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A conceptual model of depositional, rather than erosional, tidal channel development in the rapidly prograding Skagit River Delta (Washington, USA)

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Abstract

The origin and growth of blind tidal channels is generally considered to be an erosional process. This paper describes a contrasting depositional model for blind tidal channel origin and development in the Skagit River delta, Washington, USA. Chronological sequences of historical maps and photos spanning the last century show that as sediments accumulated at the river mouth, vegetation colonization created marsh islands that splintered the river into distributaries. The marsh islands coalesced when intervening distributary channels gradually narrowed and finally closed at the upstream end to form a blind tidal channel, or at mid-length to form two blind tidal channels. Channel closure was probably often mediated through gradient reduction associated with marsh progradation and channel lengthening, coupled with large woody debris blockages. Blind tidal channel evolution from distributaries was common in the Skagit marshes from 1889 to the present, and it can account for the origin of very small modern blind tidal channels. The smallest observed distributary-derived modern blind tidal channels have mean widths of 0·3 m, at the resolution limit of the modern orthophotographs. While channel initiation and persistence are similar processes in erosional systems, they are different processes in this depositional model. Once a channel is obstructed and isolated from distributary flow, only tidal flow remains and channel persistence becomes a function of tidal prism and tidal or wind/wave erosion. In rapidly prograding systems like the Skagit, blind tidal channel networks are probably inherited from the antecedent distributary network. Examination of large-scale channel network geometry of such systems should therefore consider distributaries and blind tidal channels part of a common channel network and not entirely distinct elements of the system. Finally, managers of tidal habitat restoration projects generally assume an erosional model of tidal channel development. However, under circumstances conducive to progradation, depositional channel development may prevail instead. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords: tidal channel; Skagit delta; river distributary; channel network evolution

Introduction

Models of tidal channel evolution generally hold that channel networks develop through headward growth of first-order channels, especially in youthful marshes (Allen, 2000a; Fagherazzi and Sun, 2004). Tidal channel headcutting rates can be rapid, typically averaging several metres per year, but ranging as high as 500 m a^{-1} (Knighton, 1992). Most of the sites that provide the empirical basis for models of tidal channel evolution are macro-tidal marshes with spring tide ranges of 4·5 to 12·3 m, whose tidal prisms are many orders of magnitude greater than their freshwater inputs (e.g. French and Stoddart, 1992; Knighton, 1992; Shi *et al*., 1995; Allen, 2000b).

This paper analyses historical aerial photos to examine tidal channel evolution in a rapidly prograding river delta where the spring tidal range is about 2·5 m, mean annual river discharge is comparable to tidal prism, and 2-year flood events are several times greater than tidal prism. Preliminary examination of the photos suggested the hypothesis motivating this paper, that many modern blind tidal channels in the Skagit marshes were formed when historical river

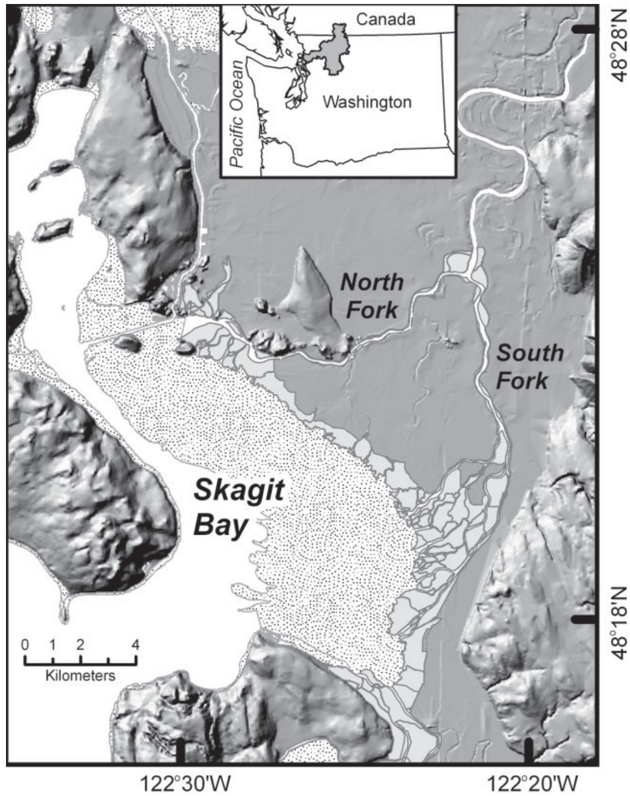

Figure 1. Vicinity map of the Skagit delta. Stippled areas are unvegetated tideflats. Light grey areas landward of the flats are vegetated intertidal wetlands. Dark grey areas are predominantly farmed lowlands. The Skagit River flows from the northeast corner of the figure to the southwest, bifurcating into the North and South Forks. Inset shows the Skagit catchment in grey.

distributaries became blocked in their upper to middle reaches (e.g. by large woody debris (LWD) with subsequent sediment accumulation) so that riverine flow was eliminated and only tidal flow flushed the resulting blind channel. According to this hypothesis most modern blind tidal channels in the Skagit marshes are relict river distributaries. The null hypothesis is that distributary blockage and sedimentation is an uncommon origin of blind tidal channels in the Skagit marshes, and instead, tidal erosion and headward channel growth are the predominant source of modern tidal channels. According to the null hypothesis most modern blind tidal channels should be spatially disjunct from historical river distributaries. The proposed hypothesis contrasts with the well-documented mechanism of tidal channel evolution through head-cutting. In the former case, tidal channels are formed by sedimentation. Sediments are deposited along river flowpaths to form marsh islands separated by river distributaries, and the distributaries are eventually blocked by more sediments to become blind tidal channels. Fluvial processes are important, and blind tidal channel networks are inherited from the antecedent distributary network. In the latter case erosional and marine processes are dominant (Allen, 2000a; Fagherazzi and Sun, 2004). This paper tests the proposed hypothesis using GIS analysis of historical aerial photos, and describes specific examples of blind tidal channel evolution in a rapidly prograding tidal marsh.

Setting

The study areas are the tidal marshes at the mouths of the North and South Forks of the Skagit River (Figure 1). The Skagit is the largest river flowing into Puget Sound (Washington, USA), providing about 34 per cent of the freshwater input to the Sound. The river drains 8544 km^2 of the Cascade Mountains while cutting through valley terraces of Pleistocene glacial and dacitic Holocene lahar sediments (Dragovich *et al*., 2000; Beechie *et al*., 2001). Elevations in the basin range from sea level to 3285 m. Mean annual rainfall ranges from 80 cm in the lowlands to over 460 cm in the mountains.

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Depositional tidal channel development

Most of the modern 308 km^2-Skagit delta was formed about 5500 years BP when Glacier Peak erupted, sending a lahar down the valley which deposited a 3-m-thick layer of debris 35 km upstream of the current mouth of the Skagit River, and an 18-m-thick layer near the current delta shoreline. This moved the historical shoreline of the delta about 12 km to the west and southwest and 9 km to the northwest to its present location (Dragovich *et al*., 2000).

