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Indirect Environmental Effects of Dikes on Estuarine Tidal Channels: Thinking Outside of the Dike for Habitat Restoration and Monitoring

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ABSTRACT: While the most obvious effects of dike construction and marsh conversion are those affecting the converted land (direct or intended effects), less immediately apparent effects also occur seaward of dikes (indirect or unintended effects). I analyzed historical photos of the Skagit River delta marshes (Washington, U.S.) and compared changes in estuarine marsh and tidal channel surface area from 1956–2000 in the Wiley Slough area of the South Fork Skagit delta, and from 1937–2000 in the North Fork delta. Dike construction in the late 1950s caused the loss of 80 ha of estuarine marsh and 6.7 ha of tidal channel landward of the Wiley Slough dikes. A greater amount of tidal channel surface area, 9.6 ha, was lost seaward of the dikes. Similar losses were observed for two smaller North Fork tidal channel systems. Tidal channels far from dikes did not show comparable changes in channel surface area. These results are consistent with hydraulic geometry theory, which predicts that diking reduces tidal flushing in the undiked channel remnants and this results in sedimentation. Dikes may have significant seaward effects on plants and animals associated with tidal channel habitat. Another likely indirect dike effect is decreased sinuosity in a distributary channel of the South Fork Skagit River adjacent to and downstream of the Wiley Slough dikes, compared to distributary channels upstream or distant from the dikes. Loss of floodplain area to diking and marsh conversion prevents flood energy dissipation over the marsh surface. The distributary channel has responded to greater flood energy by increasing mean channel width and decreasing sinuosity. Restoration of diked areas should consider historic habitat loss seaward of dikes, as well as possible benefits to these areas from dike breaching or removal. Habitat restoration by breaching or removal of dikes should be monitored in areas directly affected by dikes, areas indirectly affected, and distinct reference areas.

Introduction

Diking of estuarine wetlands and tidal channels to reduce or eliminate tidal influence has been an extensive practice throughout the United States (Roman et al. 1984; Niering 1997). Conversion of areas landward of dikes to agricultural or other uses results in significant habitat loss for plants and animals dependent on estuarine tidal channels and wetlands. This realization has spurred increasing interest in restoring these ecologically valuable areas (Raposa and Roman 2001; Warren et al. 2002). Planning and design for habitat restoration and subsequent monitoring require understanding the many varied effects of dikes on estuarine wetlands. An extensive literature considers how dikes affect sediment accretion, soil density, soil organic content, and marsh surface subsidence (Thom 1992; Bryant and Chabreck 1998; Anisfeld et al. 1999; Portnoy 1999); biogeochemistry and water chemistry (Soukup and Portnoy 1986; Portnoy 1991; Portnoy and Giblin 1997); the abundance, productivity, and distribution of vegetation (Barrett and Niering 1993; St. Omer 1994; Brockmeyer et al. 1997), benthic invertebrates (Wenner and Beatty 1988; Peck et al. 1994; Brockmeyer et al. 1997), and nekton—especially fish (Brockmeyer et al. 1997; Raposa and Roman 2001; Swamy et al. 2002); and fish diets (Allen et al. 1994).

Studies of diked wetlands generally consider only ecological effects for areas landward of dikes, which I refer to as direct dike effects to reflect the intent of dike construction to change the ecological character of landward areas. Habitat restoration generally focuses on areas landward of breached or removed dikes. Little attention has been focused on possible dike effects on areas seaward of dikes (cf., Renger and Partenscky 1974), which I refer to as indirect dike effects. The distinction between direct and indirect dike effects reflects not only the intention of the dike builders, but also a hierarchy of process; dikes indirectly affect sediment dynamics and channel geomorphology in seaward areas as a consequence of tidal prism loss that results from the dikes directly excluding tidal waters in landward areas. This paper describes several examples of indirect dike effects and discusses how consideration of indirect effects of dikes affects planning for habitat restoration and monitoring.

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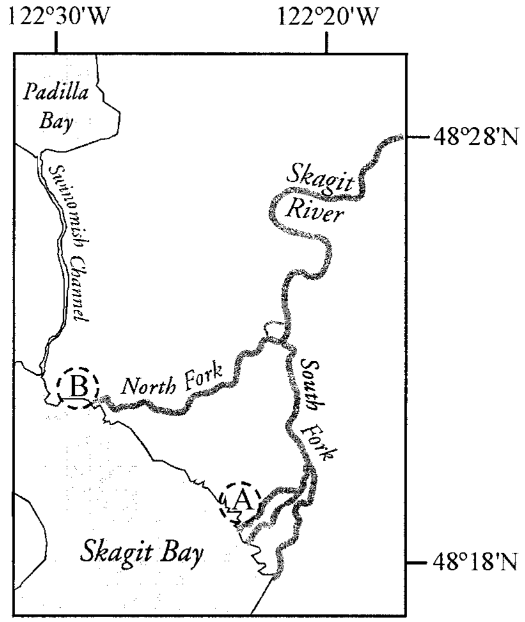

Fig. 1. Study site locations of Wiley Slough (A) and two smaller North Fork sloughs (B).

