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Anastamosing channels in the lower Neches River valley, Texas

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ABSTRACT: Active and semi-active anastomosing Holocene channels upstream of the delta in the lower valley of the meandering Neches River in southeast Texas represent several morphologically distinct and hydrologically independent channel systems. These appear to have a common origin as multi-thread crevasse channels strongly influenced by antecedent morphology. Levee breaching leads to steeper cross-valley flows toward floodplain basins associated with Pleistocene meander scars, creating multi-thread channels that persist due to additional tributary contributions and ground water inputs. Results are consistent with the notion of plural systems where main channels, tributaries, and sub-channels may have different morphologies and hydrogeomorphic functions. The adjacent Trinity and Sabine Rivers have similar environmental controls, yet the Trinity lacks evidence of extensive anastomosing channels on its floodplain, and those of the Sabine appear to be of different origin. The paper highlights the effects of geographical and historical contingency and hydrological idiosyncrasy. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: anastamosing channels; anabranching; crevasse; Neches River; path-dependence

Introduction

The planform of alluvial channels is a fundamental indicator of hydrologic regimes and the relationship between sediment supply and transport capacity. As such, planform changes may reflect changes in drainage basin sediment production, base level, tectonics, climate, and biotic effects. Dominantly multiple-channel patterns generally reflect an excess of sediment supply over transport capacity, and anastamosing patterns in particular are characteristic of aggrading valleys with frequent avulsions (Makaske, 2001; Kleinhans *et al*., 2012). However, those generalizations encompass a variety of combinations of environmental controls, disturbances, and evolutionary trajectories that may create anabranching planforms. Further, there are examples of anastomosing channels (e.g. the Channel Country of central Australia) that are not necessarily characterized by large excesses of sediment supply relative to transport capacity (Gibling *et al*., 1998; Tooth and Nanson, 2000). Discovering the causes of anastamosis is therefore important for unraveling the historical development of, and effects of environmental change on, fluvial systems. In addition, the anastamosing channels in the study area – the floodplain and valley of the lower Neches River, Texas – represent critically important fish, wildlife, and vegetation habitat, and most are part of the Big Thicket National Preserve, administered by the US National Park Service. These channels are also important in creating and maintaining very high channel–floodplain connectivity. Lewin and Ashworth (2013) noted that large rivers often have anabranching patterns of various kinds, and outlined six types of channel–floodplain connectivity, ranging from strongly coupled to decoupled. Given the high hydrological connectivity in the lower Neches, understanding the origin of the anastamosing channels may provide insight into the circumstances under which such high-connectivity systems are formed.

The rivers of southeast Texas and southwest Louisiana draining to the western Gulf of Mexico have dominantly single-channel, meandering planforms (though a surprising number of local exceptions exist; Phillips, 2008, 2009). The same has apparently been true throughout the Quaternary, with major changes in climate, sediment supply, and sea-level reflected in the size and geometry of meanders, channel sinuosity, avulsion regimes, and the transgressive-regression migration of deltas. However, on the lower Neches River there are anastamosing patterns apparently reflecting both modern and paleochannels (Figures 1 and 2). The purpose of this paper is to determine the origin of these anastamosing channels, and their implications with respect to geomorphic evolution and hydrologic patterns of the river valley. Distinguishing among several possible origins for these channels has implications for interpreting the environmental history of the northern Gulf of Mexico region; e.g. the potential role of sea-level fluctuations and climate-driven sediment supply changes. The origin of the anabranching sub-channels is also relevant to the concepts of multiple causality and historical contingency in fluvial geomorphology (as described later).

Phillips (2009) compared and contrasted the avulsion regimes in five adjacent rivers in southeast Texas, including the Neches. That study showed that all five rivers, despite their geographical proximity and similar environmental histories and controls, have different avulsion regimes. The stage of valley filling is a

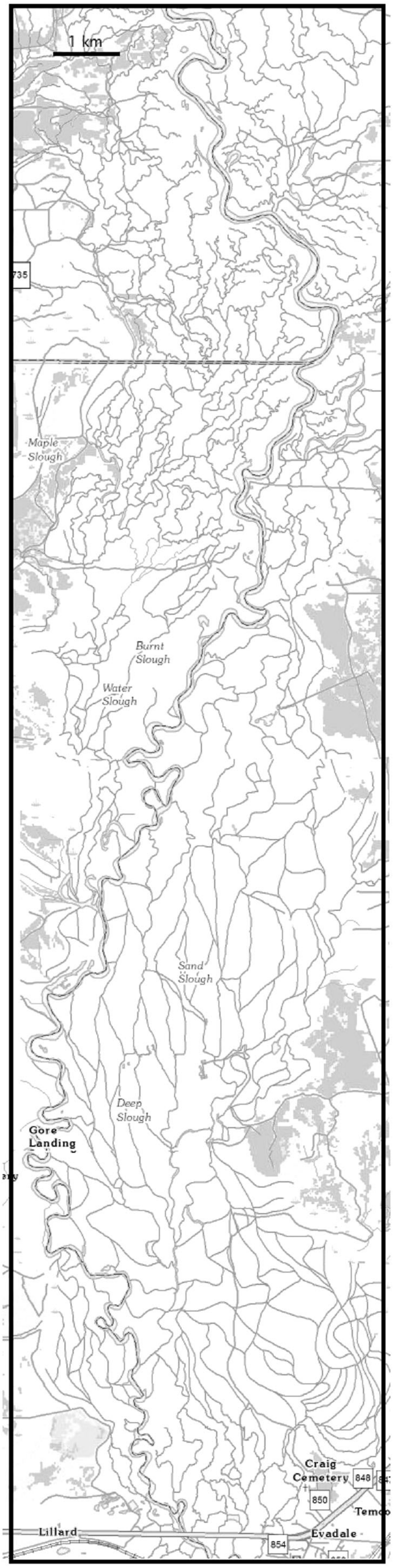

Figure 1. Study reach of the lower Neches River valley showing channels depicted on the US Geological Survey National Map. See Figure 3 for location.

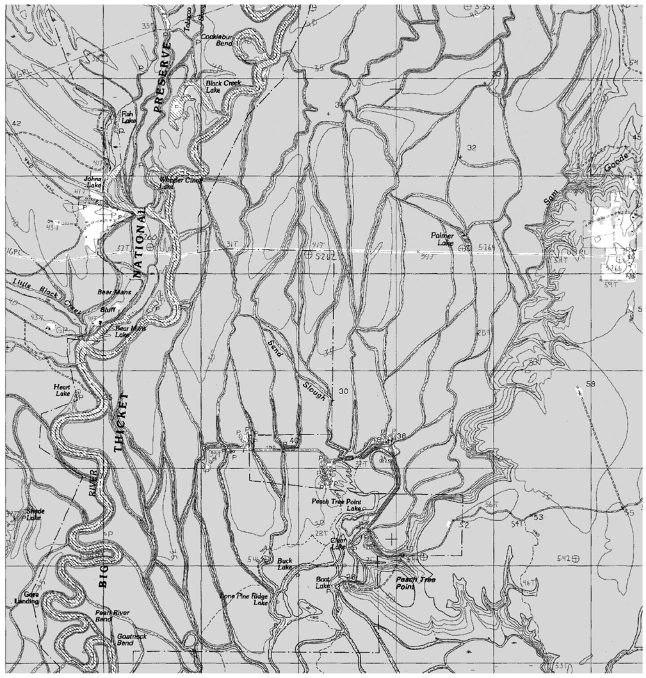

Figure 2. Close-up of anastamosing channels on the lower Neches River floodplain as shown on a portion of a 1:24 000 scale topographic map (US Geological Survey, Evadale, TX quadrangle).

