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Key Points:
- Models predicting the bifurcation or confluence angle in tributary channel systems apply to distributary channels in some cases
- Tributary and distributary channel networks exhibit congruent mean angles of channel bifurcation
- A mean bifurcation angle of 72° is found over small length scales but over all investigated time scales

Supporting Information:
- Supporting Information S1
- Table S1
- Table S2
- Table S3

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Congruent Bifurcation Angles in River Delta and Tributary Channel Networks

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Abstract We show that distributary channels on river deltas exhibit a mean bifurcation angle that can be understood using theory developed in tributary channel networks. In certain cases, tributary network bifurcation geometries have been demonstrated to be controlled by diffusive groundwater flow feeding incipient bifurcations, producing a characteristic angle of 72°. We measured 25 unique distributary bifurcations in an experimental delta and 197 bifurcations in 10 natural deltas, yielding a mean angle of 70.4° $\pm$ 2.6° (95% confidence interval) for field-scale deltas and a mean angle of 68.3° $\pm$ 8.7° for the experimental delta, consistent with this theoretical prediction. The bifurcation angle holds for small scales relative to channel width length scales. Furthermore, the experimental data show that the mean angle is 72° immediately after bifurcation initiation and remains relatively constant over significant time scales. Although distributary networks do not mirror tributary networks perfectly, the similar control and expression of bifurcation angles suggests that additional morphodynamic insight may be gained from further comparative study.

1. Introduction

Branching channel networks are a classic example of pattern formation arising from self-organization in the natural environment, forming the primary pathways for water and sediment accumulation and dispersal on planetary surfaces (Hack, 1957; Jerolmack & Swenson, 2007; Montgomery & Dietrich, 1992; Rinaldo et al., 1993; Rodríguez-Iturbe & Rinaldo, 2001). Their dendritic structure can cover continents in the case of tributary systems and set large-scale depositional patterns in river delta and deepwater distributary systems. Hence, our understanding of channel network dynamics is critical to the study of planetary science, landscape evolution, source-to-sink sediment routing, coastal sustainability, fluvial-deltaic and deepwater stratigraphy, and basin analysis.

The topology of both distributary and tributary channel networks prominently features channel bifurcations or confluences in tributary settings (Abrahams, 1984; Edmonds, Paola, et al., 2011; Olariu & Bhattacharya, 2006; Perron et al., 2012; Tejedor et al., 2015. In the context of distributary networks, channel bifurcations are defined as distinct divisions of channelized flow, where a single channel, referred to as the parent channel, branches into two or more channels, referred to as daughter channels. The daughter channels are separated by a bar, island, or shallow bay where sediment transport is significantly reduced or nonexistent, and flow is unchannelized. This study focuses on bifurcations that initiate near the distal end of the network (i.e., the interface between debouching fluvial network and relatively still basin), excluding avulsions that cause new bifurcations to form within an established network (Slingerland & Smith, 2004).

The scientific understanding of tributary and distributary systems has developed independently despite some qualitative morphological similarities. Fluvial tributary networks have been modeled for over a century as the subset of a landscape where there is sufficient shear stress imparted by a flow to transport sediment via fluvial processes (Gilbert & Murphy, 1914; Horton, 1945; Izumi & Parker, 1995, 2000). Recent studies have advanced the theory to show that tributary networks are partially (Perron et al., 2008, 2009, 2012) or completely (Abrams et al., 2009; Cohen et al., 2015; Devauchelle et al., 2012; Petroff et al., 2011, 2013) controlled by diffusive transport of fluid and/or sediment outside of the channel network. Distributary channel networks, on the other hand, have been understood as the product of sedimentation from turbulent jets that form at the mouths of rivers entering basins (Bates, 1953; Edmonds & Slingerland, 2007; Fagherazzi et al., 2015; Jerolmack & Swenson, 2007; Wright, 1977). Emergent network scales in distributary settings have been linked to the distance from a channel mouth to the locus of mouth bar aggradation, which in turn is linked to aspects of channelized flow at a river mouth, including inflow buoyancy and inertia, bed friction, the width-to-depth ratio of the channel, and sediment characteristics (Axelsson, 1967; Edmonds & Slingerland, 2007; Edmonds, Shaw, et al., 2011; Jerolmack & Swenson, 2007; Wright, 1977. Given the similar dendritic morphology of tributary and distributary network bifurcations, we find it inconsistent that tributary network structure would depend on flow outside of the network and that distributary networks would depend on aspects of flow within the network.