Methods

Site Description

The study areas are located in the estuarine marshes of the Skagit River delta (Fig. 1). The Skagit is the largest river flowing into the Puget Sound, Washington. Its 8,030-km^2 watershed drains the Cascade Mountains of northwestern Washington State and southwestern British Columbia and supports relatively large runs of anadromous salmonids, including five species of Pacific salmon (*Oncorhynchus* spp.) as well as steelhead (*O. mykiss*), cutthroat trout (*O. clarki*), and native char (Dolly Varden [*Salvelinus malma*] and bull trout [*S. confluentus*]). Puget Sound chinook salmon (*O. tshawytscha*) spend significant time rearing in estuarine habitat (Healey 1982; Simenstad et al. 1982), and were listed as threatened under the Endangered Species Act (U.S. Federal Register 1999). This has generated considerable interest in the region in restoring estuarine habitat for juvenile chinook.

The Skagit delta is approximately 32,670 ha in extent. More than 90% of the delta has been isolated from riverine and tidal influence by dikes and converted to agriculture and other uses (Collins and Montgomery 2001). The remaining undiked wetlands are located at the outlet of the South Fork of the Skagit River (48°19′N, 122°22′W), and to a lesser extent at the outlet of the North Fork (48°22′N, 122°29′W). Marsh vegetation (from low to high elevation) consists primarily of *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 higher high spring tides, the marsh surface is inundated by up to 1.5 m of water. Due to high river discharge, the marsh is oligohaline, even at its most bayward extent. Soil porewater salinity ranges from 1–8 psu (Hood unpublished data). The upper limit of tidal influence is at river kilometer 13.

Three areas were the focus of investigation: Wiley Slough in the South Fork delta and two smaller tidal channel systems, NF1 and NF2, in the North Fork delta. Between 1956 and 1965 Wiley Slough was interrupted by a dike, as were NF1 and NF2 between 1937 and 1947. The channel segments remaining outside of the dikes (remnant channels) were analyzed for changes in planform geometry from their pre-dike condition to 2000 due to sedimentation or erosion. Changes in tidal channel surface area are of particular interest in this system because tidal channels are critical habitat for ESA-listed chinook salmon (Simenstad et al. 2000) as well as other fish and wildlife (Simenstad 1984).

GIS Analysis

A Geographic Information System (GIS) was used to compare historical aerial photographs with modern digital true color orthophotos (45-cm pixel resolution) obtained from Triathlon Ltd. (Vancouver, BC). The modern photographs were taken on August 28, 2000, 10:50–11:10 Pacific Daylight Time, during a low tide of −0.6 m below mean lower low water. The smallest tidal channels that could be resolved in the 2000 photos were 0.6 m in width. Historical aerial photos of the South Fork Skagit River tidal marshes were obtained from the University of Washington (Seattle) Map and Air Photo Library. These were black and white photos at 1:20,000 scale, taken July 23, 1956, by the Washington Department of Transportation. They were converted to digital format by scanning at 600 dpi. The smallest tidal channels that could be resolved in the 1956 photos were 1 m in width. Historical photos of the North Fork tidal marshes were obtained in digital format from the U.S. Army Corps of Engineers (Seattle, Washington). They were taken on October 22, 1937, at 1:12,000 scale by the U.S. Army. The smallest tidal channels that could be resolved in the 1937 photographs were 1 m in width.

The Image Analyst Extension for ArcView 3.2a was used to rectify the historical photos relative to the 2000 orthophotos by using spatially dispersed reference points visible in both historical and recent photos, including road intersections, railroad and road crossings, corners of buildings, and occasionally corners of dikes. Potential reference points that were rejected included poorly defined road intersections in the case of unpaved roads, intersections that may have been altered by road widening or other improvements, buildings that were modified by additions or other construction, and modified or repaired dikes. No reference points were located in marsh or sandflat areas, due to the likely high variability of these areas. Because most of the upland areas in the study area were agricultural, only seven reliable and spatially distributed reference points were available for the two 1956 photographs. Rectification error was estimated by comparing a second set of nine check points between the 1956 and 2000 photographs. These points were rejected as reference points due to relative proximity to other reference points or to less than complete certainty about precisely locating them in both sets of photos. The nine check points had an average discrepancy between 1956 and 2000 of 2.5 m (SE, 0.7 m).