first-order control of the differences, distinguishing the rapidly aggrading Navasota River valley, the infilled incised Brazos River valley, and the unfilled incised valleys of the Trinity, Neches, and Sabine Rivers. Local differences in Quaternary geomorphic history, expressed in antecedent morphology, determine the differences between the avulsion regimes of the latter three. These include floodplain depressions and paleomeander scars, fault reactivation, and stream capture (Phillips, 2009). Features inherited from earlier Quaternary and Holocene fluvial changes have also been shown to exert important influences over other aspects of alluvial and deltaic landforms and process regimes in the three rivers (Rodriguez *et al.*, 2005; Anderson and Rodriguez, 2008; Phillips, 2008, 2010, 2011; Phillips and Slattery, 2008). This suggests the possibilities that sub-channels or anabranches both within and between the Neches and adjacent fluvial systems may have multiple causes, and may be strongly influenced by antecedent alluvial morphology.

The sub-channels created by avulsions, in combination with the dominant channel, create anastamosing reaches in some sections of the lower reaches of the Neches, Trinity, and Sabine. In the Trinity, however, the sub-channels themselves are of comparable size to the main channel, and represent successful avulsions that have persisted as anabranches (Phillips, 2009, 2010; Phillips and Slattery, 2008). In the Sabine, the sub-channels are in some cases similar to those of the Trinity, and in others represent multiple smaller approximately parallel channels that converge downstream (Phillips, 2008). In the Neches, however, in addition to some apparent paleochannels representing avulsions of the main channel, there exist numerous smaller, interconnected sub-channels (Figures 1 and 2). This study is motivated by a desire to identify the (apparently) local, contingent factors that distinguish the Neches sub-channels from those of the adjacent river systems.

Anabranching, Anastamosing, and Avulsions

The variety of terminologies applied to multi-channel planforms will not be reviewed here (for extensive reviews see

Carling *et al.*, 2013; Lewin and Ashworth, 2013). This paper follows Makaske's (2001) general description of anastamosing rivers as consisting of multiple interconnected, coexisting channel belts on alluvial plains. More specifically, Makaske (2001, p. 155) defines anastomosing rivers as having two or more interconnected channels that enclose flood basins, though the latter does not necessarily characterize all fluvial systems that have been characterized as anastomosing (e.g. Gibling *et al.*, 1998; Knighton and Nanson, 2000). 'Anabranching' is used here to refer in general to the development of multiple active channels, regardless of whether the resulting form is anastamosing, island- or bar-braided, wandering, etc.

According to Brierly and Fryirs (2005), anastamosing rivers are characterized by low width/depth ratios in the individual channels, with little lateral channel migration. However, the multiple channels are subject to changes in dominance or relative proportion of flow conveyed, associated with variable rates of infilling. Such systems typically form in cohesive alluvial valleys where the valley slopes are relatively low and the potential for steepening channel gradients is also low (Brierly and Fryirs, 2005, pp. 129–131). Kleinhans *et al.* (2012) proposed four general hypotheses for the formation of anastomosing patterns: (1) formation in association with deltaic branching; (2) forcing by base-level rise; (3) overloading by sediment from upstream; and (4) flow efficiency. The latter refers to the proposal that in some circumstances multichannel patterns represent maximum efficiency for water flow and sediment transport (Huang and Nanson, 2007). The first and fourth hypotheses, according to Kleinhans *et al.* (2012), imply that the anastomosing pattern is stable, while the others suggest evolution (back) to a single-channel pattern in the absence of avulsions (though this typology might not apply to dryland anastomosing systems such as those of central Australia described by Gibling *et al.*, 1998; Knighton and Nanson, 2000; Tooth and Nanson, 2000). The four hypotheses actually encompass a number of possibilities. For example, base level rise could be driven by sea-level rise, tectonic uplift, aggradation at the downstream end of the fluvial system, or natural or human damming. All the hypothesized causes lead directly or indirectly to sediment overload relative to transport capacity. Accordingly, the variety of climate, tectonic, biotic, and human factors that influence runoff and sediment delivery could conceivably drive such changes.

Indeed, though different sets of environmental controls or historical sequences produce different types of planforms, there are no simple one-to-one relationships between planform and a given process set or evolutionary model (Gurnell *et al.*, 2009; Lewin and Ashworth, 2013). Planform reflects the interaction of three fundamental factors – flow energy (transport capacity), sediment supply, and vegetation. Individual planforms have varying sensitivity to these three factors, all of which can be affected by changes in climate, biotic factors, and human agency, resulting in planform modifications or sometimes state changes from one planform to another (Gurnell *et al.*, 2009).

In coastal plain and deltaic settings such as those of the Neches River study area, anastamosing is typically driven by rapid vertical aggradation related to sea level rise (Törnqvist, 1993). In his study of alternative anastamosing and meandering patterns in the Rhine-Meuse delta, Törnqvist (1993) found anastamosing patterns to be associated with sea level rise of > 1.5 mm yr^{-1}, and cohesive subsoils, both of which exist or have occurred in the southeast Texas study area. This is consistent with Nanson and Knighton (1996), who indicate that the anastamosing varieties of multi-channel planforms are typically associated with some form of rising base level downstream. Makaske (2001, p. 168) also notes sea level rise as a common cause for this form of anabranching. Tectonic movements are another form of base level change, which is associated with some anastamosing river reaches (Nanson and Knighton, 1996; Makaske, 2001). Persistent channel sediment accumulations may also raise local base levels. For example, Smith *et al.* (2009) showed that valley plugs (relatively immobile channel and valley bottom sediment accumulations related to large inputs of eroded sediment) lead to avulsions and anastomosis in low-gradient channelized streams of west Tennessee.

In the upper Columbia River, British Columbia, Makaske *et al.* (2009) found that anastomosing occurred because of bedload transport inefficiency, coupled with limited potential for lateral channel migration due to low stream power, bank vegetation cover, and cohesive soils. Their analysis indicated that the better development of anastomosing morphology and more common crevassing in the upstream as compared to the downstream reach suggests upstream control. This suggests a general logic for a first-order discrimination between upstream- and downstream-dominated controls of avulsion and anabranching (see also Kleinhans *et al.*, 2012). That is, anabranching driven by downstream forcing should systemically increase in intensity or level of development toward the downstream end, and vice-versa.