We make a case for unchannelized flow patterns controlling distributary network structure by analyzing the angle of bifurcation in deltaic distributary networks. Recent theoretical studies of tributary channel networks excavated by groundwater seepage predicted the presence of a characteristic channel bifurcation angle of 72° that arises from diffusive groundwater flow in proximity to incipient channel bifurcations (Devauchelle et al., 2012). When the population of tributary bifurcation angles found in an incised network located in Florida was measured, this critical angle emerged as the mean angle of bifurcation, albeit with a significant standard deviation. While this finding is a remarkable advancement, questions about the critical angle remain. First, the spatial scales where the critical bifurcation angle is valid are theoretically scale invariant (Devauchelle et al., 2012) but remain untested. Second, the slowly evolving field-scale network prevents the observation of angles over time, leaving the hypothesis that incipient channels evolve toward the critical angle over time also untested. The dependence of bifurcation angle on measurement length scale and time is essential for predicting the emergent dynamics of networks.

In this study, we show that unchannelized surface flow in the presence of an incipient distributary bifurcation can also be modeled as diffusive flow using the Laplace equation. Furthermore, analysis of distributary channel network bifurcations found in experimental and field-scale river deltas also revealed a mean bifurcation angle consistent with the 72° prediction. These data also allow the valid spatial and temporal scales to be assessed and temporal evolution of bifurcations to be analyzed. We offer evidence that at the scale of individual bifurcations, dynamics of tributary and distributary networks are similar despite the obvious difference of reversed flow direction with respect to the bifurcation.

2. Theory

Devauchelle et al. (2012) (hereafter referred to as DPSR12) established that in tributary networks incised by groundwater seepage erosion, the angle of bifurcations is controlled by the groundwater flow field directly outside the channel network. The height of the water table in the groundwater flow field (h) above a horizontal, impermeable layer in isotropic media is a solution of the Poisson equation (Bear, 1972; Darcy, 1856; Devauchelle et al., 2012; Petroff et al., 2011, 2013):

$$\nabla^2 h^2 = -\frac{2R}{K}, \tag{1}$$

where K is hydraulic conductivity (L/T) and R is rate of recharge (L/T) in close proximity to a channel. Near a channel, R is negligible relative to horizontal groundwater flux, which integrates precipitation over an entire basin (Petroff et al., 2013). This means that R can be disregarded, allowing the height of the groundwater flow field outside of the channel network to be modeled as a function of the Laplace equation:

$$\nabla^2 h^2 = 0. \tag{2}$$

The water surface around an incipient bifurcation is then modeled according to equation (2), with boundary conditions imposed at the channel network. Assuming that channels extend in the direction from which flow enters the channel tip, the growth of the incipient channel is controlled by competition for groundwater flux. When the incipient angle between the converging channels is small, channel tips grow away from each other, causing the angle of the developing bifurcation to increase. When the incipient angle is large, the channel tips grow toward one another, reducing the developing bifurcation angle. When the bifurcation angle is $\alpha = 72°$, the plan view flow path entering the channel tips approaches the tips with no curvature, and thus, the bifurcation angle does not change as it grows. Hence, a critical angle of $\alpha_{\mathrm{cr}} = 72°$ represents a stable morphology for the bifurcation as it grows in a diffusive groundwater field. The derivation of α_{cr} assumes symmetry across the axis of the original channel, which means that the incipient branching channels are identical in their ability to carry seepage flow. We refer the reader to Devauchelle et al. (2012) and Petroff et al. (2013)