No reliable reference points were available for the 1937 photos, except for those centered over the town of LaConner. The 1937 LaConner photographs were first rectified relative to the 2000 orthophotos and then adjacent and overlapping 1937 photographs were rectified with reference to the 1937 LaConner photos; overlap was extensive between photographs. Supplementary reference points were encountered on prominent jutting angles of rocky shorelines of several large rocky islands in the North Fork marsh (McGlinn, Bald, Ika, and Craft Islands). The rocky shorelines in this area are composed of metasedimentary (metamorphosed sandstone and conglomerate) rock (Dragovich et al. 2002) with erosion rates of approximately 6 mm yr^{-1} (Keuler 1979).

The process of sequentially rectifying the 1937 photographs propagated errors, although this was reduced through the use of reference points on the rocky island shorelines. Rectification error was qualitatively evaluated by visually inspecting the alignment of rocky shorelines. Because there were many overlapping photographs from 1937, those with the least alignment errors were used. After digitizing tidal channels and shorelines, total rectification error was quantified using GIS to compare the distances between rocky shorelines digitized from the 1937 and 2000 photographs. Distance was measured from random points on the 2000 shoreline to the nearest point on the 1937 shoreline. The average measured distance for 53 random points was 4.9 m (SE = 0.5 m).

Additional photos from 1947 for the North Fork area and 1965 for the South Fork area were not analyzed with GIS, but were examined qualitatively for the presence of dikes and conversion of marsh to agriculture. These photos were used to bracket the time period during which dikes disrupting tidal channels were constructed.

Tidal channel margins and other shorelines were delineated by digitizing in GIS. Channel margins and shorelines were defined by the abrupt transition from vegetated to unvegetated intertidal areas. 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 very steep banks. Unvegetated sandflats also have characteristic photosignatures in the modern and historical photos. Change in tidal channel and shoreline location was analyzed by comparing past tidal channels with present channels, allowing definition of channel areas present in both the historic and modern channels (unchanged channel areas), those present only in the past (areas since filled in by sediments), and areas present only in recent times (areas since formed by erosion). As a final error check, meander bends in tidal channels were examined at scales ranging from 1:1,000 to 1:10,000 to determine whether erosion had occurred in the cut banks of the meanders and sediment deposition at the point bars, in accord with theoretical expectations (Leopold et al. 1964). The observed patterns were consistent with theoretical expectations, suggesting that rectification and digitizing error were less than historical changes in tidal channel location (Fig. 2).

Analysis of Change in Tidal Channel Planform Geometry

The Wiley Slough, NF1, and NF2 tidal channels were compared to reference channels remote from dike influences. The largest tidal channel system draining each of 11 large marsh islands in the South Fork delta (Fig. 3) and 5 islands in the North Fork delta (Fig. 4) were selected to serve as reference channels. Marsh islands were areas surrounded by delta distributary channels that were assumed to insulate the marsh islands and the tidal channels draining them from indirect dike effects. Channel surface area lost (sedimentation) between 1956 and 2000 for South Fork sites and between 1937 and 2000 for North Fork sites, surface area gained during these intervals (erosion), and unchanged areas were calculated for each channel system. The net surface area change was calculated as erosion minus sedimentation, and percent surface area change was calculated as net area change/(sedimentation + unchanged area). The area of sedimentation plus stable area is equivalent to the surface area of the tidal channels observed in the historical photos. Channels visible in the 2000 photos but not in the historical photos (presumably due to the lower resolution of the histor-