Potential causes

The anastomosing channels in the study area include active anabranches of the Neches River, and anastomosing paleochannels that are not at present connected to the river at both ends at non-flood flows. Based on field reconnaissance and previous work in the region, three potential origins for the anastamosing channels observed in the lower Neches valley were identified:

- Abandoned Neches River channels (i.e. remnants of a formerly anastamosing main river). The formerly anastamosing system could conceivably be caused by a rapid pulse of sea-level rise or a sea-level highstand earlier in the Holocene (the first has been demonstrated and the latter proposed in the region); by a large influx of sediment from upstream; by local base level change due to tectonics; or by large woody debris jams.
- Anabranching lower reaches of tributary streams, perhaps associated with large upstream sediment loads deposited as the tributaries crossed the Neches floodplain; or with aggradation and local base level rise of the Neches.
- Remnants of deltaic distributary systems from earlier sea-level highstands.

If the anastomosing sub-channels are abandoned Neches channels, this implies the possibility of fundamental environmental change resulting in a major anastomosing-to-meandering transition. This could imply, e.g. climate change (cf. Leigh, 2006) and/or could be consistent with a sea-level highstand earlier in the Holocene (cf. Blum *et al.*, 2002) or a sea-level rise pulse or flooding event (Rodriguez *et al.*, 2005; Anderson and Rodriguez, 2008). If the channels were formed along Neches River tributaries, this could indicate local increases in sediment supply or rapid aggradation of the Neches floodplain (thus raising the base level of the tributaries). If the sub-channels are remnants of deltaic distributary systems, this would imply both preservation of delta morphology and inheritance over time spans of 50 ka or more (based on the most recent occurrence of a sea-level highstand sufficient to create deltas within the study area; Thomas and Anderson, 1994; Otvos, 2005).

All the earlier mentioned are consistent with the idea of anastomosis driven by base level rise and/or sediment overloading. However, during the course of this study a fourth possibility was identified: the multi-channel patterns are formed as crevasse channels, which persist as sub-channels even though they do not result in avulsions. This differs from the concept of anastomosing patterns created by avulsions, with both the new and existing channels persisting and remaining connected. The idea explored here is that the crevasse channels themselves may form anabranching patterns. Anastamosing distributaries have been identified elsewhere, albeit in deltas or in channel breakdown areas (Smith *et al.*, 1989; Törnqvist *et al.*, 1993; Phillips, 2009, 2012; Ralph and Hesse, 2010).

Study Area and Methods

The study area (Figure 3) includes a portion of the lower Neches River downstream of its confluence with the Angelina River, and above its deltaic zone. The Neches has a drainage area of about 26 000 km^2, and the Neches River and the neighboring Sabine River both discharge to the Sabine Lake estuary near Port Arthur, Texas. These rivers, along with the Calcasieu River to the east and the Trinity River to the west, are part of a single drainage system that developed during lower sea level stands. The Neches–Sabine confluence is now drowned in Sabine Lake, and the Trinity–Sabine confluence was on what is now the continental shelf (Thomas and Anderson, 1994).

The contemporary climate is humid subtropical, and the topography ranges from virtually flat in the floodplain basins to gently rolling at the valley sides. The specific reach studied here is entirely in Quaternary material. Reviews and syntheses of the Quaternary geologic framework and sea level history of the region (and some of the debates and uncertainties involved) are provided by Blum *et al.* (2002); Otvos (2005), and Anderson and Rodriguez (2008). Recent research on the role of antecedent topography and effects of recent geologic and sea level history on current forms, processes, and evolution of southeast Texas Rivers are given for the Trinity River by Rodriguez *et al.* (2005) and Phillips and Slattery (2008); and for the Sabine River and Lake by Milliken *et al.* (2008) and Phillips (2008).

The Neches and other rivers in the region are flanked by modern floodplains and flights of several Pleistocene terraces that record aggradation–incision cycles associated with sea level change. The oldest and highest is the Beaumont terrace, into which the rivers began incising about 100 ka (Thomas and Anderson, 1994; Blum *et al.*, 1995; Otvos, 2005). Below the Beaumont surface and often merging into the modern floodplain are a series of up to three alluvial terraces. These are typically referred to as Deweyville, though they are no longer

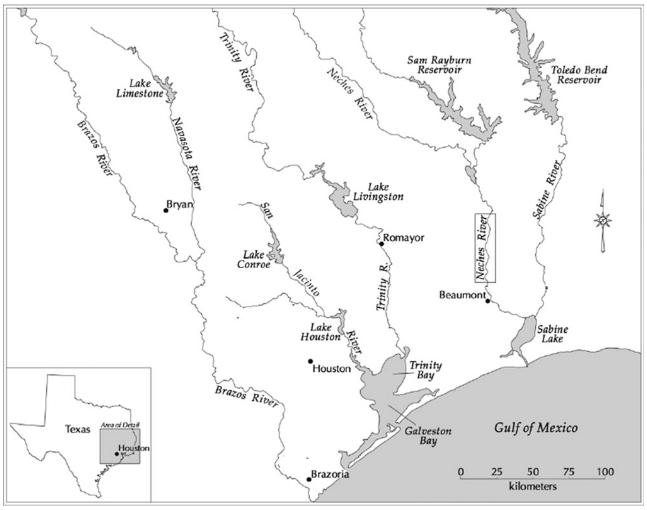

Figure 3. Major rivers of southeast Texas, with study area shown in rectangle.

interpreted as part of a single terrace system (Blum *et al.*, 1995; Morton *et al.*, 1996). In the Sabine River valley the Louisiana Geological Survey recognizes three Deweyville alloformations (youngest to oldest): Fredonia, Sandjack, and Merryville (Heinrich *et al.*, 2002).

The Fredonia surfaces are only slightly higher than the modern floodplain, and are sometimes buried by the latter, with natural levees of the active floodplain often higher than backswamps of the lower Deweyville (Alford and Holmes, 1985; Blum *et al.*, 1995; Rodriguez *et al.*, 2005). Large paleomeander scars and depressions are evident in the Trinity, Neches, and Sabine valleys, on the older Deweyville surfaces. Radii of curvature and amplitudes suggest significantly larger paleodischarges than at present, though the details of the hydrologic regime are uncertain (cf. Alford and Holmes, 1985; Blum *et al.*, 1995; Sylvia and Galloway, 2006).

Phillips (2009) identified evidence of at least 17 Holocene or historical avulsions in the lower Neches River (in a study reach longer than that of this study). For 11 of these cases, the abandoned main channel remained active as a subchannel conveying water at all flow levels. However, that study did not otherwise address the origin of anabranching channels in the area.

Methods

A combination of field surveys, analysis of digital elevation model (DEM) data, 1:24 000 scale topographic maps, and 2-m resolution orthophotos was used to identify the the anastamosing sub-channels. DEMs developed from LiDAR (light detection and ranging) data at a horizontal resolution of 3 m were obtained from the US Geological Survey (USGS). DEM data was processed and analyzed using River Tools^{TM}. The USGS topographic maps and digital orthophoto quarter-quads (DOQQ) were obtained in digital form from the Texas Natural Resources Information Service. The DOQQs were flown in 2007. Soil maps were obtained from the US Department of Agriculture in digital form (http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm).

DEM data were analyzed to determine the elevation at the lower (downstream) end of each anastomosing section, in both absolute terms and relative to that of the active Neches River channel. Depth of the sub-channels was also determined relative to the floodplain surface (in every case there were multiple channels of approximately equal depth, as indicated by the LiDAR data). At several sites in the Johns Lake area the depths and bed elevations of the sub-channels were checked by field survey and confirmed to be equal. However, LiDAR data cannot provide accurate channel depths and can be assumed to provide only approximate data on channel bed elevations. The LiDAR-derived elevation data may also not capture details in saturated or inundated depressions. Width of the anastomosing channel belt, and of the entire Neches valley were also measured, along with the number of sub- or side-channels.