Significant anthropogenic changes in the delta began with Euro-American settlement in the 1860s. By 1890, dykes had been constructed to prevent tidal flooding of most of the delta, while extensive levees were constructed to prevent riverine flooding of the delta. Most of the delta is now bordered by only a narrow fringe of tidal marsh (<0·5 km wide), with significant remnant marsh only near the North and South Fork outlets. Upriver anthropogenic changes include logging, bank hardening, and dam construction on the Skagit River and a tributary, the Baker River. The dams intercept water and sediment flows from about 47 per cent of the Skagit basin. The largest Skagit River tributary, the Sauk River, is still undammed and drains 23 per cent of the Skagit basin.

Sediments in the vegetated marshes are principally organic-rich silt, silty clay and fine sand, while unvegetated tidal flats are fine to medium sand. Tidal marsh vegetation in the delta consists primarily of (in ascending order of elevation) *Scirpus americanus* (American threesquare), *Carex lyngbyei* (sedge), *S. validus* (soft-stem bulrush), *Typha angustifolia* (cattail), *Myrica gale* (sweetgale), *Salix* spp. (willow), *Lonicera involucrata* (black twinberry), *Rosa* spp. (wild rose), and *Picea sitchensis* (Sitka spruce). During high spring tides, the marsh surface is inundated by up to 1·5 m of water. Due to high river discharge, marshes of the North and South Forks are oligohaline even at their most bayward extents. Soil pore water salinity ranges from 1 to 8 psu. The upper limit of tidal influence is at river kilometer 13.

Tidal channels in the delta, particularly blind tidal channels, provide important rearing habitat for juvenile Chinook salmon (*Oncorhynchus tshawytscha*) which are listed under the Endangered Species Act as a threatened species in Puget Sound (US Federal Register, 1999). This habitat is also important to a wide variety of other fish and wildlife, ranging from commercially important invertebrates to marine mammals (Simenstad, 1983).

Methods

GIS analysis

A geographic information system (GIS) was used to compare infrared (2004) and true colour (2000) digital orthophotos, and black and white historical aerial photos (1937, 1956, 1965, 1972 and 1991). The infrared orthophotos had 15-cm pixels and were flown on 30 August 2004 during a low tide of −0·3 m mean lower low water (MLLW). The true colour orthophotos had 45-cm pixels and were flown on 28 August 2000 during a low tide of −0·6 m MLLW. The smallest tidal channels that could be resolved in the 2004 and 2000 photos were 0·3 m and 0·6 m in width, respectively. Historical aerial photos were obtained from Brian Collins (1937: University of Washington, Department of Earth and Space Sciences), the University of Washington Map and Air Photo Library (1956, 1965, 1972), and the Washington Department of Natural Resources (1991). Photos were flown on 22 October 1937 at 1:12 000 scale by the US Army; 23 July 1956 by the Washington Department of Transportation at 1:20 000 scale; 7 May 1965 by Pacific Aerial Survey at 1:60 000 scale; and 2 September 1972 by the US Army Corps of Engineers at 1:24 000 scale. The flight date and scale of the 1991 photos are unknown. The 1956, 1965 and 1972 flights were flown during low tides of approximately −0·3 m MLLW. The 1937 photo was flown during an approximately +1·8 m MLLW low tide, but this tide was sufficient to expose unvegetated intertidal sand flats. All historical photos were converted to digital format by scanning at 600 dpi. The smallest tidal channels that could be resolved were 1 m in width in the 1937, 1956 and 1972 photos; 1·5 m in the 1991 photo; and 1·7 m in the 1965 photo. Additionally, a georeferenced 1889 US Coast and Geodetic T-sheet of the North and South Fork marshes was obtained from the Puget Sound River History Project at the University of Washington. This map was used to identify historic marsh extent and channel distributaries, but the map resolution was too poor to identify blind tidal channels.

A GIS was used to rectify the historical photos relative to the 2000 orthophotos by using reference points visible in both historical and recent photos. Reference points included historically static road intersections, corners of buildings, and occasionally corners of dykes. Additional reference points included prominent jutting angles of rocky shorelines of several large islands in the North Fork marsh (McGlinn, Bald, Ika, and Craft Islands). The rocky shorelines in this area are composed of metamorphosed sandstone and conglomerate rock (Dragovich *et al*., 2002) with erosion rates of approximately 6 mm per year (Keuler, 1978). No reference points were located in marsh or sandflat areas, due to the likely high variability of these areas.

Tidal channel margins and other shorelines were delineated for all photos by manually digitizing in the GIS. Channel margins and shorelines were defined by the abrupt transition from vegetated to unvegetated intertidal areas.

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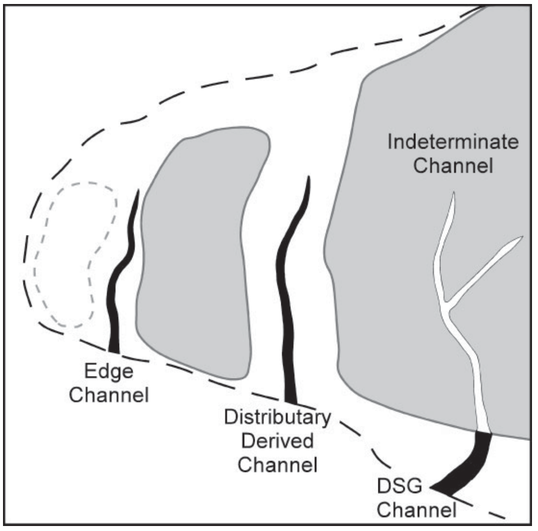

Figure 2. Illustration of channel classification scheme. Grey areas represent marshes visible in a historical photo. The dark dashed line represents the current extent of the prograded marsh. The light dashed line represents a presumptive marsh island that was an intermediate stage in marsh progradation for which photographic evidence is unavailable due to the long time interval between photos. Modern channels (black) were classified as 'distributary-derived' if they are aligned between two historical marsh islands. They were classified as 'edge' channels if they are aligned along one historical marsh island. 'DSG' channels were channel segments formed during marsh progradation from downstream growth or extension of previously established channels. Channels were designated 'indeterminate' (white) if they were not associated with any observed historical marsh islands and if there was no evidence of headward growth over a series of historical photos (tidal erosion).

This transition is sharp because all but the smallest channels (which are not visible in the historical photos) are approximately 1–2·5 m deep with generally steep banks. Additionally, unvegetated sandflats have characteristic photo-signatures in the modern and historical photos. Shoreline and channel delineations were extensively ground-truthed and delineation errors were exceedingly rare for the modern photos. Comparison of relatively static sites between historical and modern photos provided confidence that the grey-scale photo-signatures in the historical photos were being properly interpreted.

