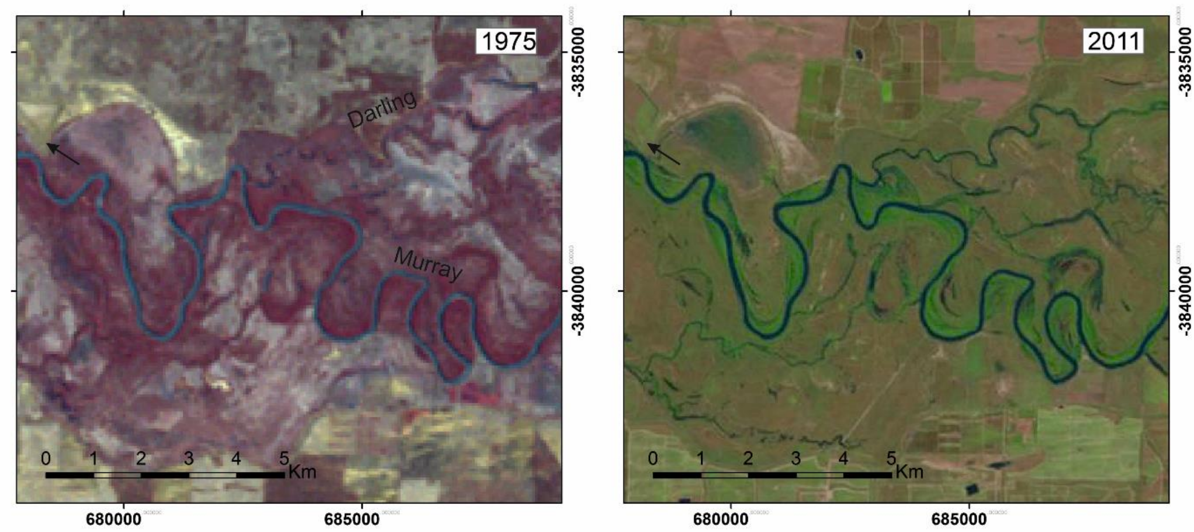

Figure 13 – Landsat images showing the confluence of the Murray and Darling rivers in Australia. The images show abandoned meander loops in the floodplain surface suggesting historic channel mobility, but over the 36-year image sequence there is no evidence of active meandering and the confluence position remains fixed.

confluence movement. The Ganges-Jamuna junction is perhaps the type example of this type of environment. This river system has high discharges and sediment loads driven by high uplift rates in the Himalayas, monsoonal-dominated floods, coupled with ongoing subsidence in the Bengal Foredeep (Goodbred and Kuehl, 1999; Goodbred et al., 2003; Reitz et al., 2015) promoting basin wide deposition (Best et al., 2008). High rates of channel and bar migration are present, with the Jamuna River being particularly dynamic even where kilometre scale bars are extremely mobile, which may migrate up to 3km yr^{-1} (Best et al., 2008). These factors likely contribute to the active migration observed for the Jamuna-Ganges confluence. Likewise, in meandering rivers, such as the Mississippi-Arkansas confluence, the junction position may change due to similar reasons. At the confluence of the Mississippi-Arkansas, the rivers flow through thick, Holocene alluvium (Rittenour et al., 2007) and have a high suspended sediment load that contributes to the formation of abundant islands and bars that can become stabilised by vegetation (Knox, 2008). The rates of channel migration in the Mississippi River were quantified by Hudson and Kesel (2000) who showed an average meander bend migration rate for the 825 km section of the lower Mississippi containing the Arkansas confluence to be 38.4 myr^{-1}. However, for the four measurement points closest to the confluence, there is an average meander bend migration rate of around 60 m yr^{-1} (Hudson and Kesel, 2000). The Arkansas River provides a large input of medium sand to the main river and the shallower slope of the Mississippi River in the vicinity of the confluence, as compared to up- and down- stream (Schumm et al., 1994), promotes deposition of this sediment input. The high sediment load in both the Arkansas and Mississippi rivers, coupled with the easily erodible floodplain, and possible paucity of clay plugs restricting migration in this region (Hudson and Kesel, 2000) contributes to rapid bank erosion in the Arkansas River, with rapid migration of the meander bends yielding rapid changes in confluence location.