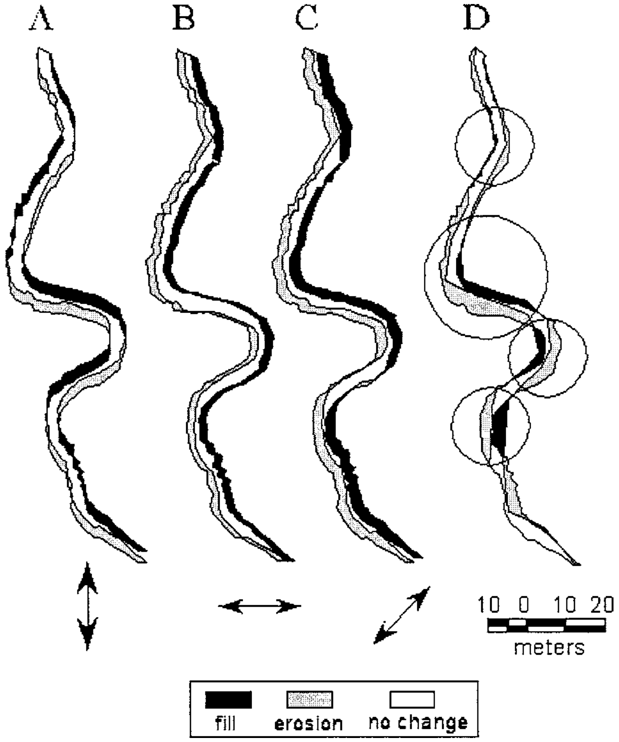

Fig. 2. Comparison of channel erosion and filling patterns resulting from image rectification errors that misalign channels along the y-axis (A), x-axis (B), and both the x- and y-axes (C) with the observed pattern of change from 1956 to 2000 for a typical channel in the South Fork marsh (D). Channels A, B, and C were offset by approximately 4 m to demonstrate possible error patterns. Circled areas in the observed channel enclose erosional areas at concave channel bends paired with sedimentation areas on the opposite convex bend, in agreement with geomorphic theory. These patterns are not consistently present in channels A–C, so misalignment errors must have been small compared to the observed channel changes.

ical photos rather than erosion of new channels) were omitted from analysis. This produced a conservative estimate of reference channel erosion.

Distributary channel sinuosity was calculated from polygon shapefiles of digitized tidal channels for the 1956 and 2000 photos of the South Fork delta. Perimeters and surface area were calculated by the GIS for each channel polygon. Sinuous channel length was calculated as $(P - U - D)/2$, where P = perimeter, U = upstream channel width, and D = downstream channel width. Straight length was measured as the shortest distance between the midpoints of the upstream and downstream ends of the channel segments. Sinuosity was the ratio of sinuous length to straight length (Leopold et al. 1964). Mean channel width was calculated as channel surface area divided by sinuous channel length. The extent of the distributary channel segments over which measurements are shown in Fig. 5.

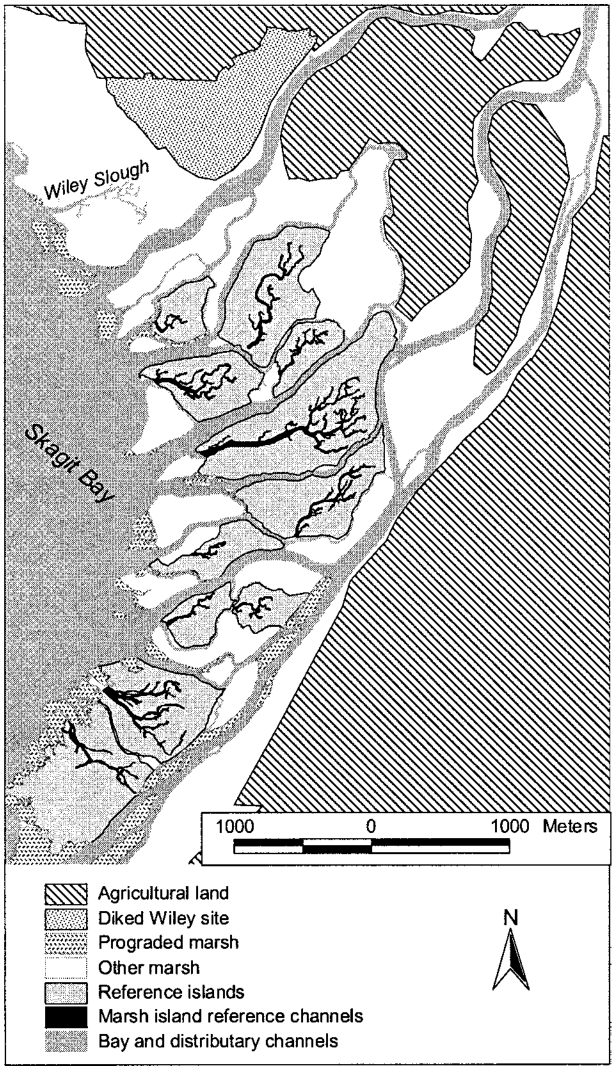

Fig. 3. Location of reference marsh islands in the South Fork Skagit delta and the largest tidal channel draining each island. Except for Wiley Slough, other blind tidal channels are not shown for the sake of graphic clarity. Prograded areas have accumulated since 1956.