Within each anastomosing section the dominant channel was identified, based on size, prominence on images, and hydrologic dominance by routing flow in the vicinity. The latter is based on a D8 algorithm included in River Tools whereby flow paths are established along the path of steepest descent between adjacent elevation grid cells. The slope gradient and sinuosity of this path was calculated, along with that of the parallel reach of the Neches, and the valley slope of the reach.

Field mapping and observations were conducted in 2008, 2009 and 2012, by motor vehicle, on foot, and via canoe and kayak. This involved mapping the location of sub-channels, observing the presence and direction of flow, and classifying channels and paleochannels (following Phillips, 2009) as infilled, semi-active, active, tributary-occupied, or sloughs (billabongs). An example is shown in Figure 4.

The channel systems vary substantially with respect to whether (or the extent to which) they are visible on various kinds of maps and imagery. Thus in the results sections various map or image types are employed to best display the anastomosing channels.

Results

Anastamosing channels

The anastamosing channels in the study area are of type 1(b) in Nanson and Knighton's (1996) classification of anabranching patterns: cohesive sediment/anastomosing; humid climate; organo-clastic. In general, these types are associated with relatively fine-grained alluvial rivers and are associated with some form of rising base level downstream. All the channels in the study occur within a dense forest cover; there is no evidence of recent changes in size or shape of the islands between channels.

Unlike some of the Pleistocene anabranching planforms Leigh (2006; Leigh *et al.,* 2004) observed on Atlantic Coastal Plain rivers, the multiple channels on the Neches Rivers are not always clearly evident on aerial and satellite photographs, and are incompletely represented on topographic maps. The channels on the Neches floodplain observed in the field were originally thought to be fragments of paleochannels (sloughs, billabongs, or tributary-occupied paleochannels) associated with a general lateral channel migration. However, more detailed investigation showed that the channels are generally continuous rather than fragmentary. Further, field surveys showed that multiple channels were commonly at similar elevations and at similar stages of infilling and vegetation succession. This is consistent with a more or less contemporaneous formation (in the San Antonio River delta, Texas, successive avulsions of sub-channels result in (paleo)channels in clearly different states; Phillips, 2012), but there is no independent evidence to support this. Many Neches sub-channels are essentially ponded at low flows, with little or no hydraulic connection to the modern river, but commonly convey considerable discharge at high flows. Other channels convey flow virtually all the time and receive considerable water inputs from runoff and tributaries rather than from the river.

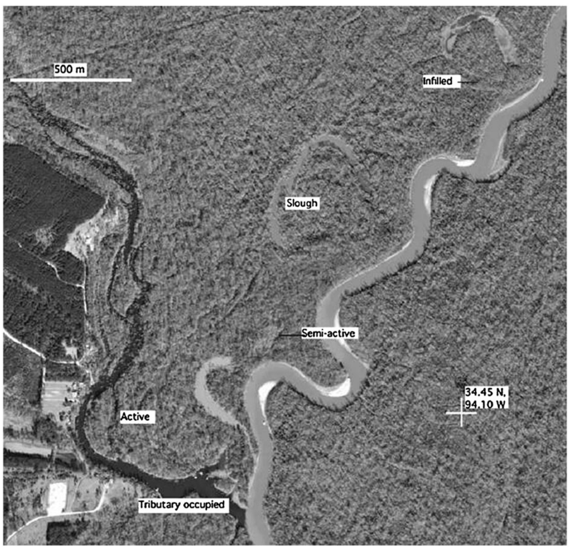

Figure 4. Classification of paleochannels and sub-channels in the John's Lake area of the lower Neches River.

At sub-banktop flows many of the sub-channels convey flow independently of the Neches River – that is, they are not fed by distributary flows from the main channel. Some are clearly fed by tributaries from the valley sides; in other cases the channels derive flow from local surface and ground water inputs within the floodplain. The independence of flows is based on field observations of an absence of connections from the river to the anastomosing channels, and obvious differences in color observed in the field and on imagery. Some backwater flooding from the river occurs in the lowermost reaches of the anastomosing channels, particularly when they flow through Neches paleochannels such as Johns Lake and Gore Lake. At near-banktop flows in the Neches, water begins to pass through low points in the natural levee, into the side channels. These observations from fieldwork and imagery were taken at a range of sub-banktop flows, and during both rising and falling stages (Table I). As these include flows ranging from the lowest 10% of mean daily flows to just under bankfull, the observations may not be applicable to higher flows.

Five anastamosing channel zones were initially identified on the basis of apparent differences in morphology, and connectivity with each other and the modern Neches River channel (Figure 5). These are assigned letter designations A–E, and also a local place name of one or more prominent sub-channel features within the zone. Characteristics of the zones are shown in Tables II and III.

All the anastamosing systems evaluated are inset into the modern floodplain. This is based on the elevation of the surfaces the channels occupy relative to other surfaces in the valley, and the soils mapped in each area (Table IV). Zones A, D, and E are almost entirely mapped as the Estes-Angelina complex, comprised mainly of the nominal series. Zones B, C are mapped as Urbo-Mantachie complex, again composed almost entirely of the nominal series. In both cases the complex is dominated by a clay-textured soil with vertic properties (Estes, Urbo series), with inclusions of coarser-textured soils (Angelina, Mantachie). The different mapping units are associated with different county soil surveys within the study area, and may reflect this rather than actual pedologic variations. However, both the Estes-Angelina and Urbo-Mantachie soils are interpreted as forming on active Holocene floodplains.

The anabranching reaches are relatively short, ranging from 2 to 17.5 km (valley distance) (Table II). The width of the anastomosing section relative to the entire Neches valley width is nearly half in zones B, C. In the other three cases the anastomosing system width is 8% to about 20% of the valley width. Elevations at the downstream end are identical to the modern river in the vicinity in zones A, B, C, and 1 to 2 m higher in D and E. Given uncertainty in channel bed elevations in the LiDAR data, this implies no more than approximate accordance in zones A, B, C, and slightly higher elevations in zones D, E. All the anastomosing reaches vary internally in the number of channels, with a total range of two to 13.

Valley, channel, and main channel slopes are quite variable (Table III). In zones A, C, E, the channel slope of the largest or most apparent of the anastamosing channels greatly exceeds that of the adjacent main river channel. In one case (zone D) it is much less than the main channel, and in zone B slightly lower. Sinuosity is lower in the main anastamosing path in all cases, but in zone C only slightly. In both of the latter cases (zones D and B) the main anastomosing path is more sinuous than the other sub-channels, which may account for the lower slopes.