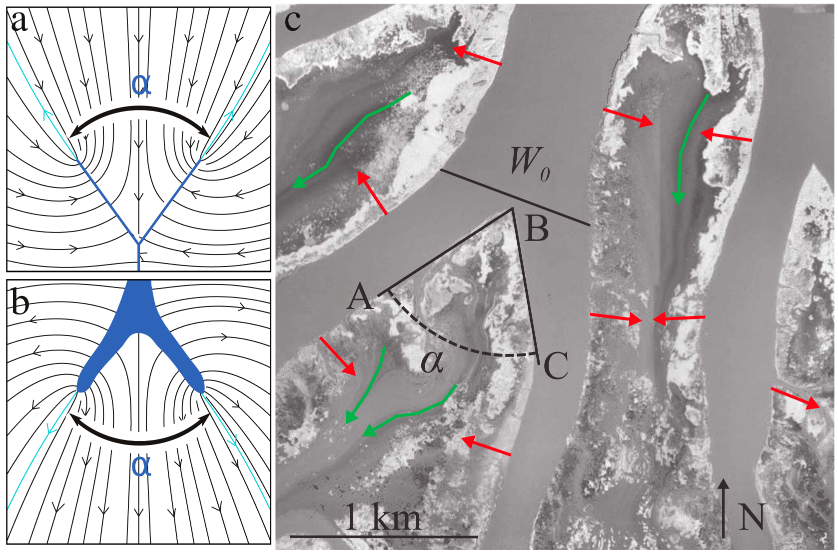

Figure 1. (a, b) Conceptual diagram of flow fields outside of channel bifurcations. Black flowlines indicate the external flow direction field $\left(\hat{d}\right)$ in tributary channel networks (Figure 1a modified from Devauchelle et al. (2012)) and distributary channel networks (Figure 1b). The dynamics of the external flow field in both networks define the critical angle of bifurcation, α_{cr}. (c) Method of bifurcation angle measurement on the Wax Lake delta. See Figure 2a for location. W_0 indicates channel width directly upstream of bifurcation. The bifurcation angle, α, is measured using limb lengths L equal to one normalized channel length (or one channel width, L/W_0 = 1) downstream of the bifurcation, shown in the figure as $\angle ABC$. Flow path of unchannelized water departing the channel is indicated with red arrows. Note how external flow patterns (traced by green arrows along the streaklines) compare to schematic flow patterns in Figures 1a and 1b.

for detailed derivations of α_{cr}. DPSR12 validated this prediction with 4,966 bifurcations measured in a natural seepage tributary network in Florida, USA, which showed a mean characteristic angle of 71.98° ± 0.88° (95% confidence interval assuming normally distributed angles), consistent with the theoretical prediction of α_{cr}.

The flow patterns in surface water outside of distributary channels behave similarly to the groundwater flow patterns in seepage networks. Theory developed by DPSR12 shows that a critical angle of 72° is dependent on two primary assumptions: that (a) channels grow forward in the direction from which water enters them and that (b) flow outside of the channel network can be described by the Laplace equation.

In order to apply this theory to distributary systems, we make several assumptions: (a) hydraulic connectivity between the channel and interdistributary bay, (b) diffusive flow surrounding the channel, which assumes an already well-developed mouth bar surrounding the channel mouth, and (c) channel extension from channel tips in the local direction of flow. Recent work on the Wax Lake Delta (WLD, Figure 2a), a ~100 km^2 river delta in coastal Louisiana with many bifurcations, shows that its distributary channels are hydraulically connected to interdistributary bays via flow over subaqueous levees and through many small tie channels (Hiatt & Passalacqua, 2015; Passalacqua, 2016; Shaw et al., 2016). This hydraulic connectivity allows significant amounts of water to depart channels laterally and travel through the delta as unchannelized flow (Figure 1c). While most analysis of deltaic channel-interchannel exchange has been done on the WLD, it is likely to be the rule rather than the exception for actively building natural deltas: all deltaic deposition occurs subaqueously, meaning that water must cover the actively growing portion of a delta with some recurrence. During these flooded conditions, pathways connecting the distributary channel network and unchannelized regions of islands are present.

Further measurement of the WLD shows that channels extend from their downstream tips via erosion of delta front sediments (Shaw & Mohrig, 2014). Channel extension was observed primarily during periods of low river flow when tidal reworking of the deposit was dominant. The direction of channel extension occurred in the direction that flow departed channel tips (Shaw et al., 2016). If channels can be assumed to extend along the flow path from which flow departs channel tips, and this flow path can be modeled, then a characteristic bifurcation can be found using methods similar to DPSR12.

Flow in surface water directly outside of channels in salt marshes and tidal flats has also been shown to be diffusive (Rinaldo et al., 1999; Van Oyen et al., 2012). While the river deltas studied here are constructed through primarily fluvial processes, the flow field outside of the channel network can be conceptualized using the same theory. Rinaldo et al. (1999) showed that for flat, unchannelized areas that were hydraulically connected to channels and that were small relative to the tidal wavelength, the water surface elevation within the unchannelized portions of these systems could be simplified to

$$\nabla^2 h = \frac{\Lambda}{h^2}\frac{\partial h}{\partial t}, \tag{3}$$

where h is the elevation of the water surface above the flat, unchannelized bed and Λ is a dimensionless friction coefficient. Similar to precipitation in seepage networks, shown in equations (1) and (2), the magnitude of vertical flux associated with tidal range ($\frac{\partial h}{\partial t} < 10^{-5}$m/s) is small relative to horizontal flow velocities ($\sim 10^{-1}$ m/s), meaning that $\frac{\partial h}{\partial t}$ can be neglected, yielding