In contrast, where there is significant geological control, confluences may be essentially static over decadal timescales, as illustrated by the confluence of the Congo and Kasai Rivers (Figure 12). At this location, the confluence remains fixed due to the inability of either channel to migrate laterally in the presence of bedrock control. Changes in climate may also lead to a change in confluence dynamics, as is likely in the case of the Murray-Darling rivers (Figure 13). River discharges in this region were much higher than at present during the last glacial maximum (LGM) through to the early Holocene (Page et al., 1996; Nanson et al., 2008; Fitzsimmons et al., 2013), with channel size and lateral migration decreasing since the LGM (Nanson et al., 2008; Fitzsimmons et al., 2013). The average annual flood and long-term mean annual discharge have also been reduced substantially over the later part of the 20th century by human intervention through water diversions, and the construction of dams (Maheshwari et al., 1995) and over 3600 weirs (Arthington and Pusey, 2003). As a result, the present day Murray-Darling River has a remarkably low annual discharge for its catchment area (Maheshwari et al., 1995; Arthington and Pusey, 2003), resulting in a confluence with no detectable movement over decadal timescales. Within-channel engineering works have also had a direct impact on the movement of the Padma-Meghna and Yangtze river confluences described herein, by introducing an artificial hardpoints that prevent the migration of these junctions.

5. A new classification of planform confluence behaviour

A new classification of confluence morphodynamics over management timescales is proposed herein (Figure 14) that divides junctions into three broad categories: i) **Fixed**: confluence location remains static on decadal timescales, with only minor migration of the scour zone, ii) **Pinned**: the movement of previously migratory confluences is greatly diminished as the confluence encounters a hardpoint; and iii) **Upstream adjustment**: tributary planform adjustments drive larger-scale migration of the confluence location (Figure 14, Table 2). A range of confluence styles may exist within the latter category, responding to upstream controls in sediment and water supply. Four types can be discerned within this latter category: i) *Mouth bar migration*, where channel position remains fixed, but bars within the confluence zone form, erode, and/or migrate; ii) *Braid belt migration and braid channel avulsion*, where the position of the dominant flow moves within a braided tributary channel, driving movement of the confluence location; iii) *Tributary meander bend neck cut-off*, where the cutoff of meander loops, near the confluence, drives movement of the confluence position; and iv) *Confluence location migrating downstream*, where lateral migration of a tributary channel moves the confluence and its scour zone. Due to the difficulty in categorically determining from satellite data the rates over which braided river morphodynamic processes are occurring, and thus whether a braid channel is eroding into older deposits, the migration or avulsion of braid channels and the braid belt itself are treated herein as a single process in this proposed classification. Further detailed case studies over longer time periods could elucidate whether these are separate processes.