A series of sections across the anastamosing valley reaches over the entire study area were examined using the orthophoto,

Table I. Flow conditions (mean daily flow) associated with field or image-based observations of flow patterns and hydrological connections, and reference flow conditions

Date (day/month/year)	Observation type or source	Discharge ($m^3 s^{-1}$)	Gage height (m)	Hydrograph
1/19/04	Color image	123.2	2.99	Rising
10/21/05	Color image	75.6	2.26	F/R[a]
3/09/08	Field	141.0	2.97	Rising
3/10/08	Field	142.2	2.98	Rising
3/11/08	Field	147.0	2.98	Rising
1/30/09	Color image	37.9	1.62	Falling
3/11/10	Color image	244.1	3.95	Falling
11/10/11	Color image	12.2	1.08	R/F[a]
2/10/12	Field	188.9	3.41	Falling
2/11/12	Field	177.3	3.30	Falling
2/28/13	Color image	43.3	1.57	F/R[a]
Mean annual mean daily flow, 1904–2003	Asquith *et al.*, 2007	178.4		
Median annual mean flow, 1998–2007	Asquith and Heitmuller, 2008	113.3		
Mean daily flow, 1% exceedance probability[b]	Asquith and Heitmuller, 2008	934.5		
Mean daily flow, 99% exceedance probability[b]	Asquith and Heitmuller, 2008	24.1		
Bankfull stage, Evadale gage	National Weather Service[c]	246.4	3.96	
Flood stage, Evadale gage	National Weather Service[c]	1175.1	5.79	

Note: All values are for the Neches River gaging station at Evadale Texas, at the downstream end of the study area.
[a]Falling from previous day and rising to following day (F/R) or vice-versa (R/F).
[b]Based on 1998–2007 water years.
[c]US National Weather Service, Advanced Hydrological Prediction Service, http://water.weather.gov/ahps2/hydrograph.php?wfo=lch&gage=-evdt2&hydro_type=2. Flood stage indicates stage at which significant impacts on infrastructure occur.

map, and DEM data, supplemented with geologic map and soil survey data. On these cross-sections four surfaces or levels were identified: the active Sabine or Neches River channel, the most prominent (or deeply incised) sub-channel, the active floodplain surface, the Fredonia (lowest Deweyville) surface, and the higher Deweyville terrace surfaces (the latter were lumped together, as distinguishing between them requires detailed field investigation). Elevations of each were taken from the DEM data. Down-valley trends of elevation against valley distance are shown in Figure 6. The lower end of the anastamosing channels corresponds with the convergence of the modern floodplain and Fredonia surfaces or the burial of the latter. This pattern is consistent with the spatial correspondence of the lower end of the anabranches with the lowermost mapping of the Fredonia/lowest Deweyville terrace surface. At the lower end of the profile the elevations of the main river channel and sub-channels converge. The modern valley slopes, based on the floodplain surface elevations, are less than slopes of the Deweyville terrace surface (Figure 6), a finding consistent with other studies in southeast Texas.

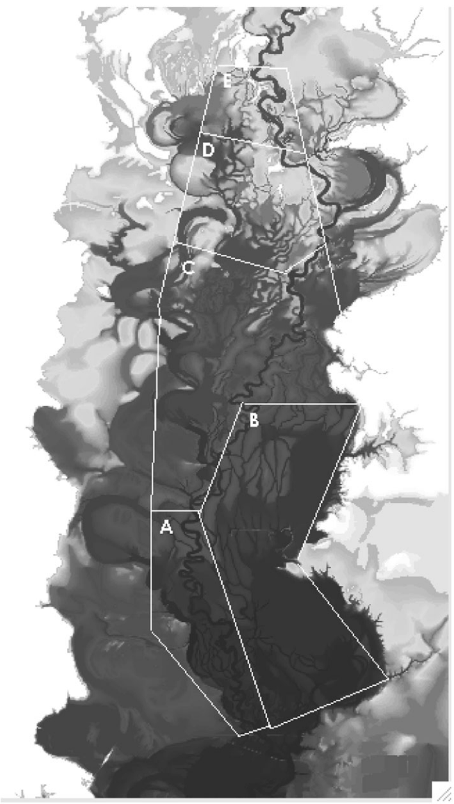

Figure 5. Zones of anastamosing channels shown on density map derived from 3-m digital elevation model.

Evaluation of potential causes

An origin as former delta distributaries can be ruled out due to the Holocene age of the sub-channels, because no sea levels high enough to result in delta formation within the study area have occurred for at least 50 ka, which is consistent with field interpretations of sediments in the lower Neches and Sabine Lake region (Fisher *et al.*, 1972). The anastamosing channels also do not appear to be remnants of a formerly multi-channeled Neches River. The discontinuity of the anastamosing zones, and their bisection by the modern channel shows that they were not a single channel system. Further, as the current river channel offers a significant slope advantage in only one case, it is highly unlikely that avulsions occurred from the anastamosing zones to the modern channel. Finally, the anastamosing channels flow toward floodplain basins rather than directly down the valley, as described in more detail later.

The sub-channels were also not formed primarily by tributaries, though some currently capture tributary flow. Many are unconnected with tributaries originating from uplands outside the valley bottom. Others capture tributary flow before it can reach the Neches, but the alignments indicate the anastamosing channels were not formed as part of the tributaries (Figure 7).

As the potential causes initially identified were ruled out, a fourth possibility emerged: an origin as multi-thread crevasse

Table II. Channel elevation, channel depth, width of the anastamosing channel belt and the alluvial valley, length of the anastamosing reach, and number of anabranches

Section	Elevation[a]	Depth (m)	Width (km)	Valley width (km)	Length (km)	N[b]
A (Gore Lake-Round Lake)	5.03; 0.00	3.0	1.1	9.8	10.9	2–8
B (Deep Slough-Side Pocket Lake)	5.82; 0.10	2.5	3.9	8.2	17.5	3–7
C (Johns Lake)	8.24; 0.23	1.8	4.3	9.4	13.6	4–13
D (Tater Patch Lake)	12.20; 2.00	2.5	2.3	10.6	4.7	3–6
E (Black Creek)	12.21; 1.01	2.5	1.3	9.9	2.0	2–3

[a]Approximate channel elevation at downstream end, MASL; elevation relative to modern river channel.
[b]Number of sub-channels

Table III. Slopes and sinuosities of the anastamosing channel sections and the modern (main) channels in the same valley reach

Section	Valley slope	Channel slope[a]	Main channel slope[b]	Sinuosity[a]	Main channel sinuosity[b]
A (Gore Lake-Round Lake)	0.0014118	0.0007024	0.0001530	1.60	2.01
B (Deep Slough-Side Pocket Lake)	0.0005476	0.0002738	0.0003107	1.40	2.00
C (Johns Lake)	0.0005640	0.0003000	0.0001389	1.82	1.88
D (Tater Patch Lake)	0.0000035	0.0000020	0.0002071	1.32	1.76
E (Black Creek)	0.0010294	0.0005306	0.0000935	1.48	1.94

[a]Main or most prominent anabranch.
[b]Modern Neches River channel in same valley reach.

Table IV. Study area soils

Soil series	Taxonomy[a]	Landform	Comments
Angelina	Typic Fluvaquents	Floodplains	Loamy stratified alluvium; minimal pedogenic development
Estes	Aeric Dystraquerts	Floodplains	Alluvium with high smectitic clay content
Mantachie	Fluventic Endoaquepts	Floodplains	Loamy alluvium
Urbo	Vertic Epiaquepts	Floodplains	Clayey alluvium with some smectitic clays

[a]US Soil Taxonomy.