Tidal channel location error for the historical photos (which includes rectification error, digitization error, and some channel meandering) was estimated as follows. Digitized channels from the modern and historical photos were displayed simultaneously and those whose planform geometry had changed little over the period of record were selected for sampling. This selection process minimized the influence of channel meandering on the error estimate. Next, the displacement between modern and historical channels was measured at 30 random points on the modern channels. The 1937 and 1965 photos had mean absolute error estimates of 2·6 and 2·5 m, respectively, while the 1956, 1972 and 1991 photos each had mean absolute errors of 1·5 m.

Modern blind tidal channels and channel segments were characterized according to their association with historical landscape features (Figure 2). Channels were classified as arising from marsh erosion if their antecedent was marsh rather than a distributary, and if a sequence of historical photos showed consistent headward channel elaboration. Blind channels associated with the historical distributaries separating marsh islands were classified as 'distributary-derived'. Those aligned with historical marsh island margins were classified as 'edge' channels. Edge channels were hypothesized to form through the same evolutionary process as distributary-derived channels, the difference being that for edge channels the coarse temporal resolution of the photos precluded observation of marsh island development on the opposite bank of the future blind channel. It is possible that some edge channels were only coincidentally associated with historical marsh margins and that in these cases no additional island developed. Instead, continuous marsh progradation was accompanied by tidal erosion of a channel in the new marsh surface. However, many distributary-derived channels were observed in this study, while no eroded channels were observed, suggesting a low probability that edge and distributary-derived channels are genetically distinct. Rather, their distinct classification represents different degrees of confidence that channels originated as hypothesized, i.e. near certainty for distributary-derived channels and relatively high confidence for edge channels. Channel segments formed in the course of marsh progradation by downstream growth (DSG) of previously established channels were classified as DSG channels.

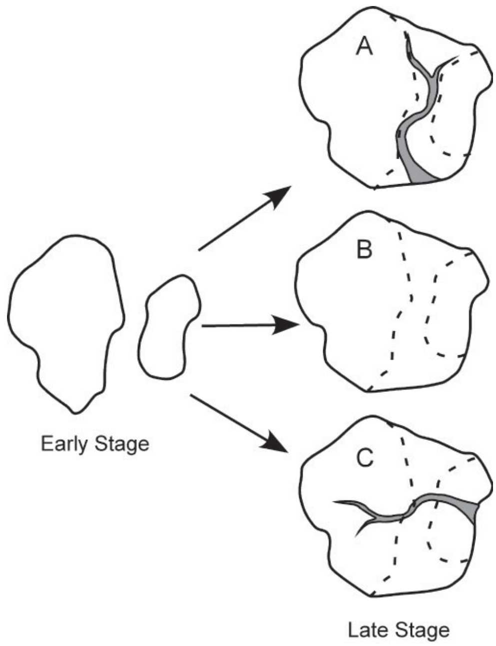

Figure 3. Possible evolutionary trajectories resulting from blockage and sedimentation of a distributary channel between two marsh islands: (A) development of a blind tidal channel aligned with the antecedent distributary channel; (B) complete infilling of the distributary channel; (C) development of a blind channel unaligned with the antecedent distributary channel. If blind tidal channel development in prograding marshes is constrained by antecedent distributaries then pathway A should be frequently observed, pathway B occasionally observed, and pathway C never observed. Under the null hypothesis of no relationship between historical distributaries and modern blind channels, equal frequencies of all three pathways should be observed.

Channel segments that were not clearly of erosive origin, were not associated with any historical landscape feature, and were upstream of all other channel types were classified as 'indeterminate'. The origin of indeterminate channels could include headward erosion or the hypothesized evolution from a distributary. The coarse temporal resolution of the historical photos limited observation of the development of some tidal marsh and channels, while the coarse optical resolution of the historical photos limited detection of small channels. Both limitations contributed to the 'indeterminate' classification. Blind tidal channels present in the 1937 photos were not classified, unless they were associated with an 1889 distributary or marsh edge. The 1889 map showed almost no blind tidal channels. Its utility was limited to depiction of distributary channels and tidal marshes.

Statistical analysis

In a prograding marsh, two marsh islands separated by a distributary channel can continue as two separate islands or merge into one island where the distributary has evolved toward three possible outcomes: (i) a blind tidal channel aligned with the antecedent distributary (Figure 3A); (ii) a completely filled distributary (Figure 3B); and (iii) a filled distributary and an independent blind tidal channel not aligned to the historical distributary (Figure 3C). If the hypothesis that blind modern channels originate from historical distributaries is correct, type A outcomes should be frequently observed, type B occasionally observed, and type C never observed. If the null hypothesis of no relationship between historical distributaries and modern blind channels is true, i.e. an independent erosional origin for blind tidal channels, all outcomes should be observed equally frequently. Chi-squared contingency analysis (Zar, 1999) was used to compare observed outcome frequencies with those expected from the null hypothesis. Outcome frequencies were determined by using GIS to superimpose modern blind channels over historical distributaries and thereby compare channel location, orientation and width. The water body between two marsh islands was identified as a distributary when the distance between two islands was less than the width of the smaller island. Otherwise the water body was considered part of Skagit Bay. Historical distributaries that apparently filled in with marsh were field-checked to confirm that narrow tidal channels covered by vegetation or below the resolution of the modern photos were not overlooked.

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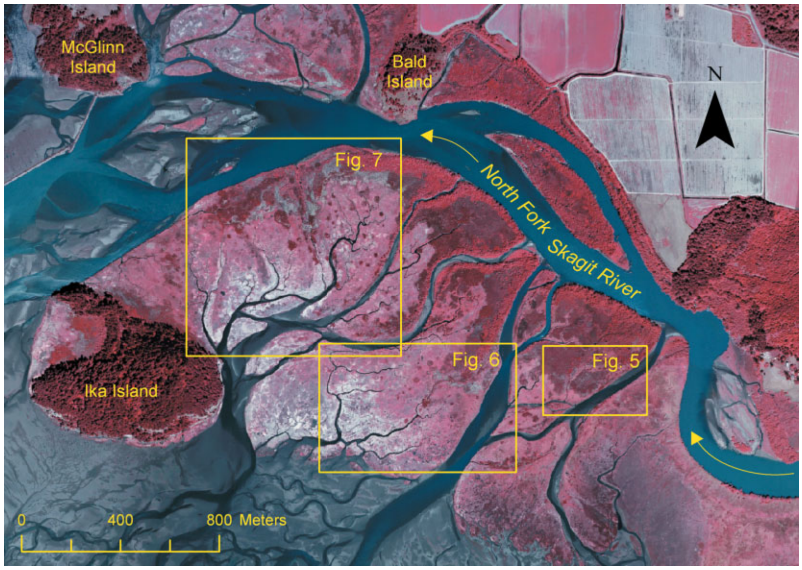

Figure 4. Location map of three North Fork examples of channel evolution that are detailed in Figures 5–7. Farmland bounds the marshes to the northeast. Skagit Bay is to the west and south. Forested areas without channels are hills. Arrows denote river flow direction. The photograph was taken in 2004. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Three-dimensional chi-squared contingency analysis (Zar, 1999) was used to investigate the interdependence of site (North Fork versus South Fork), fate (filled, blind tidal channel or distributary), and photograph year (1889, 1937, 1956, 1965, 1972, 1991) for historical distributaries. This was done to investigate possible temporal patterns in the fates of historical distributaries, e.g. were older distributaries more likely than newer ones to produce marsh-filled areas, and were newer distributaries more likely than older ones to remain distributaries.