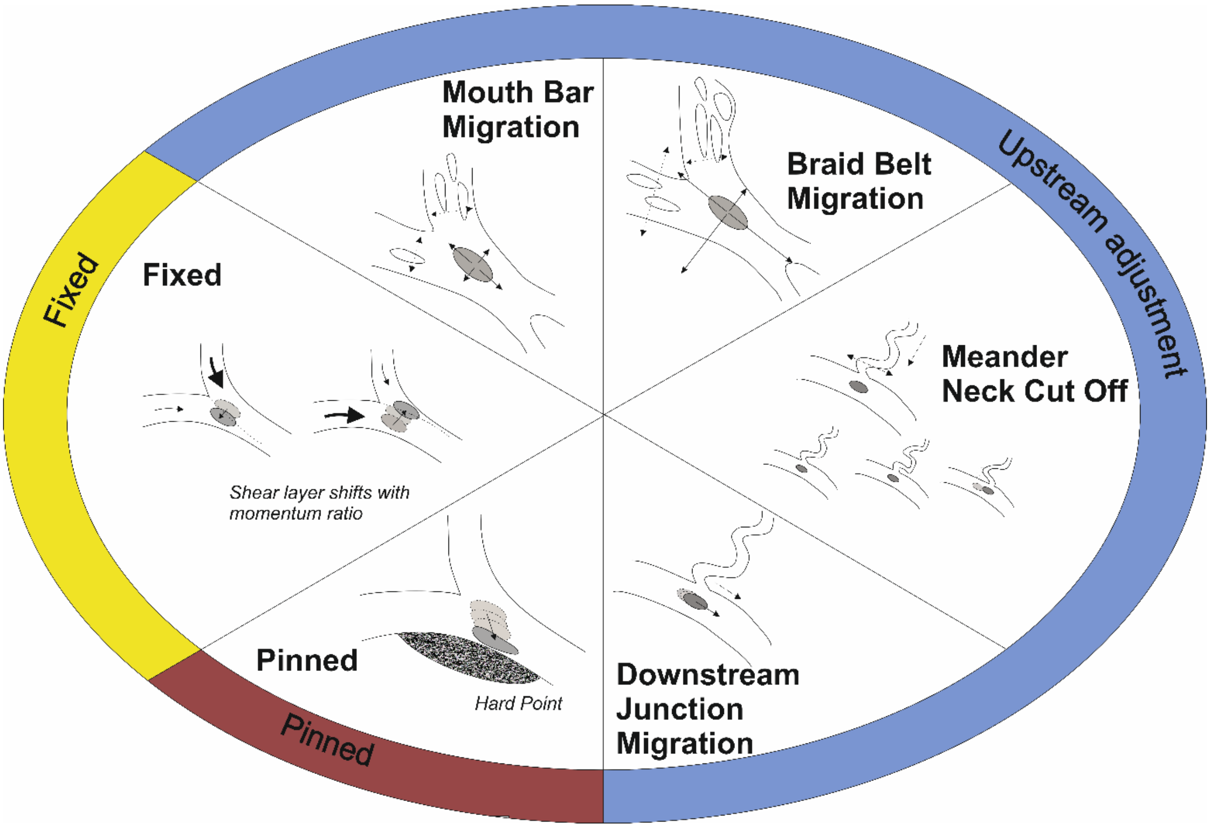

Figure 14 – A classification of confluence types based on analysis of Landsat imagery. See text for explanation.

Having identified these different styles of behaviour, the abundance of confluence types in different basins can now be addressed. In order to begin to answer this issue, 117 confluences for which both tributary channels were greater than 250m wide were identified in two of the world's largest river basins: the Ganges-Brahmaputra-Meghna (GBM) (Figure 15) and the Amazon (Figure 16). Landsat imagery spanning the period 1988 to 2014 was used to classify each confluence according to the classification scheme given in Figure 14. This analysis demonstrates that for channels of a similar size, the GBM and Amazon basins represent confluences with a very different mobility (Table 2), with over 80% of the large river confluences in the GBM basin being mobile over decadal timescales, whereas in the Amazon basin less than 40% of large river confluences are mobile.

As discussed above, the characteristics of the GBM basin that produce such high rates of channel change are the highly seasonal monsoonal discharge regime, low cohesive bank strength and high sediment yields. The majority of sediment delivered to tributaries of the GBM is fine sand, with a relatively low silt fraction from Precambrian metasedimentary rocks (Datta and Subramanian, 1997; Mukherjee et al., 2009). The sediments in the channels are thus primarily unconsolidated, with the high sediment yields leading to a dynamic braiding/anabranching pattern in the majority of channels within the GBM basin.