$$\nabla^2 h = 0. \tag{4}$$

Equation (4) requires that flow be friction dominated. Rinaldo et al. (1999) also derived dimensionless parameters for inertia (S) and friction (R) relative to local effect of gravity in the tidal flat. The ratio of the inertia and friction parameters, S/R, is defined as follows:

$$S/R = (C^2 D_0 \omega)/(gU_0), \tag{5}$$

where C is the Chezy coefficient, D_0 is a characteristic maximum flow depth, ω is time scale of temporal variation (i.e., tidal range), U_0 is characteristic depth-averaged flow velocity, and g is the gravitational constant. If $S/R << 1$, the flow can be assumed to be friction dominated. We test for friction dominance using characteristic values for these variables on the Wax Lake Delta. Chezy coefficient values range from 50 to 100 m$^{1/2}$/s, mean flow depth in the interdistributary bay is approximately 0.5 m, $1/\omega$ for the WLD region of the Gulf of Mexico is 6 h, and U_0 is approximately 0.1 m/s (Shaw et al., 2016), giving $S/R << 1$ range for all reasonable parameter ranges in the interdistributary bays of the Wax Lake Delta, meaning that flow in those regions is friction dominated; therefore, the Laplace equation derived in Rinaldo et al. (1999) applies to the delta front of the WLD, and flow according to equation (4) is a valid assumption.

Groundwater in the vicinity of a seepage channel (equation (2)) and surface water in the vicinity of a delta or marsh channel (equation (4)) then both satisfy the Laplace equation, albeit with the h raised to a different exponent in each case. However, the h exponent is inconsequential for predicting channel extension direction, as equations (2) and (4) produce the same flow direction field. Flow direction is the unit vector of the gradient $\hat{d} = \frac{\nabla h}{|\nabla h|}$ (Figure 1) and $\frac{\nabla h^2}{|\nabla h^2|} = \frac{2h\nabla h}{|2h\nabla h|} = \frac{2h\nabla h}{2h|\nabla h|} = \frac{\nabla h}{|\nabla h|}$. Hence, if the boundary conditions set by the channels are the same, the flow magnitudes (speeds) will be different between the two systems, but the flow directions traced by groundwater flow and distributary surface water will be similar. Under these conditions, growing channel tips will compete for nourishment area that channels can supply water to, similar to how tributary channel tips compete for drainage area from which water is supplied — this comparable flow behavior should yield congruent critical bifurcation angles in tributary and distributary environments.

The DPSR12 model assumes friction-dominated flow surrounding an incipient bifurcation with daughter channels of arbitrary length, so long as these channels are far from neighboring distributaries (Figure 1b). The delta front morphology of the Wax Lake Delta shows that deep (2–3 m) channels are surrounded by shallow, low relief regions (<1 m deep), satisfying this assumption. This differs from the way delta front processes are sometimes conceptualized, where an abrupt channel mouth enters into a basin of near-uniform depth. Turbulent jets occur in this situation (Bates, 1953; Canestrelli et al., 2014; Wright, 1977). However, it is possible that the DPSR12 model adapted for distributary networks could adequately describe flow patterns over emergent subaqueous topography that was initially produced by a stable turbulent jet.

3. Methods

We test for the presence of a critical angle $\alpha_{cr} = 72°$ in distributary channel bifurcations using measurements from field- and laboratory-scale deltas (Figure 2). These measurements, including coordinates, scales of measure, and time stamps for experiments, are included in the supporting information. Bifurcation angle measurements (α) were made using ImageJ, an open-source image analysis software (https://imagej.nih.gov/ij/).