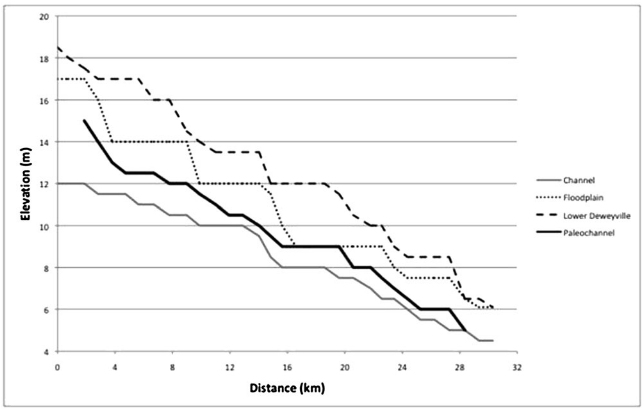

Figure 6. Longitudinal profiles of the study area based on elevations of the Neches River channel, dominant anastamosing sub-channel (labeled as paleochannel), active floodplain surface, and youngest Deweyville terrace (Fredonia alloformation).

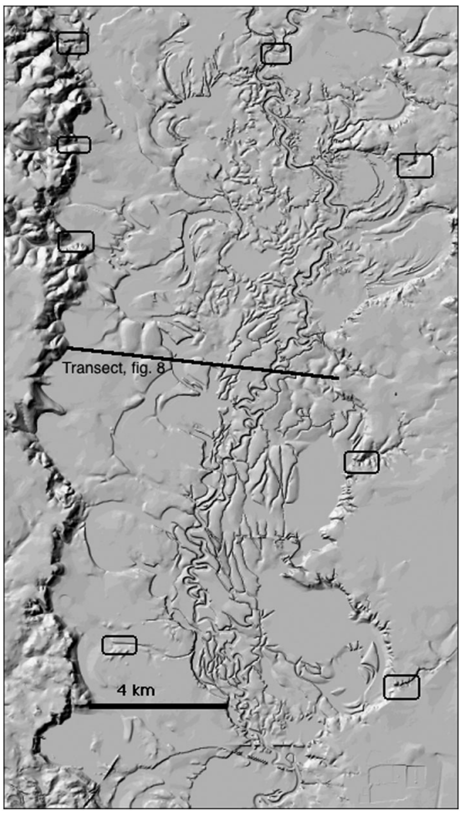

Figure 7. Shaded relief map of the study area, with boxes showing larger tributaries to the lower Neches valley.

channels. In this scenario, levee breaches during floods create crevasse splays with multiple interconnected channels; or a single crevasse channel divides as it encounters local obstacles. Because of locally steep cross-valley gradients toward floodplain depressions, these anabranching channels were able to incise, creating persistent channel systems. Figure 8 shows the large floodplain depressions in the study area, which help create the locally relatively steep cross-valley gradients, and serve as local base levels for the crevasse channels.

The topographic cross-section in Figure 9 shows a typical situation, in that the sub-channels are well below the elevation

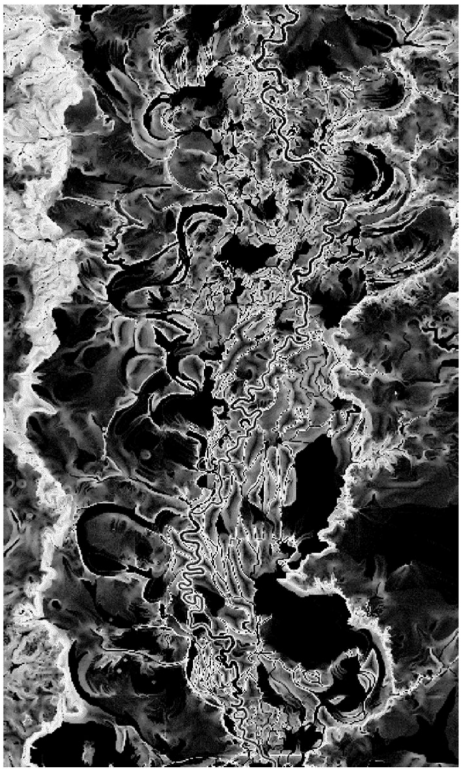

Figure 8. Grayscale slope map of study area showing the large depressions in the lower Neches River floodplain (black = zero slope to white = maximum slope ≈ 0.06).

of the floodplain surface, only slightly higher than the main channel elevation, and < 15 m above sea level. These channels thus intersect the water table, and with slope gradients mostly greater than those of the main channel (see Table III), this is apparently sufficient to keep the channels open. The crevasse origin is also supported by the small channels connecting the anastamosing channels with the Neches River at their upstream end, and the fact that most of these connector channels slope away from the river and levee, toward backswamp areas (Figure 10). The steeper slope gradients in the anastamosing channels are also consistent with this origin.

Keeping crevasse channels open would depend on slowing vegetation invasion, which can be accomplished by frequent inundation, and by shear stress sufficient to prevent extensive sediment accumulations. Shear stress per unit bed area (in N m^{-2}) is given by:

$$\tau = \gamma d \cdot S \tag{1}$$

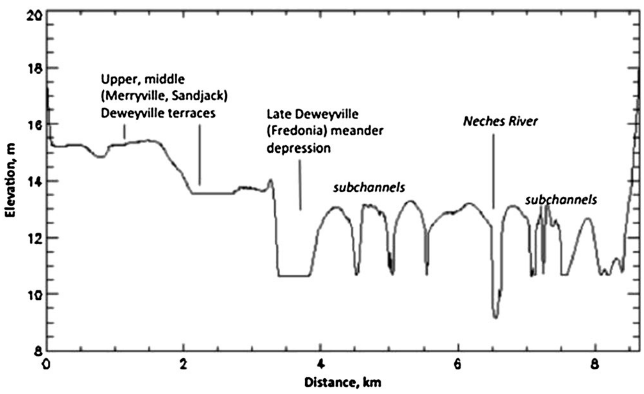

Figure 9. Cross-valley elevation transect (see Figure 7 for location). Terrace surfaces are indicated. Levee elevations for the Neches and sub-channels on this cross-section are comparable; in most of the study area those on the main channel are higher.

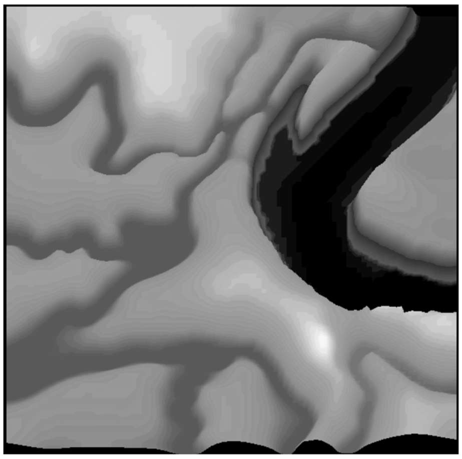

Figure 10. Topographic detail of Neches River connections with anastamosing channels at the upper end of zone A (see Figure 4).

where γ is specific gravity of water (= 9810), d is mean depth in meters, and S is slope gradient. Figure 11 shows that for slopes typical of the Neches anastamosing channels, shear stresses are sufficient to mobile the sand and finer material available for depths of 0.1 m or more. Where these channels are incised into the finer-grained Estes and Urbo soils, the high cohesion could also help maintain the channels by inhibiting bank slumping.