STATISTICAL ANALYSIS

Kruskal-Wallis single factor non-parametric analysis of variance (ANOVA) and non-parametric multiple comparisons (Zar 1984) were used to compare net surface area change for tidal channels thought to be affected by dikes and reference channels draining marsh islands. Because the North Fork delta is prograding rapidly while the South Fork delta is more stable (Hood unpublished data), and because morphometric change was compared from 1937 to 2000 in the North Fork and from 1956 to 2000 in the South Fork, the two reference areas were treated distinctly when compared to the diked areas. Statistical compari-

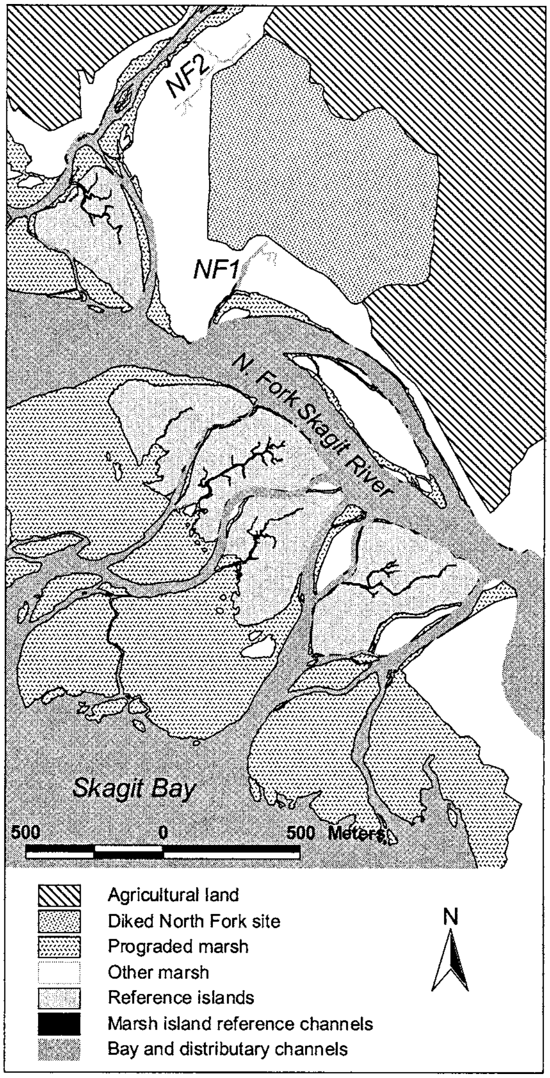

Fig. 4. Location of reference marsh islands in the North Fork Skagit delta and the largest tidal channel draining each island. Except for NF1 and NF2, other blind tidal channels are not shown for the sake of graphic clarity. Prograded areas have accumulated since 1937.

sons were judged significantly different when $p < 0.05$.

Results

Aerial photographs from 1956 show only a spur dike, not enclosing any area, in the Wiley Slough area. Aerial photographs from 1965 show ring dikes, in the same configuration as the present, enclosing approximately 80 ha of formerly tidal oligohaline marsh in the upper Wiley Slough area. The 1956 spur dike was the first step in land conversion, suggesting that subsequent ring dikes were likely built closer to 1956 than 1965.

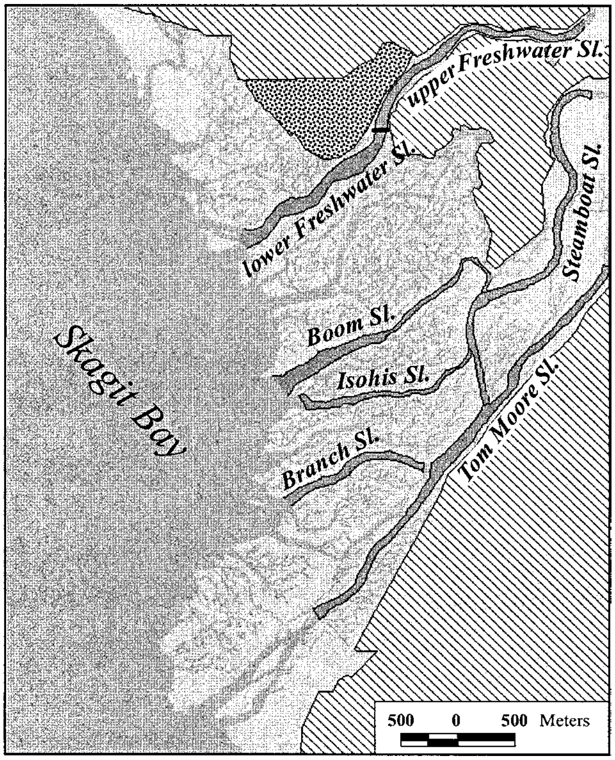

Fig. 5. Map of the distributary channels of the South Fork Skagit River that were measured for changes in sinuosity, 1956–2000. Hatched areas are agricultural areas, landward of dikes. Stippled area is the Wiley Slough area, diked between 1956 and 1965.