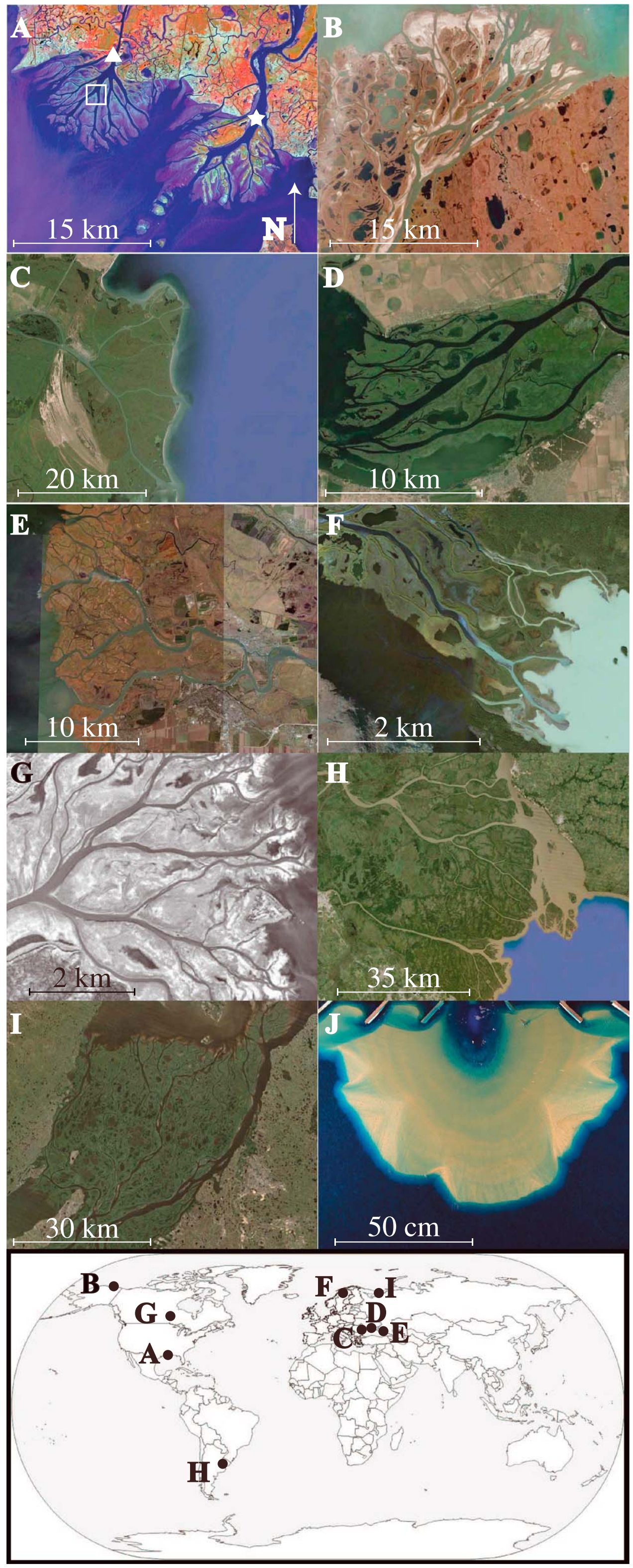

Figure 2. Delta images used for this study. All images of field-scale deltas shown are the images used for data collection. A time series of experimental delta images was used in data collection. (a) Atchafalaya and WLD (respectively, indicated by the star and triangle), (b) Colville, (c) Danube, (d) Dnepr, (e) Don, (f) Laitaure, (g) Mossy (Edmonds & Slingerland, 2007), (h) Parana, (i) Pechora, and the (j) experimental delta. World map icons approximately correspond to field-scale delta locations. White square in Figure 2a represents the approximate location of Figure 1c.

The angle is defined as $\alpha = \angle ABC$, where B is placed at the apex of the island and A and C are placed some linear distance L down the island flanks (Figure 1c). On natural islands (e.g., Figure 1c), α is length-scale dependent, hence, α was measured over L normalized to the channel width directly upstream of the bifurcation (W_0). Our primary analyses were performed on angles where $L/W_0 = 1$. However, we also varied L/W_0 to determine the importance of measurement length scale on bifurcation angle. We measured bifurcation angles from a selection of field-scale deltas (Figures 2a–2i). These deltas were chosen because their networks are composed of interpreted channel mouth bifurcations (Edmonds & Slingerland, 2007). Bifurcations in which one of the daughter channels displayed a width narrower than 20% of the width of the opposite channel were not measured. This criterion excludes significantly asymmetric bifurcations from our measurements. This is done because the derivation of α_{cr} implicitly assumes symmetric daughter channels. However, the criterion includes slightly asymmetric bifurcations that are common in nature (Edmonds & Slingerland, 2008). In addition to the exclusion of asymmetric bifurcations, bifurcations interpreted to form via avulsion are excluded from the sample based on spatial scaling-dependent criteria (Jerolmack & Swenson, 2007).