Comparison with adjacent rivers

Given the differences compared to the adjacent and similar Trinity and Sabine Rivers, with which the Neches coevolved, the relationships between the modern channel and the Pleistocene paleomeander depressions were compared.

The study reach of the Neches is 50 km long, terminating at the Evadale gaging station. Points of similar elevation were selected along the lower Trinity and Sabine Rivers, and a 50 km reach upstream identified. DEM data (3 m resolution, LiDAR-derived) was used in each reach to identify floodplain depressions associated with Pleistocene meanders. These were then examined to determine whether any plausible flow path exists from the levees adjacent to the modern channel to the depression. Depressions that are spatially contiguous and hydraulically connected to each other (based on topographic flow routing)

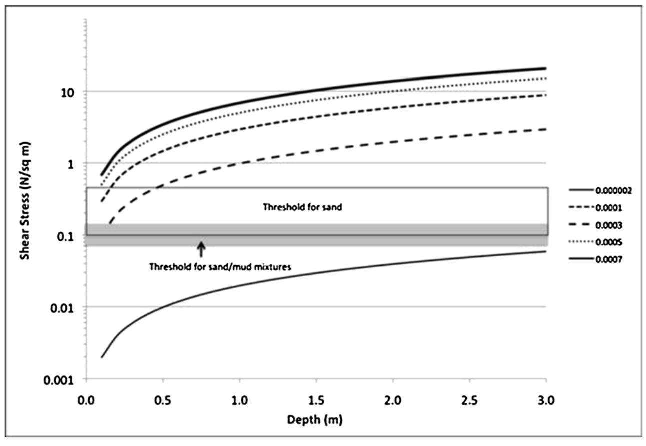

Figure 11. Shear stress–depth relationships for various channel slopes. Lowest curve is the minimum slope measured in anastamosing channels in the study area; the other four curves represent the typical slope gradients in those channels. Thresholds for mobility of very fine to very coarse sand (box) from Fischenich (2001); for sand/mud mixtures (shaded area) from Ahmad *et al.* (2011).

were combined. For each, the depression center was identified, and the shortest flow distance from the river levee to the center measured. The shortest straight-line distance from the depression center to any point on the modern channel not downstream was also measured. The main river channel and depression elevations as reflected in the DEM data (recognizing imprecision with respect to water-covered areas) were recorded, along with the maximum levee-top elevation.

The Neches study reach has seven such depressions, with a mean flow distance of about 5.5 km (range 0.27 to 9.69), and a mean straight-line distance from the main channel of 1.76 km (range 0.27–3.10) (Table V). Omitting the depression at the downstream end of the reach immediately adjacent to the river levee system, the mean flow distance is 6.41 km (minimum 2.85), and straight-line distance is 2.01 km (minimum 1.61). The depression elevations are all greater than DEM-derived channel elevations, but on average about 3 m below the levee elevations (Table V).

Only three potentially hydraulically connected Pleistocene depressions occur on the comparable reach of the Trinity River. These are roughly similar to the Neches in terms of routed flow distance from the modern channel, but generally farther away in straight-line distance (Table V). The depression elevations are higher relative to those of the channel (mean 7.3 m versus 1.6 m in the Neches), but comparable with respect to elevation relative to levees.

The comparative reach of the Sabine River also contains seven connected Pleistocene depressions, on average closer to the channel than in the Neches (mean flow distance 1.07 km; straight-line 0.76). The maximum flow distance of the Sabine features (1.99 km) is greater than all but one of those for the Neches. Depression elevations are apparently close to those of the nearby main channel, with five appearing to be lower than the channel (Table V). The mean levee-depression elevation difference (1.26 m) is less than half that of the other rivers.

Discussion

Available evidence rules out the three potential origins of the anastamosing floodplain sub-channels identified at the outset of this project. They do not represent a formerly anabranching course of the Neches main channel, and do not exhibit the morphological traits that would be expected from anastamosis due to downstream base level rise. The most likely cause of base level rise in the study area is sea-level, but other factors such as tectonics or woody debris jams at the downstream end of the study area are also not consistent with the evidence. There is no evidence of systematic downstream-to-upstream (or vice-versa) gradients in the degree of development of anastomosing that would be expected if it were triggered by either base level or sediment supply effects on the Neches River. The lack of continuity, even with respect to traces of former channels, much less contemporary hydrologic connectivity, also argues against this origin. As all the channels are inset into Holocene surfaces, they are too young to represent remnants of deltaic distributaries from pre-Holocene sea-level highstands. Finally, their alignment and orientation indicates they were not formed by Neches River tributaries.

Evidence is consistent with an origin as crevasse channels functioning as distributaries to flood basins (floodplain depressions). The existing anastamosing channels are discontinuous, and flow to or through large floodplain depressions. Where they connect to the main channel at their upstream ends, the bed elevations are well above that of the Neches River, and the channels slope away from the river and natural levee, toward backswamp areas. The typical slopes are sufficient to transport sand and finer material with moderate depths, accounting for the persistence of the channels. Anastamosing systems are often (though not always) associated with avulsions, and avulsions begin as crevasse channels. However, in this case the crevasse channels themselves are anastamosing, rather than creating anabranches of the main channel.

Anastamosing distributary channels are known in a variety of environments, including the Saskatchewan River, Canada (Smith *et al.*, 1989), the Rhine-Meuse delta of the Netherlands (Törnqvist *et al.*, 1993), modern bayhead deltas in Texas (Phillips, 2009, 2012), and dryland rivers of Australia (Ralph and Hesse, 2010). However, these examples are all in deltaic settings or (in the case of Ralph and Hesse, 2010) a channel breakdown situation where a single-thread river repeatedly bifurcates to create a wetland-channel complex. Multi-channel

Table V. Comparison of Pleistocene paleomeander depressions potentially hydraulically connected to the modern river for comparable 50 km reaches of the lower Neches, Trinity, and Sabine Rivers.