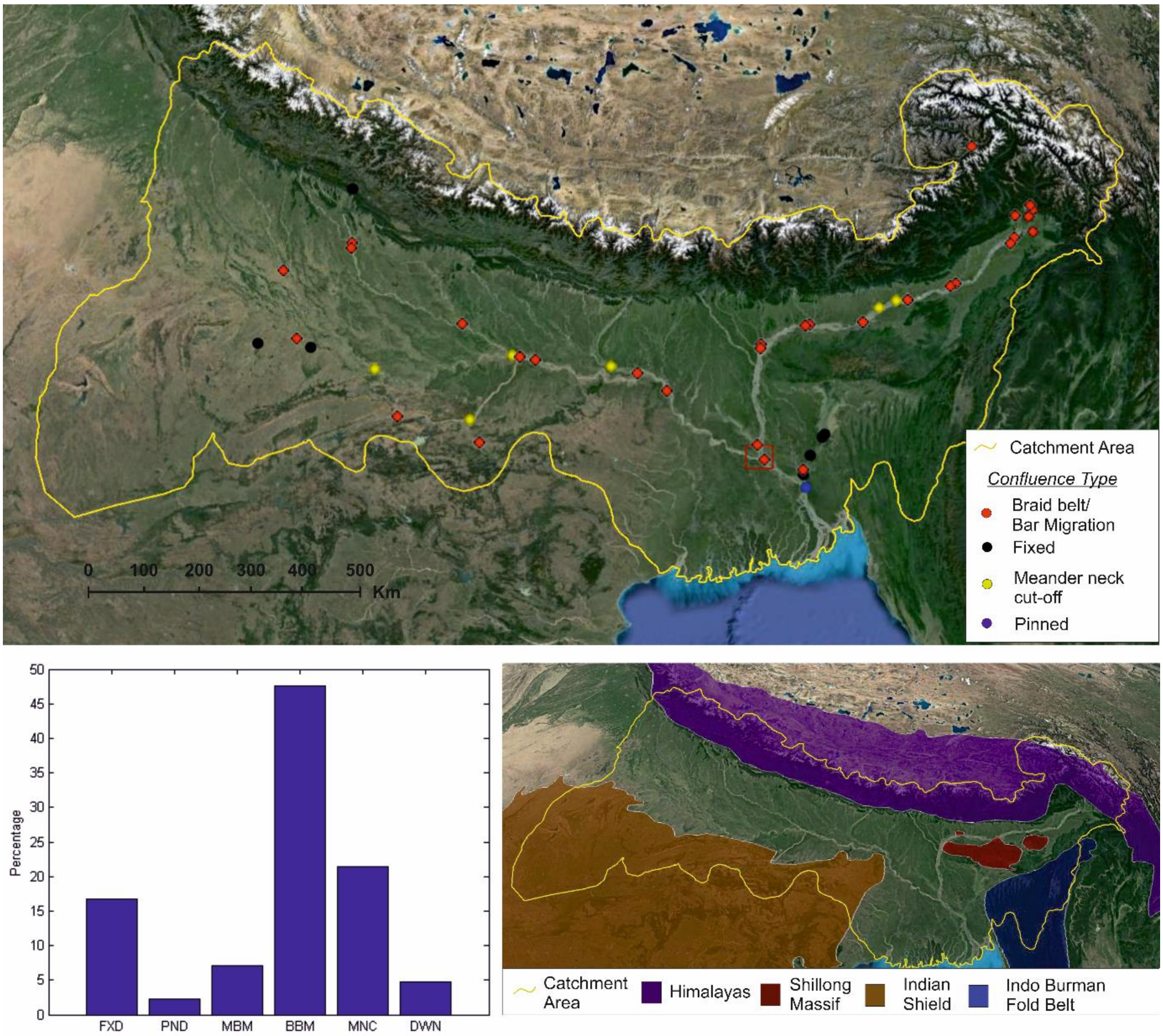

Figure 15 – Confluence classification for the Ganges-Brahmaputra-Meghna basin (n=42). Insets show the percentage occurrence of confluence types in the basin (FXD – Fixed, PND – Pinned, MBM – Mouth Bar Migration, BBM – Braid Belt Migration, MNC – Meander Neck Cut-off, DWN – Downstream Migration), and the broad geological zones in the basin, the non-highlighted areas in the geological map being lowland sedimentary basin. The majority of confluences (n=23) are mobile through braid bar/belt migration due to high sediment loads from Himalayas.