The mean width of each classified blind tidal channel or channel segment was calculated by dividing channel surface area by half its perimeter. Perimeter consisted of only the channel margin. It did not include channel outlet widths or the upstream and downstream widths of channel segments. The resulting data were graphically assessed for normality by plotting their cumulative frequency distribution. Data were log-normal, so log-transformed values were used in two-factor ANOVA with SYSTAT 10·2 (Systat Software, Inc., Point Richmond, CA, USA) to test for differences in mean channel width among factors. One factor was site (North Fork versus South Fork). The other was channel origin classification (distributary derived, edge, DSG, indeterminate). Channels clearly arising from marsh erosion were not observed and therefore not included in the analysis. Tukey's HSD test was used for *post hoc* multiple comparisons among all cell means of the factorial ANOVA (Zar, 1999). All statistical tests were deemed significant when $p < 0{\cdot}05$.

Results

Detailed inspection of historical photos showed individual blind tidal channels evolving from river distributary channels. This is illustrated by three representative examples from the North Fork Skagit River tidal marshes (Figure 4). The simplest is shown in Figure 5, where a modern blind tidal channel is superimposed over historical marshes. The modern channel aligns perfectly with a 14-m-wide distributary channel in the 1937 photo, except for the north–south trending headward end of the modern channel which is visible only in the 2000 and 2004 orthophotos. In the 1956 photo, the distributary has narrowed to a mean width of 5 m and the modern channel continues to be aligned with the distributary. By 1972, the distributary has closed at its upstream end and is now a blind channel averaging 2·5 m wide. The 2004 channel is narrower still, averaging 1·0 m wide in that portion of the channel within the footprint of the historical distributary. The north–south trending headward segment of the channel averages 0·7 m wide, below the resolution of the historical photos, so its origin cannot be determined. It may have been present in 1937, or it may have evolved from tidal erosion of the marsh surface since 1937.

Figure 6 shows a more complicated example, where in 1937 the spaces between three marsh islands, α, β and γ, barely suggest the routes of future blind tidal channels. By 1956 island α has prograded substantially towards the

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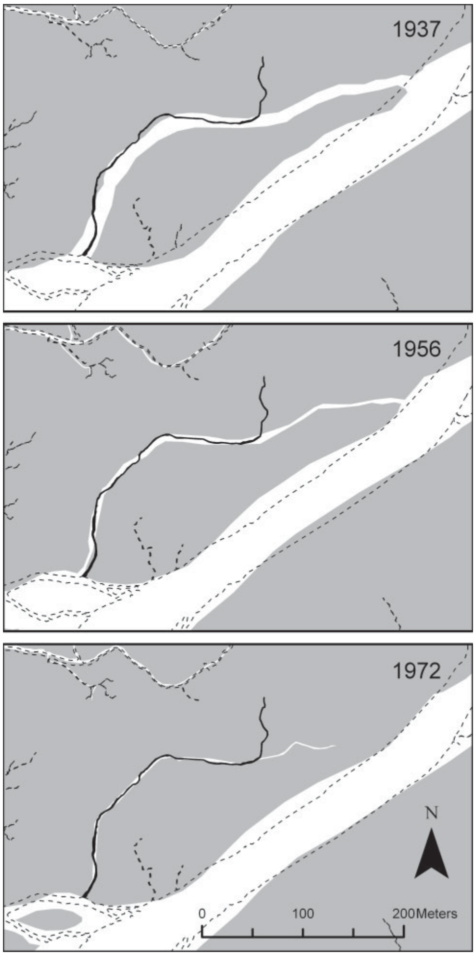

Figure 5. Evolution from a distributary channel in 1937 to a narrower distributary in 1956 to a blind channel by 1972. The 2004 channel (solid black) is superimposed on all figures. Dashed lines are marsh boundaries in 2004.

west. Island β has become part of island γ and the space that formerly separated the two islands is now a blind channel that disappears after 1956. The space between islands α and γ is now a distinct 33 m-wide distributary aligned with the upper half of the modern blind channel C. Additionally, several new marsh islands appear in the 1956 photo and the spaces between them presage the modern blind tidal channels. Most of the mainstem of modern channel A is aligned with the space between islands α and θ. The upper portion of modern channel D is aligned with the space between islands γ and δ, while the lower portion is aligned with the space between islands δ and ε. A small 0·8-m-wide branch of channel D aligns with an 11-m-wide space between islands γ and ε, while another 0·8-m-wide branch is aligned with the approximately 5-m-wide space between δ and ι. Portions of channel B and a branch of channel C align with the edges of islands θ and η, respectively. By 1965 islands θ and η have become incorporated into island α, and islands δ, ε and ι have coalesced into island γ. The distributary between islands α and γ has elongated, narrowed to a mean width of 28 m, and now contains most of the future mainstem of channel C. The upper portion of channel B and much of the lowest tributary to channel C are aligned with the edge of island α at this time. By 1972 the distributary between islands α and γ has narrowed to a mean width of 14 m. Island κ has formed on the southern edge of island α, giving rise to a 3-m-wide distributary which is the precursor to 1·1-m-wide channel B and a 1·0-m-wide portion the lowest tributary to channel C. By 1991 (not shown) this distributary is blocked in the middle, resulting in the two modern blind channels. The association of channel B and the lowest tributary to channel C with the margin of marsh island α in 1965, followed in 1972 by development of κ island and the resulting distributary between islands α and κ, suggests many modern blind tidal channels associated with historic island margins but missing photographic evidence of intermediate stages of

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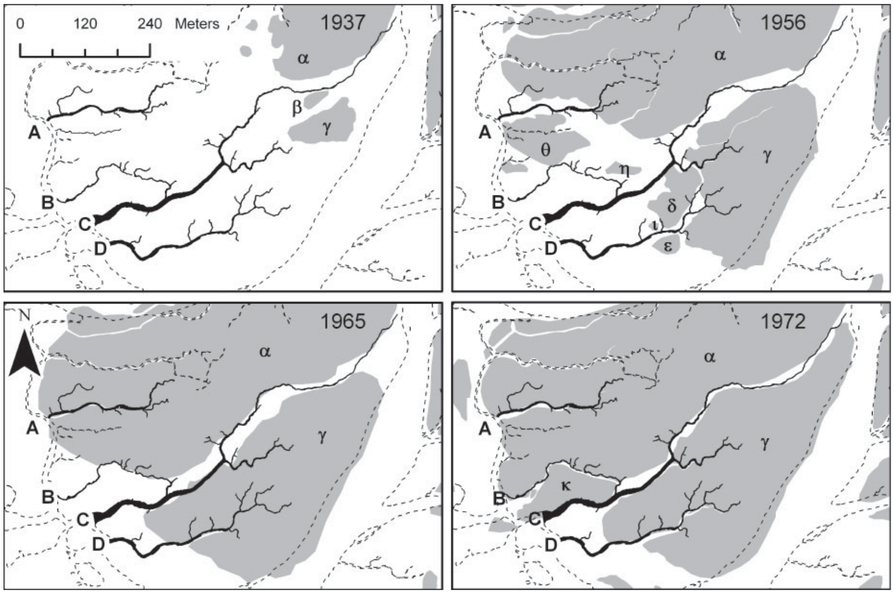