In addition to 80 ha of tidal marsh, 6.7 ha of oligohaline tidal channels were also isolated within the dikes between 1956 and 1965. Barley or corn are now grown landward of the dikes and seasonally flooded for use by migratory ducks. Most of the former tidal channels landward of the dikes no longer exist or are severely degraded, choked with sediment and containing stagnant water. In addition to these obvious changes to formerly estuarine habitat within the dikes, comparison of the 1956 aerial photos with orthophotos from 2000 indicates that during the intervening years 9.6 ha of tidal channel were lost seaward of the dikes in the lower Wiley Slough area (Fig. 6); more tidal channel surface area has been lost seaward than landward of the dikes. A soil core, taken with a hand augur in the area where the seaward channel filled in with sediment, passed through 2 m of silt before reaching a layer of sand that typifies tidal channel substrates in the Skagit delta. A similar pattern of tidal channel habitat loss can be seen near the outlet of the North Fork, where 51 ha of tidal marsh were diked between 1937 and 1947 and converted to agriculture (Fig. 7). Two tidal channel systems were affected in this area, NF1 and NF2. Changes in tidal channel surface area landward and seaward

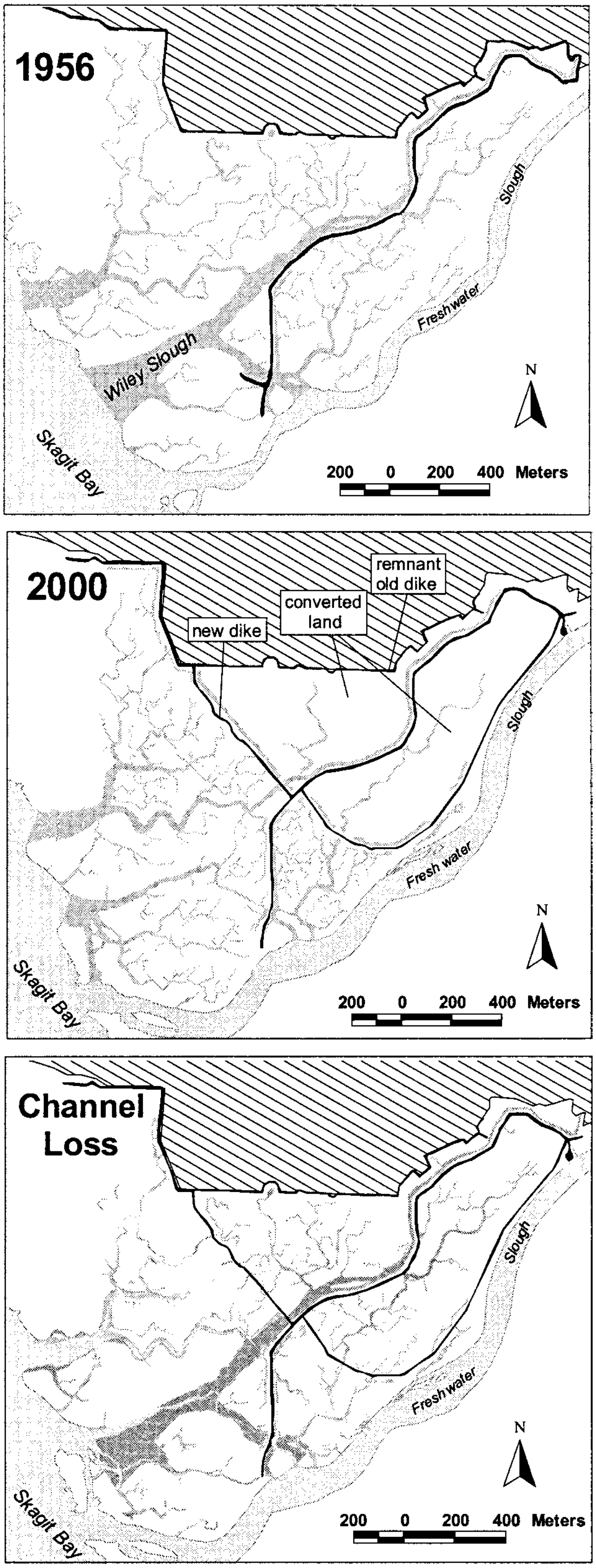

Fig. 6. Wiley Slough in 1956 and 2000, and the channel loss (dark shading in bottom frame) landward and seaward of the dikes during this period. Dikes are represented by thin, heavy, black lines. Hatched areas are drained agricultural lands.