The experimental data set was measured from delta-building experiment WY-9 conducted at the University of Wyoming (Figure 2j). During the experiment, water and sediment composed of well-sorted medium-grained sand entered an enclosed basin through a pipe directly beneath base level, which was held constant during the experiments. A constant fluid discharge of 18 L/min and a sediment discharge of 0.05 L/min were used. The experiment spontaneously produced many islands that migrated laterally and downstream, forming a distributary network. Islands and their associated bifurcations were removed when they were either eroded away or merged with a neighboring island due to sedimentation in the intervening channel.

Populations of bifurcation angles were compared to α_{cr} to test for consistency with the DPSR12 model that indicated bifurcation angle is controlled by diffusive flow outside of the channel network. The same statistical methods utilized in DPSR12 are applied here for comparative purposes, which assume that individual bifurcation angles are sampled from a normal distribution with some mean μ and standard deviation σ. Bifurcations measured on all field-scale deltas were combined into a single population because individual field-scale deltas do not contain a sufficient number of bifurcations to resolve emergent behavior. If $\mu = \alpha_{cr}$ for all deltas, then the combined population would also have a mean equal to α_{cr}, regardless of whether σ varied between deltas. Conversely, if $\mu \neq \alpha_{cr}$ for all deltas, then it is unlikely the mean of the combined population will show a mean of approximately 72°. Experimental bifurcations were measured over time, but only the first measurement from each bifurcation was used to test for a mean bifurcation angle to insure measurement independence. This meant that the population contained angles measured at different times during the experiment, unlike the field measurements.

In order to study the behavior of distributary channel bifurcations over both spatial and temporal scales, the angle of bifurcation was measured as a function of normalized channel length on the Wax Lake, Atchafalaya, and Mossy Deltas (Figures 2a and 2g) and as a function of time elapsed since formation of bifurcation in the experiment. Bifurcation angle was measured as a function of L/W_0 ranging from 0.25 to 16. In the experiment, bifurcation angle was measured at 30 s time increments to a limit of 450 s—although some bifurcations were extant for nearly half of the experiment, α was only analyzed when there were sufficient ($n > 25$) measurements.

To examine whether distributary channel bifurcations exhibited a critical bifurcation angle, the multiple-mean method was used to estimate the 95% confidence interval of the mean of the distribution (μ) (Mendenhall et al., 2012). If the 95% confidence interval of μ overlapped α_{cr}, then the sample was determined to be consistent with a critical angle and diffusive flow could be considered the likely control on the bifurcation angle. If the range of μ did not include α_{cr}, then the hypothesis of diffusive flow was deemed inconsistent. This analysis is not a statistical test of whether $\mu = \alpha_{cr}$ but provides an objective method for comparing natural systems that exhibit variability to the theoretical prediction.

4. Results

The mean bifurcation angle (μ) of both distributary network populations sampled in this study is consistent with the mathematically predicted $\alpha_{cr} = 72°$ (Figure 3a). The experimental and field-scale delta mean bifurcation angles and 95% confidence intervals were 68.3° ± 8.7° and 70.4° ± 2.6°, with σ of 22.3° and 18.6°, respectively. Hence, the distributary channel bifurcations in field and laboratory settings are consistent with