Valley side	Flow distance (km)	Minimum distance (km)	Channel elevation (m)	Depression elevation (m)	Maximum levee elevation (m)	Channel – depression	Levee – depression
Neches	*5.54*	*1.76*	*8.44*	*10.05*	*13.05*	*−1.61*	*3.01*
L	2.85	1.85	11.81	14.70	15.81	−2.89	1.11
L	3.84	1.61	10.79	12.32	15.50	−1.53	3.18
R	5.45	2.45	10.22	12.22	15.39	−2.00	3.17
R	7.37	2.80	9.20	10.58	13.11	−1.38	2.53
L	9.39	3.10	6.00	7.57	13.08	−1.57	5.51
R	9.59	0.25	5.88	6.87	10.13	−0.99	3.26
R	0.27	0.27	5.17	6.06	8.36	−0.89	2.30
Trinity	*4.75*	*2.72*	*7.03*	*14.32*	*17.25*	*−7.28*	*2.93*
L	3.17	2.61	11.00	18.48	21.23	−7.48	2.75
L	5.39	2.38	7.04	12.97	17.49	−5.93	4.52
R	5.70	3.17	3.05	11.50	13.03	−8.45	1.53
Sabine	*1.07*	*0.76*	*9.14*	*9.02*	*10.28*	*0.12*	*1.26*
R	1.15	1.08	10.92	10.74	12.20	0.18	1.46
L	1.14	0.65	10.79	10.69	11.88	0.10	1.19
R	1.99	1.06	10.38	10.64	11.86	−0.26	1.22
L	0.78	0.74	8.83	8.39	9.86	0.44	1.47
L	0.62	0.38	8.47	8.38	9.42	0.09	1.04
R	1.23	0.91	7.68	7.72	8.54	−0.04	0.82
R	0.56	0.48	6.90	6.55	8.20	0.35	1.65

planforms may be quite stable in some circumstances (Huang and Nanson, 2007), and this seems to be the case in the study area. The anastomosing planform is explicable on the basis of sediment overload, as flow passing through levee breaches typically has high sediment loads, but spreading and decelerating flow quickly reduces transport capacity. In many cases this would simply lead to a crevasse splay deposit rather than channels, but the steep gradients toward the floodplain depressions allow channels to be incised. However, it has not been resolved where the sediment associated with the crevasses is deposited. Some of the depressions appear (in DEM data) to have fan or delta-like deposits where channels enter them, and these have been observed in the field in two cases. However, there have been no detailed analyses of these deposits or attempts to quantify their extent.

The similar environments of the adjacent rivers raises the question of why there should be several anastamosing floodplain distributary systems on the lower Neches, whereas none have yet been identified on the Trinity or Sabine. The answer is at least partly due to the number of floodplain depressions, defined as those that appear as zero-slope flat areas in images produced from the 3 m DEM data (though standing water in the depressions may have limited the ability of LiDAR to resolve topographic details within the depressions). Referring to Figure 8, note the black zero-slope areas indicating the depressions (these correspond to the flat areas in Figure 7). Many of these occur far enough away from the main channel so that when crevasses occur, gradients toward the depressions may cause channels to be cut. Where depressions are adjacent to the channel, crevasses are likely to result in splay deposits rather than distributary channels. However, if the depressions are adjacent to the valley side slope, with intervening sub-channels or alluvial ridges, crevasse flows from the main channel will not reach them. Figures 7 and 8 show that the Neches study area has many flood basins that are neither adjacent to the modern river or abutting the valley side with intervening channels or ridges.

The lower Trinity River both has fewer depressions, and some of those are mainly along the valley walls without strong gradients from the modern River (Phillips and Slattery, 2008). Of the two exceptions, one has been identified as a likely spot for future avulsions (Phillips and Slattery, 2008), and the other (within the delta area) has multiple distributary channels (Phillips and Slattery, 2007). On the Trinity reach that is directly comparable with the Neches study area, there are only three potentially hydraulically connected depressions, and they are much higher relative to river channel elevations than those of the Neches.

On the Sabine River, by contrast, the major depressions are mainly adjacent to the river (Figure 12). On the comparable lower Sabine Reach, there are also seven potentially hydraulically connected depressions. As compared to the Neches, however, they are closer to the modern river with elevations closer to that of the river, and with less relief relative to the delta. Crevasses connecting to these depressions are more likely to deposit splays, as suggested by the topography of the depressions in Figure 12. The origin of paleo- and sub-channels in the lower Sabine River is the subject of ongoing research.

Thus the Neches–Trinity–Sabine contrasts are related to historically contingent geomorphic development of the river-floodplain system in at least two respects: formation and preservation of floodplain basins, and lateral migration of the modern river relative to these depressions. The floodplain depressions are either Pleistocene 'Deweyville' meander scars, or basins bounded by alluvial ridges due to avulsions. At the stage of valley filling of the Neches, Trinity, and Sabine Rivers these are unlikely to be eliminated by filling alone. However, lateral migration across the valley bottoms can obliterate these

Figure 12. Topography (from 3-m resolution LiDAR DEM) of portion of the lower Sabine River valley south of Bon Weir, Texas and Merryville, Louisiana. The Sabine River channel is directly adjacent to large depressions on the west (Texas) side of the valley, so if crevasses into these occur they form splays rather than channels. Note also the multiple sub-channels on the east (Louisiana) side of the river.

depressions. Thus, despite the similar environmental setting and controls, and common history of external forcings, local details in the three rivers lead to qualitatively different sub-channel and floodplain morphologies and patterns of hydrologic connectivity.

While this discussion has focused on the anastamosing floodplain distributary origin of the Neches sub-channels, these channels are connected to and affected by former sections of the main channel abandoned by avulsions, tributaries, oxbows, and sloughs (see Figures 1, 5 and 7). The lower Neches fits Lewin and Ashworth's (2013) concept of a plural system whereby main, sub, and tributary channels may all have different morphologies and flow regimes. However, it does not precisely fit the classification they provided. Their system 3(b)(i) (Lewin and Ashworth, 2013, table 3) is termed a plural sedimentation system, contra-style, accessory, described as one where off-takes from the main channel or other drainages internal to the floodplain are of a different style to the main channel. Usually this involves a braided main channel and a sinuous single sub-channel. In the study area there is a single sinuous main channel and anastamosing sub-channels. The lower Neches also bears resemblance to the 'floodbasin prominent' type, where the valley floor is dominated by ponded water (floodplain lakes), but without major sub-channels. This lack of strong correspondence is not surprising, as Lewin and Ashworth (2013) do not present their typology as a classification, and claim only to identify some common styles. No typology or categorization of reasonable size is likely to capture all the variety observed in nature, and this study suggests that there are perhaps many varieties of plural sedimentation systems.

Conclusions

The lower valley of the Neches River includes multiple anastomosing sub-channels on the modern floodplain. There are at least five distinct anastomosing channel systems upstream of the river delta. While channel–floodplain hydrological connectivity with the main channel is very high, the sub-channels are hydrologically independent in the sense that their flow mainly derives from sources other than the main channel (tributaries and local runoff and ground water) at sub-banktop flows of the Neches.

These channels, all incised into Holocene floodplains, have a common origin as crevasses along the meandering Neches River and are strongly influenced by antecedent morphology. When levee breaching occurs during high flows, cross-valley gradients direct the flow toward floodplain basins associated with Pleistocene meander scars. Such events apparently created the multi-thread channels, and they persist due to capture of tributary flow from the valley sides, groundwater input, and distributary flows from the main channel. As a result, at least 50 km of the valley above the delta has a floodplain with numerous intersecting sub-channels. The lower Neches River is an example of a plural system where main channels, tributaries, and sub-channels have different morphologies and hydrogeomorphic functions. Though the lower Neches differs from types of plural systems previously identified, the findings are consistent with the general notion of plural systems, and the probable mechanisms are not unique to the study area.

The adjacent Trinity and Sabine Rivers have similar environmental controls, and, along with the Neches, are part of the same Quaternary drainage system. Yet the anastomosing channels of crevasse origin are not found on the other rivers. The difference is due to the number and location relative to the modern channel of floodplain depressions. This highlights the effects of geographical and historical contingency in producing path-dependent development and a degree of hydrological idiosyncrasy.

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