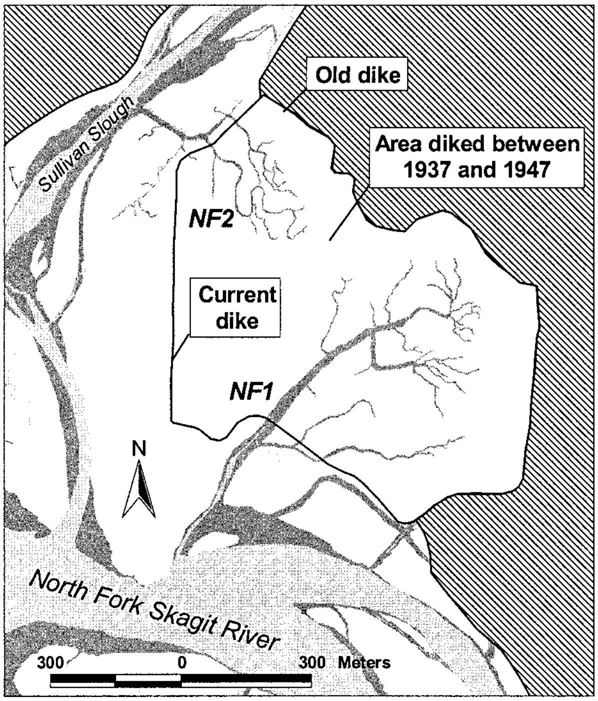

Fig. 7. Tidal channel loss (dark shading) for NF1 and NF2, 1937–2000. Hatched areas are drained agricultural lands. The area diked between 1937 and 1947 was subsequently used for agriculture.

of dikes are summarized in Table 1. Estimates of channel surface area lost are conservative for the Wiley, NF1, and NF2 channel systems because the lower resolution of the historical photos did not permit narrow channels to be distinguished as easily as in the modern photos and so their loss could not be quantified.

An ANOVA of net surface area change for the diked channel remnants (channels remaining seaward of the dikes for NF1, NF2, and Wiley sloughs) and reference tidal channels draining marsh islands in the North ($n = 5$) and South Fork ($n = 11$) deltas, indicated significant differences between groups ($X^2_2 = 7.22$, $p < 0.05$). Multiple comparisons indicated significant differences between channel remnants and North Fork reference channels ($Q_{0.05,3} = 3.23$, $p < 0.005$) and between channel remnants and South Fork reference channels ($Q_{0.05,3} = 3.09$, $p < 0.01$). North and South Fork reference channels were not significantly different ($Q_{0.05,3} = 0.14$). On average, the channel remnants lost 63.7% of their pre-diking surface area to sedimentation, while the North Fork reference chan-

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TABLE 1. Tidal channel surface area lost landward and seaward of dikes. A channel remnant is that portion of a tidal channel not cut off and isolated behind a dike, i.e., the portion that remained seaward of the dike.

	Channel Area Lost Landward of Dikes (ha)	Net Channel Area Lost Seaward of Dikes (ha)	Percentage of Channel Remnant Lost to Sedimentation	Seaward Loss as Percentage of Total Area Lost
NF1	1.4	0.3	47	18
NF2	0.2	0.2	63	50
Wiley Slough	6.7	9.6	83	59

nels increased in surface area through erosion by an average of 17.5% and the South Fork reference channels increased by an average of 6.4%. The combined average surface area increase for the North and South Fork reference channels was 9.9%.

Prior to dike construction, the study tidal channels exhibited channel geometry similar to that of reference tidal channels in the Skagit marshes that were relatively distant from human disturbance. The surface areas and perimeters of the study channels were consistent with the allometric pattern for reference channels (Fig. 8). Immediately after dike construction, the truncated channels remaining seaward of the dikes were geometrically very different from reference channels. Tidal channel perimeter was reduced by channel truncation to a much greater degree than surface area, and this new geometry was unstable. By 2000 the truncated channels re-sized by filling in with sediment and became geometrically similar to the reference channels.

Comparison of sinuosity change and mean channel width change from 1956 to 2000 for the major distributaries of the South Fork indicates that channel sinuosity declined more than twice as much in lower Freshwater Slough (adjacent to and downstream of the Wiley Slough dikes) as in any other distributary, while channel width increased much more in lower Freshwater Slough than any other distributary (Fig. 9, Table 2). Changes in distributary sinuosity were correlated with changes in mean channel width ($r = -0.82$, $p < 0.05$).