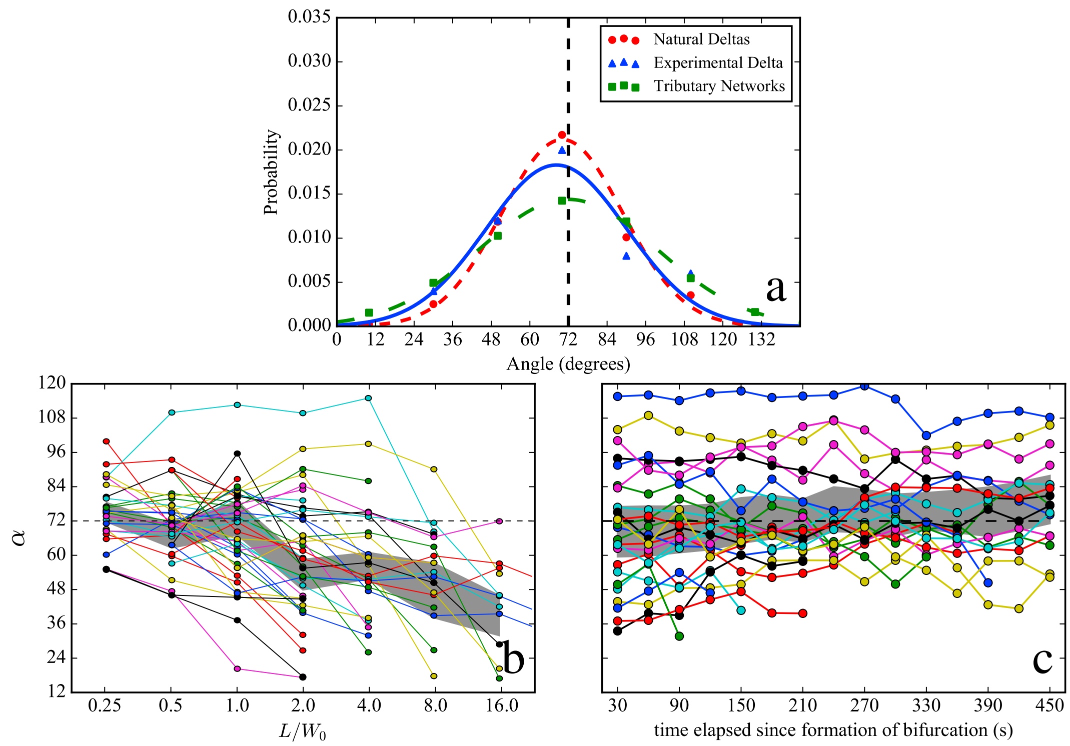

Figure 3. (a) Histogram and probability density function of bifurcation angles for distributary channels measured in our study and tributary channels measured in Devauchelle et al. (2012). Vertical line marks the mathematically determined critical angle of 72°. Bin size is 20°. Solid line represents experimental data (see Figure 2j), short dashes represent the field-scale deltas (see Figures 2a–2i), and long dashes represent the tributary system (Devauchelle et al., 2012). All bifurcation angles were measured at $L/W_0 = 1.0$. (b) Angle of bifurcation versus normalized channel length for the Wax Lake, Atchafalaya, and Mossy deltas (see Figures 2a and 2g). Dotted line indicates the critical angle of 72°; each colored line represents the progression of a single bifurcation angle moving downstream, and the shaded gray area indicates the 95% confidence interval of the mean bifurcation angle for each increment. The 95% confidence interval for the sample of bifurcations is within the predicted range at normalized channel lengths ≤ 1.0. (c) Angle of bifurcation (degrees) versus time elapsed since formation of bifurcation (seconds). Data collected from experimental delta WY-9 (see Figure 2j). Dashed black line represents the critical angle of 72°, individual colored lines/points represent a unique bifurcation over time, and the shaded gray area represents the 95% confidence interval for all bifurcation angles at each time increment. The elapsed 450 s over which observations were made represents a significant portion of time relative to sediment flux—total sediment added to the basin over this time scale was equal to as much as 50% of the total available volume overlying the delta. All bifurcations were measured at $L/W_0 = 1.0$.

the hypothesis that their angle is controlled by diffusive flow outside of the channel. Likewise, the mean bifurcation angle measurements are also consistent with the mean angle of tributary network bifurcation measured in DPSR12.

When the bifurcations from the Wax Lake, Atchafalaya, and Mossy Deltas were analyzed as a function of measurement length scale normalized to channel parent channel width (L/W_0), μ was consistent with α_{cr} for $L/W_0 \leq 1$. However, for $L/W_0 > 1$, the mean bifurcation angle was significantly less than α_{cr} and the 95% confidence interval fell below 72°. As L/W_0 increased, the mean bifurcation angle continued to decrease without appearing to converge on a different emergent angle.

Experimental bifurcation angles were measured as a function of time since bifurcation initiation to investigate the temporal evolution of α (Figure 3c). Individual islands were generally present for less than 450 s during the experiment. This represents about half the time required to fill the channel network with sediment, meaning that evolution was measured at significant time scales relative to network construction. The 95% confidence interval of μ overlapped with α_{cr} for each time interval; despite this, the mean increased slightly over time. Inspection of the data suggest that this increase occurred because individual bifurcations that initiated at less than 72° either increased over time or were removed due to island erosion or merging. In contrast, bifurcations that initiated with angles greater than 72° rarely decreased, and they existed for longer periods. Despite this gradual trend in the mean behavior, the standard deviation of α decreased only gradually from $\sigma = 22.25°$ at 30 s to $\sigma = 17.18°$ at 450 s.