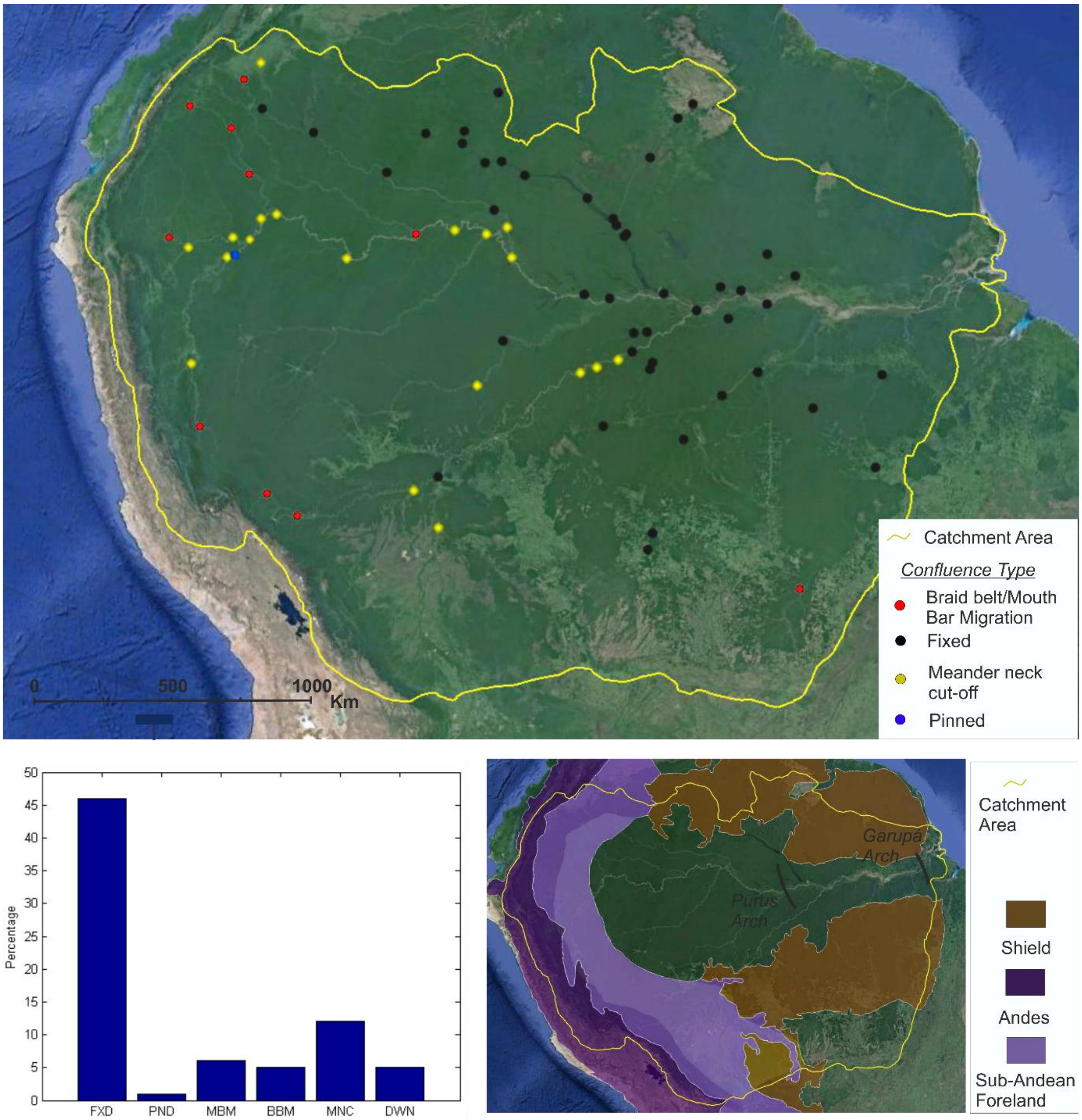

Figure 16 – Confluence classification for the Amazon basin (n=75). Insets show the percentage occurrence of confluence types in the basin (FXD – Fixed, PND – Pinned, MBM – Mouth Bar Migration, BBM – Braid Belt Migration, MNC – Meander Neck Cut-off, DWN – Downstream Migration), and the broad geological zones in the basin, the non-highlighted areas in the geological map are lowland sedimentary basin. The majority of confluences are fixed (n=46), with mobile confluences of meander neck cut-off type in the upper trough and sub-Andean foreland and braid bar/belt migratory type in Andes.

Confluence Type	GBM		Amazon	
	N	%	N	%
Fixed	7	16.7	46	61.3
Pinned	1	2.3	1	1.3
Mouth Bar Migration	3	7.1	6	8.0
Braid Belt Migration	20	47.6	5	6.7
Meander Neck Cut Off	9	21.4	12	16.0
Downstream Junction Migration	2	4.8	5	6.7
Total	42		75	

Table 2 – Proportion of confluence types within Ganges-Brahmaputra-Meghna and Amazon basins

Only ~17% of confluences in the GBM basin are fixed and these are restricted to five confluences in the Meghna basin and two confluences in the southwest of the GBM basin with dam construction in the upstream tributaries. The dammed tributaries are likely to have experienced a substantial reduction in both total annual discharge and sediment yield (Syvitski et al., 2005), that is reasoned to reduce the rate of morphological change at the junctions, and may have contributed to fixing the planform morphology. The preponderance of fixed confluences in the Meghna basin could be due to its low sediment yields compared to the Ganges-Brahmaputra, with the Meghna contributing ~12% of the GBM water discharge but just ~2% of its sediment load (Milliman and Farnsworth, 2013). Although the Meghna River drains the tectonically active uplands of the Shillong Massif crustal block and the Tertiary mud- and sand- stones of the Indo-Burman foldbelt (Mukherjee et al., 2009), most sediment yield is extracted within the subsiding Sylhet Basin upstream of the confluence (Goodbred et al., 2003)