Figure 6. Marsh progradation from 1937 to 1972 with associated evolution of distributaries into blind tidal channels. Year 2004 channels (solid black and labelled with Roman letters) are superimposed on all figures and are the focus of discussion. Dashed lines represent other 2004 marsh boundaries. Marsh islands are labelled with Greek letters.

additional island/distributary development, such as that provided in this case by the 1972 photo, are nevertheless distributary-derived channels.

Figure 7 shows another complicated example of blind channel evolution from distributaries. Many new marsh islands developed in this area from 1937 to 1956, along with distributary channels ranging from 5 m to 84 m mean width. In later photos the distributaries narrow and become blocked, forming modern blind channels. Throughout the photo series, modern blind channels C, D, E, H, and portions of F are aligned with historic distributaries. Modern channels A, B, G, I, and portions of F are associated with island margins, suggesting that intervening stages of island development near these margins occurred between the dates of the available historical photos. Such development was evident in the previous example with κ island. It is also evident in this example for the upper portion of channel C, which is associated with a marsh edge in the 1937 photo and clearly associated with a distributary by 1956.

Finally, Figure 8 shows a representative example from the South Fork tidal marshes. Modern channel A aligns with the 1889 edge of island α, but by 1937 island ι flanks the other side of the channel, revealing that a 20-m-wide distributary was the channel antecedent. The distributary narrows to 6 m by 1956 and then closes upstream in 1972 (not shown). The remaining modern channel averages 0·9 m wide. The much longer and wider modern channel B aligns with a long 1889 distributary between islands α and β, which closes upstream by 1937. Additionally, by 1937 island κ has developed near the now conglomerated islands α–δ to form a separate distributary that anticipates the downstream portion of channel B. Modern channel C aligns perfectly with narrow 1889 distributaries between islands β and γ, and between δ and both β and γ. Channel D aligns with the 1889 edge of island γ. Channel E, which currently averages 1·0 m wide, aligns with a 40-m-wide 1889 distributary between islands ε and ζ. This distributary narrows to 2·5 m by 1937 and closes upstream by 1956. The upstream portion of channel F aligns with the 1889 edge of island θ, while the downstream portion aligns with a narrow 1937 distributary between islands η and θ. Channel G aligns with a narrow 1937 distributary between islands λ and η; the middle portion of channel H aligns with the 1889 edge of island η; the upper tip of channel I aligns with the 1889 edge of island η, while most of the rest of the channel aligns with the 1956 edge of the island; and channel J aligns with the 1889 edge of island η. Finally, the upper third of channel K aligns with the 1889 edge of island θ, while the lower two-thirds of the channel align with an 1889 distributary between islands η and θ that ranges in width from 30 m upstream to 110 m downstream. By 1937 island η has extended upstream so that all of channel K is aligned with the distributary which has narrowed to 5 m. The modern blind channel now averages 4 m wide.

In the North Fork, aerial photo interpretation indicated that 46 historical distributaries evolved into spatially coincident blind tidal channels; no historical distributaries were found with misaligned modern tidal channels; and 19

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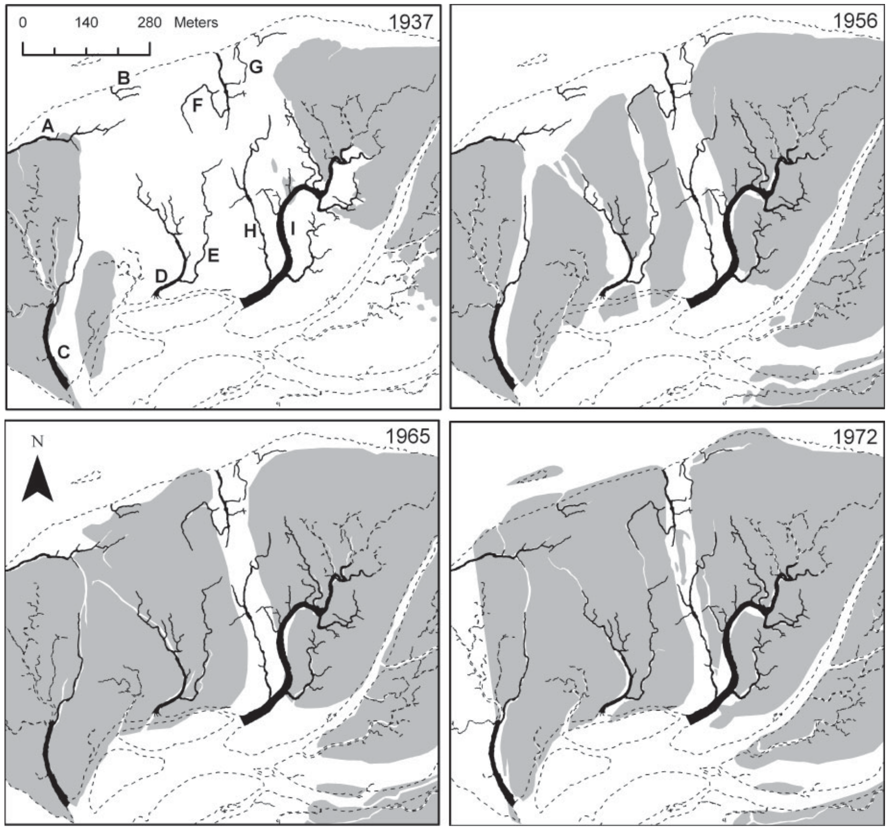

Figure 7. Marsh progradation from 1937 to 1972 with associated evolution of distributaries into blind tidal channels. Year 2004 channels (solid black) that are the focus of discussion are superimposed on all figures. Dashed lines represent other 2004 marsh boundaries. The straight border on the western edge of the 1972 marsh marks the limit of photo coverage for that year.

historical distributaries evolved into marsh rather than tidal channels. When the 19 apparently marsh-filled distributaries were groundtruthed, five were found to actually consist of very narrow blind channels that were indistinct in the photos. The remaining 14 former distributaries were truly marsh-filled, in some cases by shallow swales filled with low-elevation marsh vegetation. In the South Fork, 58 historical distributaries evolved into blind tidal channels (including four that required ground-truthing for accurate classification), none were found with misaligned modern channels, and 13 evolved into marsh.