5. Discussion and Conclusions

The mean bifurcation angle for both experimental and field-scale distributary bifurcations is consistent with the critical angle of 72° (Figure 3a), suggesting that flow directly outside the channel network is controlled by the Laplace equation. This previously unexamined aspect of deltaic distributary networks has numerous potential applications. A stratigrapher or reservoir engineer could apply the behavior to predict the trajectory of channel bodies in deltaic strata. A coastal engineer could use it to predict future delta growth and flow patterns in either natural or controlled diversion settings, contributing to coastal sustainability efforts (Paola et al., 2011).

Analysis of field-scale deltas suggests that both the characteristic angle and the dynamic model are applicable to a wide variety of field-scale distributary networks. The assumed exchange of channelized flow and unchannelized flow has only been directly reported from the Wax Lake Delta (Hiatt & Passalacqua, 2015; Shaw et al., 2016). However, this process is an underlying assumption to the presence of a critical angle. We therefore expect similar connectivity between channelized and unchannelized regions in the other measured deltas, and possibly bifurcating deltas in general.

While the mean bifurcation angle is consistent with the theoretical prediction of 72°, we noticed that bifurcation angle is dependent on length scale of measurement and relatively independent of time scale since initiation. Measurement of several deltas showed that the α_{cr} test held at small channel lengths, but as channel length increased to $L/W_0 > 1$, the 95% confidence interval dropped below $\alpha_{cr} = 72°$, and mean angle consistently decreased (Figure 3b). This indicates that diffusive flow outside of channel networks controls bifurcation dynamics at scales up to the parent channel width. At scales larger than the channel width, other processes may be more pertinent. It has been shown that deltas organize their planform geometry so that the characteristic distance to a channel is a few channel widths (Edmonds, Paola, et al., 2011). The processes controlling this channel spacing could control the bifurcation angle when measured over these scales. This dependence differs from seepage channel networks, where angles were measured by linearizing channels at the reach scale (Devauchelle et al., 2012).

The experimental and field-scale distributary channel bifurcations exhibited significant standard deviations, similar to their tributary counterparts. DPSR12 hypothesized that incipient bifurcations do not initiate at α_{cr} but grow toward that angle over time (Devauchelle et al., 2012). However, analysis of experimental bifurcations showed that mean angle was immediately consistent with α_{cr}, yet σ decreased by only 23% over half the channel network-filling time scale. Hence, bifurcations appear to initiate from a distribution centered at α_{cr}, and α_{cr} appears to be a weak attractor of bifurcation angle at best in distributary systems. The gradual increase in μ suggests that the bifurcation may even be more consistent at initiation than over very long time scales. An explanation for the continued angle variability within the system may involve the effect of additional processes on α_{cr}, such as moderate discharge asymmetry between the daughter channels. Even so, the mean bifurcation angle appears independent of discharge asymmetry or other processes involved in bifurcation formation.

Deltaic distributary networks are not completely analogous to tributary river networks. For example, the nested drainage basin morphology in tributary systems is not possible in a delta where all flow paths must eventually traverse the entire delta and reach the receiving basin (Shaw et al., 2016). Further, while the morphology of tributary networks is scale invariant over many orders of magnitude (Caldarelli et al., 1997), there are several aspects of deltas (such as island size) that are not scale invariant (Edmonds, Paola, et al., 2011). Additionally, the tributary channel network from DPSR12 used for comparison purposes is not characteristic of all tributary channel networks; for example, a mean bifurcation angle of 72° is not observed in arid regions where there is insufficient groundwater flow (Seybold et al., 2017). Despite these differences, the critical angle of 72° found on deltas suggests that this aspect of distributary channel network morphology is controlled by unchannelized flow patterns, similar to groundwater seepage tributary channel networks. In essence, the direction of flow through the bifurcation and in the surrounding unchannelized regions does not matter. This contrasts with established distributary network theory, which predicts bifurcation formation as a function of hydrodynamics within channels or at channel termini (Fagherazzi et al., 2015; Wright, 1977).

Although jet dynamics may be responsible for depositing the initial delta front sediments, it appears that the dynamics of bifurcation require diffusive flow. Channelized and unchannelized hydrodynamics are not necessarily mutually exclusive because they are used to predict different aspects of the network (distance between bifurcations and bifurcation angle, respectively). However, the emergence of a critical angle based on simplified unchannelized flow patterns suggests that extrachannel flow is also involved in the initiation of a bifurcated channel network. Continued examination of the relationship between delta channel network dynamics and extrachannel flow patterns may yield further insight into delta depositional patterns and also provide a new analogue for studies of tributary networks.

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