In contrast to the GBM basin, in the Amazon Basin 61% of junctions are fixed confluences (Figure 16), which show a strong correlation between confluence type and broad physiographic setting (see geological map inset, Figure 16). Ninety-two percent of confluences that are fed from the Guiana and Brazilian cratonic shield, as well as those within the lower trough downstream of a structural high (Purus Arch), are fixed. The confluences that are in the upper part of the trough, upstream of the Purus Arch, typically display a dynamic behaviour linked to tributary meanders, whilst those rivers fed from the Andes almost always exhibit dynamism associated with braided channels or channel migration. The sub-Andean foreland represents a transition from dynamic confluences of a braided type to those of a meandering nature. This pattern of confluence mobility closely matches the rates of meander migration in the Amazon basin reported by Constantine et al. (2014), who found high rates of bend migration and cut-off in the Andean-fed rivers, lower migration rates in rivers draining the Guiana and Brazilian shields and moderate rates for the central trough.

There are currently 67 dams in operation in the Amazon basin (International Rivers, 2015), largely in the Andean and sub-Andean foreland zones. Dammed headwaters would be expected to have reduced sediment supply, although we cannot identify any different confluence behaviour on the short timescales of Landsat image coverage for pre- and post- dam construction. Further detailed studies of the effects of damming on confluence morphodynamics would help identify any effects and temporal lag in response.