If tidal channel evolution were unrelated to historical distributaries, one would expect 21·7 of the 65 former North Fork and 23·7 of the 71 former South Fork distributaries to be associated with each of three possible outcomes: blind channel coincident with the former distributary, marsh-filled distributary, and blind channel misaligned with the former distributary. Chi-squared analysis indicated that the observed associations were not random for the North Fork ($\chi^2 = 64{\cdot}1$, d.f. $= 2$, $p < 0{\cdot}0001$) or the South Fork ($\chi^2 = 78{\cdot}4$, d.f. $= 2$, $p < 0{\cdot}0001$), i.e. modern blind tidal channels are associated with historical distributaries in both areas. Additionally, the observed relationships agree with the expectation of many distributary-aligned blind channels, few marsh-filled former distributaries, and no misaligned channels.

Three-dimensional contingency analysis indicated that the hypothesis of mutual independence between site, distributary fate, and year should be rejected ($p < 0{\cdot}001$). Subsequent tests of partial independence (at $\alpha = 0{\cdot}01$, to account for multiple tests and to achieve a group α of 0·05) indicated that site and photo year had no bearing on distributary fate. A follow-up two-dimensional contingency test indicated significant interaction between site and year ($p < 0{\cdot}001$). Examination of observed versus expected values indicated that distributaries in 1889 and 1937 were less common than expected in the North Fork and more common than expected in the South Fork. The reverse was true in 1956, 1972 and 1991: distributaries were more common than expected in the North Fork and less common in the South Fork. Distributaries in 1965 were as common as expected at both sites.

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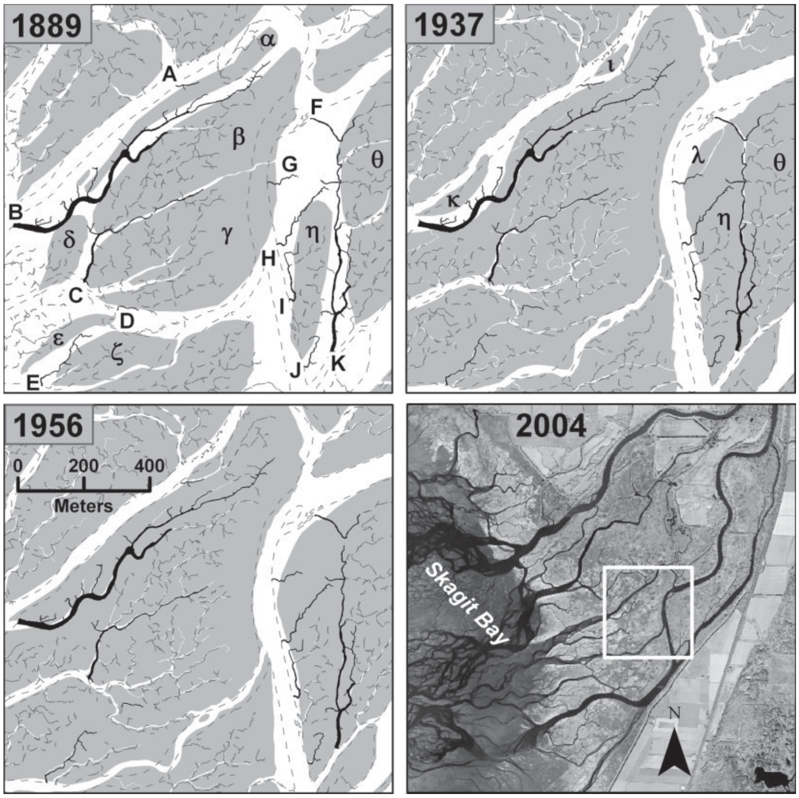

Figure 8. Marsh progradation from 1889 to 1956 with associated evolution of distributaries into blind tidal channels. Year 2004 channels (solid black and labelled with Roman letters) are superimposed on the historical marshes and are the focus of discussion. Superimposed dashed lines represent other 2004 marsh boundaries. Marsh islands are labelled with Greek letters. The lower right frame depicts the modern South Fork Skagit River tidal marshes and the location of the 1889, 1937 and 1956 frames.

Table I. Percentage distribution of modern blind tidal channels in the North and South Fork Skagit marshes according to their likely origin

	Distributary	Marsh margin	Downstream growth	Indeterminate
By channel length				
North Fork	23·0	13·8	9·3	53·9
South Fork	11·5	9·2	5·2	74·1
By channel surface area				
North Fork	36·9	16·6	18·0	28·4
South Fork	24·1	9·2	15·0	51·7

Distributary, historical distributary was antecedent to the modern blind channel; *Marsh margin*, modern channel associated with historical marsh margin; *Downstream growth*, downstream channel elaboration during marsh progradation; *Indeterminate*, origin could not be resolved.

The origins of most blind tidal channels in the North and South Fork marshes could not be determined due to limited optical and chronological resolution of the historical photos. Of the remainder, those evolving from distributaries were the most abundant as measured by both channel length and surface area, followed by channels associated with historical marsh margins and those resulting from downstream channel growth during marsh progradation (Table I). There was no clear evidence of any tidal channels arising from headward erosion.

ANOVA revealed significant differences in mean channel segment width depending on channel origin (distributary, marsh edge, DSG, indeterminate) and site (North Fork marshes versus South Fork marshes), with no significant interaction between these two factors (Table II). *Post hoc* tests indicated that all channel types differed significantly

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Table II. ANOVA summary for effect of channel origin (historical distributary, historical marsh margin, downstream growth and indeterminate) and site (North Fork versus South Fork) on mean channel width

Source	Sum of squares	d.f.	F	p
Origin	20·783	3	113·578	<0·0001
Site	1·848	1	30·303	<0·0001
Interaction	0·427	3	2·335	NS
Error	116·438	1909		

from each other in mean width ($p < 0{\cdot}001$ for all pairwise comparisons, except one for which $p < 0{\cdot}05$). Distributary-derived blind tidal channels were the largest with mean widths of 1·3 m in the North Fork and 1·1 m in the South Fork. The next largest were DSG channels with mean widths of 1·4 m in the North Fork and 0·9 m in the South Fork, followed by marsh margin channels with mean widths of 0·9 m in the North Fork and 0·7 m in the South Fork. Channels of indeterminate origin were the smallest with mean widths of 0·6 m in the North Fork and 0·5 m in the South Fork, well below the resolution of the historical photos (1–1·7 m). North Fork tidal channels were on average 22 per cent wider than South Fork channels across all channel types. The cause of this size difference is unclear. In both the North Fork and South Fork marshes, the smallest observed distributary-derived modern blind tidal channels had mean widths of 0·3 m, at the resolution limit of the modern orthophotos. Thus, channel evolution from distributaries can account for the origin of very small tidal channels.