Overall, the main channel of the lower Amazon system has low sinuosity, and is entrenched and confined to its valley over a scale of hundreds of kilometres (Mertes et al., 1996; Mertes and Dunne, 2008). Here the combination of intracratonic deformation and structural highs results in a channel system that is relatively immobile (Mertes and Dunne, 2008), with structural features such as the Purus and Garupá arches (Figure 16 geological inset) promoting entrenchment of the river and restricting channel movement (Mertes et al., 1996). Thus, as the morphodynamics of junctions are inextricably linked in scale and process to the morphodynamics of their confluent channels, the junctions of the lower Amazon are also immobile.

It has been argued that deep confluences have a high preservation potential in the rock record (e.g. Huber and Huggenberger, 2015), and it thus logically follows that deep and migratory confluences (i.e. those that both create large amounts of accommodation space that is then filled) will have the greatest chance of being preserved. Based on the evidence presented above, the World's largest river basin, the Amazon, with a high proportion of fixed confluences over decadal timescales, may thus leave very little in absolute areal extent in the sedimentological record, particularly in comparison to more morphodynamically active rivers. Although to the present study only concerns confluences over decadal timescales, the dominance of geological controls on the morphodynamics of the Amazon-Solimões suggests the entrenchment of rivers in the lower basin is likely to lead to very low rates of morphological change (Mertes et al., 1996; Mertes and Dunne, 2008; Constantine et al., 2014) and thus also fixed confluences over longer timescales.

6. Sedimentological implications of confluence mobility

Identifying the type and scale of erosional surfaces in the sedimentary record is important for reconstructing palaeoenvironments and palaeoenvironmental change (Bristow et al., 1993; Miall and Jones, 2003). However, in order to have confidence in such interpretations, it is essential to discriminate between different scales of scour and their driving autocyclic and/or allocyclic mechanisms. The present analysis has demonstrated that large river confluences may display a range of behaviours from static to highly mobile, and that confluences in areas of weak bank material and high sediment supply will tend to be more dynamic. The present analysis thus demonstrates that for river catchments where such conditions are prevalent (e.g. the Jamuna-Ganges), the majority of confluences may be mobile and create a significant driver for the creation of accommodation space and its subsequent fill. This observation, that mobile confluences may represent the norm over large areas of some large catchments, has three important implications interpretation of the sedimentological record.

Firstly, Best and Ashworth (1997), based on analysis of the depth of the Ganges-Jamuna confluence, questioned the criteria for identifying the scour surface and deposits of incised valleys (allocyclic scour) from deep autocyclic confluence scours. However, this contention has been questioned by Holbrook and Bhattacharya (2012, pg.278) who stated "*it is not clear whether confluence scours could migrate sufficiently over time to produce a deep regional composite scour surface that would resemble an incised valley*". However, the analysis presented herein shows that the potential areal extent of autocyclic confluence scour erosional surfaces is both much greater, and more common, than previously recognized (i.e. mobile confluences are not the exception to the rule). Given that the mobility of a confluence scour zone may extend over 20 times the channel width, as shown for the Jamuna-Gangadhar and Jamuna-Dud Kumar confluences, it is evident that autocyclic processes can produce scours whose regional extent could be comparable to an incised valley. The temporal sequence of satellite images for the Jamuna-Ganges confluence shows this scour depth has combed over a 14.2 km longitudinal section within a 40 year timespan, largely driven by the southerly migration of the Ganges River, but also potentially over a 4.2 km lateral zone driven by switches in the dominant flow location at the mouth of the Jamuna River. This represents a type of significant autocyclic erosional surface that must be considered when interpreting scour surfaces in sequence stratigraphic models.

For instance, due to the depth of autocyclic confluence scour (Best and Ashworth, 1997), fluvial thickness is an unreliable criteria on its own for distinguishing valley and channel fills. Furthermore, as shown herein, migrating scour holes could create a locally continuous erosion surface with the underlying strata, although this is unlikely to be over a wide enough extent to create a truly regional surface (Holbrook and Bhattacharya, 2012) and certainly not between river basins. The present data thus supports previous work that valleys should not be distinguished solely on the presence of a deep scour over non-conformable strata. Holbrook (2001) suggests the presence of at least two stacked channel stories, or a reasonable surrogate for these be used to identify a valley, and whilst there will be valleys which fail to meet these criteria, it is reasonable to assume deposits which do meet them are indeed valley fills. Importantly, in order to unambiguously identify a sequence boundary a scour surface would need to be traced beyond a single valley scale (Holbrook, 2001).

Secondly, the examples presented herein show confluence migration to be a complex process, involving multiple, overlapping, areas of confluence migration and shifting (e.g. Figure 4, Figure 7). As confluence scour zones migrate across and through areas of older scour fill, they may thus rework previous deposits and, depending on aggradation rates, may leave truncated facies and newer deposits that may have different orientations if the direction of migration differs from that of previous deposits. Therefore, in actively migrating confluence zones, the sedimentary product may likely comprise multiple stacked, truncated deposits of differing orientations that may prove difficult to interpret except for the most recent depositional phase. Such a complex, overlapping sequence of scour and fill would suggest the recent model proposed by Ullah et al. (2015), where the scour fill comprises a single large set, is not necessarily representative of potential confluence scour preserved in alluvial stratigraphy. The mobile confluences described herein share a sedimentological character more in common with the model proposed by Siegenthaler and Huggenberger (1993), where multiple erosion surfaces are viewed as a defining characteristic.

Lastly, the present data demonstrate that channel avulsion can result in confluence positions that change from one location to another, resulting in potentially separate, unconnected scours, as opposed to the migratory movement of confluence position that results in a continuous scour surface. Examples of the former include the Mississippi and Arkansas river confluence, which moved ~ 5km (or 4 channel widths), and the Ganghara and Sarda River confluence which moved ~ 23km (or more than 11 channel widths) due to upstream channel avulsions. These examples were typically complete within 10 years, with abandoned channels appearing to infill rapidly. Other larger-scale channel avulsions, such as that of the Brahmaputra in the late 18th century (Best et al., 2007), may also relocate the locations of major river confluences by large distances, in this case by approximately 125km.

7. Conclusions

The planform morphodynamics of river confluences have received little attention in the literature, potentially leading to a perception that such junctions tend to be fixed nodal points within a channel network. The case studies presented herein demonstrate that, far from being fixed, confluences in large rivers can display a range of adjustments in response to external forcing. These adjustments range in scale from within-channel change, to bar deposition and erosion within the confluence zone, to channels migrating within a defined belt via meandering or braiding, to highly mobile confluences that migrate an order of magnitude greater than the channel width.

Initial basin-wide analysis of the patterns of confluence mobility for the Amazon and Ganges-Brahmaputra-Meghna rivers, suggests that confluent channels with high sediment loads have a higher probability of being mobile, in contrast to confluent channels with low sediment loads (such as in cratonic settings) that are more likely to be fixed. Where tributary channels have a braided planform, confluence mobility is likely to be high and driven by changes in the position of dominant flow within the braid belt(s). In meandering channels with high sediment loads, the confluence location will be strongly dependent on meander neck cut-off in the tributary channel(s). Where the tributaries have any combination of very low sediment loads, low discharge variability or banks with high resistance to erosion, confluences will likely be fixed in their positon or migrate far more slowly.

The present results suggest several implications for the interpretation of scour surfaces in the stratigraphic record and reconstructions of past environmental change. Mobile confluences may generate scour over an area much wider than that of the channel width at the junction, thus generating significantly larger, and more complex, erosional surfaces than suggested in previous models (Bristow et al., 1993). The The present study highlights the need for further research into the scour and fill of large river confluences, in order to further refine the diagnostic criteria (Best and Ashworth, 1997) that may differentiate such scours from depositional signatures driven by larger-scale allocyclic processes.

Acknowledgements

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