Comparison of historical and modern photos indicated that unvegetated intertidal sandflats at the mouths of the North and South Forks have been consistently characterized by a multitude of shallow, anastomosing, distributary channels since 1937. These channels have been very dynamic, moving many channel widths or disappearing entirely in as few as four years. Even the largest sandflat distributaries (>100 m wide) have sometimes moved one channel width within a decade. Distributaries became relatively stable once vegetation colonized their banks. In contrast, blind tidal channels were rare in the sandflats. The few that could be found were probably momentary remnants of abandoned sandflat distributaries. There was no correlation between historical sandflat distributaries and modern, marsh-draining blind tidal channels. All of this suggests that modern tidal channels in the Skagit marshes were not inherited from preexisting dynamic sandflat channels, rather they evolved from relatively stable, marsh-bordered river distributaries.

Discussion

GIS analysis of modern and historical aerial photos reveals clear associations between blind tidal channels in the modern Skagit marshes and historical tidal marsh features and river distributaries. These associations suggest that depositional, rather than erosional, processes were responsible for blind tidal channel evolution in this system. As sediment accumulated at the river mouths, vegetation colonization created marsh islands that splintered the river into distributaries. The marsh islands eventually coalesced when the distributary channels gradually narrowed until they finally closed at the upstream end to form a blind tidal channel, or in mid-channel to form two blind tidal channels. Distributary abandonment can be caused by loss of gradient advantage, catastrophic infilling during floods or storms, upstream changes in channel morphology, and log jams (Coleman and Prior, 1982). Many tidal channels in the Skagit marshes have significant accumulations of LWD (Figure 9), which suggests this may be a common cause of distributary channel closure. Some historical distributary channels are now blind tidal channels visibly choked with LWD for more than 100 m of their length. In most channels such LWD accumulations are probably no longer visible due to their burial by accreting sediments, and marsh vegetation development on the soil surface. Additionally, marsh progradation (evident in the historical photos) elongates distributaries and thereby diminishes channel gradient and stream power. This causes channel infilling and narrowing and can close a distributary even without LWD blockage.

Once a channel is obstructed and isolated from distributary flow, only tidal flow remains and channel persistence becomes a function of tidal prism and tidal or wind/wave erosion (Friedrichs and Perry, 2001; Williams *et al.*, 2002). The observation that some historic distributary and blind tidal channels are now completely filled by marsh shows that blind channels do not always persist after distributary abandonment. Insufficient tidal prism and competition between channels for drainage probably causes tidally transported sediments to accumulate and fill the channels (Hood, 2004).

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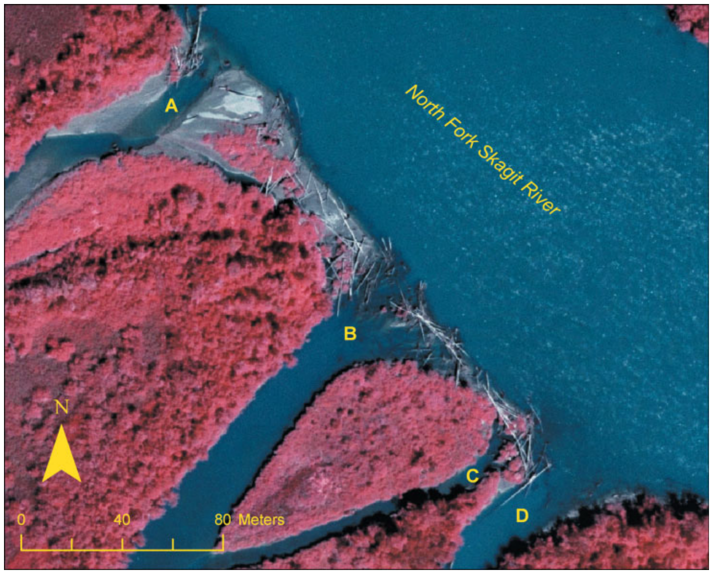

Figure 9. Large woody debris (LWD) accumulations block or partially block the inlets of four tidal distributaries (A–D) of the North Fork Skagit River in 2004. A portion of the river appears in the upper right corner of the photo; the river is flowing from lower right to upper left and the distributaries are nearly perpendicular to the river. LWD completely spans inlet C and approximately 60 per cent of inlet B. Sediments blocking inlet A include partially buried LWD. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Channel origination and persistence are variations of a single process in erosional systems (Allen, 2000a), but they are two different processes in depositional systems like the prograding Skagit delta.

Coleman and Prior (1982) observed that distributary abandonment is often 'an accident'. This suggests that older distributaries are more likely to be abandoned than younger ones, because over time a distributary is increasingly likely to have experienced a random channel obstructing event. However, contingency analysis indicated distributary fate was independent of year, contradicting this reasoning. Over the short time scale of this study (*c*. 100 years) factors other than distributary age may more strongly affect distributary fate. From first principles it follows that distributary fate depends on sediment transport through a channel, which depends on channel flow. Flow depends on the spatial pattern of, and interaction between, distributary network geometry, distributary channel geometries (e.g. width, depth, sinuosity), channel gradients and marsh progradation. All of these factors in turn are likely to affect the probability that random events (e.g. flood inputs of LWD or sediment) may lead to channel obstruction, evidently to a greater degree than does distributary age.

Contingency testing indicated that 1889 and 1937 distributaries were less common than expected in the North Fork and more common than expected in the South Fork, while the reverse was true in 1956, 1972 and 1991. This pattern is consistent with recent Skagit River history. The South Fork was an important navigation channel in the 19th century, but it began to shoal around 1896 and freight boats began to use the North Fork instead. Federal engineers attempted to reverse this process in 1910 by placing a sill at the head of the North Fork to divert water to the South Fork. In 1919 they dredged a bar at the head of the South Fork to encourage flow to the South Fork. Efforts to control natural flow partitioning between the North and South Forks were abandoned by 1928 (ARCE, 1928). With river flow and associated sediment delivery finally switching dominance from the South Fork to the North Fork by the 1920s, marsh progradation began to accelerate in the North Fork and to decelerate in the South Fork. Areas of accelerated marsh progradation would have a higher frequency of new distributaries separating new marsh islands compared to areas of decelerating progradation.

Distributary abandonment has probably created most blind tidal channels in the Skagit marshes, including some as small as 0·3 m mean width. Admittedly, the origin of half the blind tidal channels in the system could not be determined, either because their small size was below the resolution of the historical photos, or because the photos were spaced too far apart in time to completely follow marsh and channel development. Thus, an erosional origin for these channels cannot be completely ruled out. However, when these unobservable channels are excluded, those remaining originate largely through the process of marsh island growth coupled with distributary channel narrowing and blockage. This suggests most of the unobservable channels have also originated from depositional rather than erosional processes.

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Depositional tidal channel development

Depositional tidal channel development may have several implications. From a practical perspective, tidal habitat restoration projects generally assume an erosional model of channel development (e.g. Allen, 1997; Zeff, 1999; Williams *et al*., 2002). However, under circumstances of high sediment availability and marsh progradation, depositional channel development may prevail instead. Delta splay restoration projects in the Mississippi delta are one such example (Letter and Nail, 1997; Boyer *et al*., 1997). Another might be dam removal projects such as the one planned for the Elwha River, Washington (Wunderlich *et al*., 1994). Two dams on the Elwha River have reduced river sediment flux to the coast by 98 per cent since their construction in 1912 and 1926, and it has been estimated that dam removal to restore Chinook salmon habitat will release 14 million cubic metres of sediment downstream, much of which will be deposited in the river delta (Randle *et al*., 1996). If this new sediment flux results in significant delta progradation it could create new river distributaries and blind tidal channels in a manner similar to that described for the Skagit system. The current sediment-starved condition of the Elwha delta, where only a single river channel exists, could be restored to a condition comparable to that shown in the 1872 General Land Office Survey of the delta, where four major river distributaries are mapped.

From a more general perspective, depositional channel evolution means distributaries and blind tidal channels are related phenomena. In the Skagit delta, distributaries evolve into blind tidal channels and blind tidal channels can revert to distributaries, although analysis of historical aerial photos indicates that the former is more common than the latter. Blind channel reversion to distributary form involves lateral migration of a large distributary with accompanying marsh erosion at the head of an adjacent blind tidal channel (personal observations). Thus, the two types of channels are part of one system of water and sediment dispersal. Examination of large-scale channel network geometry in sediment-rich systems should therefore treat distributaries and blind tidal channels as part of a continuum of channel form and not as entirely distinct elements of the system.

Depositional channel development in the Skagit contrasts with more commonly described erosional development (Zeff, 1988; French and Stoddart, 1992; Knighton, 1992; Shi *et al*., 1995; Allen, 2000a, b). Erosional channel development has been described where waves and tides are dominant physical forces and where riverine energy is negligible. In contrast, the Skagit River has a high gradient, high discharge relative to tidal prism, significant sediment load, and extensive river levees that since their construction in the late 19th century have reduced floodplain storage and increased sediment transport to the North and South Fork outlets (Collins and Montgomery, 2001). Furthermore, Skagit Bay is relatively sheltered and shallow (mostly intertidal sandflat) and these conditions favour depositional processes. Depositional distributary development through crevasse splays has been described in the Mississippi delta (Coleman, 1988), but the resolution of these studies has been too coarse to describe a similar process for blind tidal channels. Redfield (1972) described depositional tidal channel development in a prograding coastal New England marsh sheltered by a 9-km-long sand spit: 'As [broad sounds] gradually shoaled they were invaded by marsh and thus narrowed to form the creeks which now drain the high marsh'. Sediment inputs to this system were of coastal origin, which indicates that depositional channel development is not limited to river deltas.

Estuaries are perhaps the most varied and complicated of all coastal ecosystems, and this is reflected in the diverse classification schemes that attempt to organize our understanding of their form, function, and genesis (Perillo, 1995; Eisma, 1998, pp. 319–320; Jay *et al*., 2000). A number of physical processes have been linked to estuarine form and function, and used as a basis for classification schemes. Chief among these are the relative dominance and character of river discharge, tidal energy, wave energy, sediment supply, tectonics, topographic relief and climate (e.g. Dalrymple *et al*., 1992; Perillo, 1995; Eisma, 1988, p. 319). Tidal channels are a common and important feature in nearly all types of estuarine systems, yet there is no comparable diversity in the conceptual models of tidal channel formation. The dominant paradigm for tidal channel formation is a tidal analogue to terrestrial channel development. Ebbing tide waters are concentrated by topographic irregularities in tidal flats, which leads to channel erosion (Eisma, 1998, p. 327; Fagherazzi and Sun, 2004). As the tideflats aggrade, vegetation colonizes the flats and stabilizes the tidal channels so that sandflat tidal channels are inherited by the aggraded marsh (Garofalo, 1980; Eisma, 1998, pp. 327–328; Marani *et al*., 2003). Further tidal channel development occurs as headward erosion and elongation caused by tidal energy (Knighton, 1992; Shi *et al*., 1995). A less prominent model is that vegetation colonization of the tideflats occurs first and produces hummocks that direct and concentrate ebb tide flow; as the marsh aggrades the incipient channels deepen (Yapp *et al*., 1917). Recently, two additional models of tidal channel development have been suggested. One describes channel origination from wind/wave erosion and elongation of salt pans in the marsh surface (Perillo and Iribarne, 2003). The other links channel initiation to groundwater drainage mediated by crab burrowing activity, sometimes enhanced by physical disturbance associated with fish predation on the crabs (Perillo *et al*., 2005). This paper proposes a fifth model of tidal channel development in a rapidly prograding delta dominated by river discharge. The dominant paradigm and the Yapp model are associated primarily with tidal erosion, the salt pan model is associated with wind/wave erosion, and the model proposed in this paper is associated with predominant riverine processes. At least superficially, there is a resemblance to the Dalrymple ternary estuarine classification scheme based

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on the relative influences of river, tide and wind/wave energy on estuarine geomorphology (Dalrymple *et al*., 1992). The crab/groundwater model, because it is not purely physical in nature, is an exception to this scheme. Too few studies of tidal channel development and too many divergent estuarine classification schemes exist to confidently infer a strong relationship between estuarine classification schemes and tidal channel formation models. However, it is possible that the physical processes (tides, waves, river discharge, sediment supply and character, tectonics, topographic relief, etc.) that are differentially responsible for diverse large-scale forms of estuaries may also be differentially involved in forming common smaller-scale components of estuaries, like tidal channels.

Two questions arise from the work presented here. First, how widespread is depositional blind tidal channel development – is it more common than has been previously recognized? Second, what circumstances favour depositional over erosional blind channel development? While this paper has suggested some factors that might distinguish these two processes, further depositional examples are needed to better contrast depositional and erosional channel development.

Conclusions

In contrast with more commonly described models of blind tidal channel origin and development through tidal and wind/wave erosion, blind tidal channel formation in the Skagit delta is primarily depositional. Sediment deposited at the river mouth forms intertidal sandbars that grow in size until vegetation colonization can occur and convert the sandbars into islands of tidal marsh. At this point the islands splinter the river into distributary channels. As the islands continue to grow, some of the distributaries between them fill with sediment and narrow until channel blockage occurs (usually at the upstream end of the distributary, but sometimes near the midpoint of the distributary) and the distributaries are transformed into blind tidal channels. Channels as little as 0·3 m wide can arise from distributary channel abandonment, so one should not assume that very small tidal channels are formed only by headward erosion. Distributary blockage is probably often mediated through LWD accumulations. Which distributaries become blind tidal channels and which remain distributaries is likely to be a function of distributary network geometry and associated spatially variable dynamics of marsh progradation, channel geometry and channel gradient. In the Skagit delta marshes, blind tidal channels are inherited from antecedent distributaries. This suggests that in this and similar systems the network geometry of blind tidal channels is an expression of the more fundamental network and hydraulic geometry of the river distributaries. The conceptual model of blind tidal channel evolution presented here may be applicable to river restoration projects that involve dam removal and the resulting release of accumulated sediments to the river delta.

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