Discussion

The strong contrast in channel change between remnant tidal channels seaward of dikes and reference channels (64% mean decrease in surface area versus 10% mean increase, respectively) supports the inference that Skagit dikes are directly and indirectly responsible for habitat loss for threatened chinook and other aquatic organisms—dikes cause seaward as well as landward channel habitat loss. While aquatic habitat loss due to channel filling results in the development of new marsh seaward of dikes, the amount of new marsh hardly compensates for marsh habitat loss landward of the dikes; 80 ha of marsh lost landward of the Wiley dikes versus 9.6 ha of marsh gained through channel sedimentation, and 51 ha

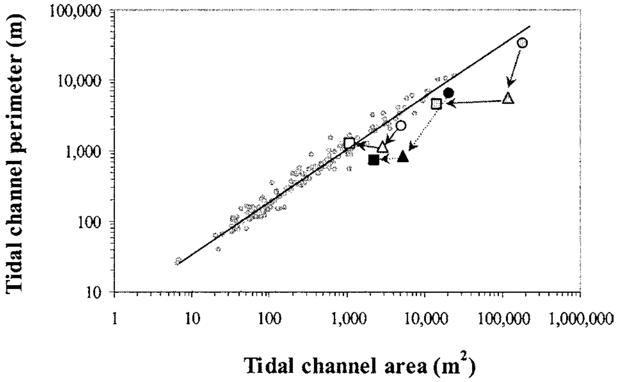

Fig. 8. The allometry of natural reference channels (small gray dots) compared to the geomorphic trajectories of tidal channels cut off by dike construction. Circles are the pre-dike channels. Triangles are the downstream truncated channels remaining immediately after diking. Squares are the downstream truncated channels in 2000. Wiley Slough is represented by gray symbols, NF1 by white symbols, NF2 by black symbols.

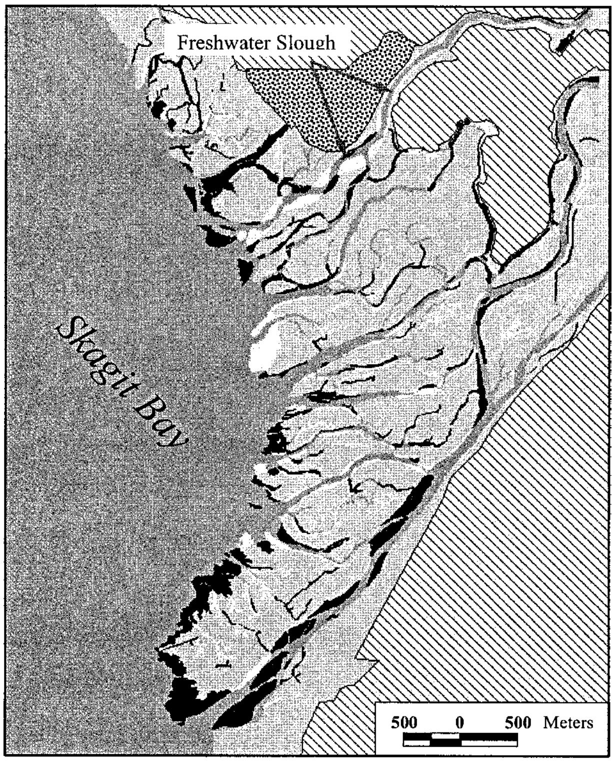

Fig. 9. Erosion (white) and sedimentation (black) in tidal channels of the South Fork Skagit marshes, 1956–2000. Hatched areas are agricultural areas, landward of dikes. Stippled area is the Wiley Slough area, diked between 1956 and 1965.

TABLE 2. Change in channel sinuosity and width for distributary channels of the South Fork Skagit River, 1956–2000. Distributions are ranked in descending order of sinuosity change in the first column and ascending order of mean width change in the second.

Sinuosity Change (%)		Mean Width Change (%)	
3.3	Boom Slough	−27.4	Tom Moore Slough
3.1	Steamboat Slough	−18.2	Steamboat Slough
−1.0	Tom Moore Slough	−4.1	Isohis Slough
−1.9	Isohis Slough	−3.5	Boom Slough
−2.8	Upper Freshwater Slough	32.8	Upper Freshwater Slough
−3.5	Branch Slough	46.1	Branch Slough
−7.5	Lower Freshwater Slough	73.4	Lower Freshwater Slough

of marsh lost landward of the 1937–1947 North Fork dikes versus 0.5 ha gained.

Sediment delivery alone did not cause channel habitat loss. Even where sediment accumulation and marsh progradation has been greatest (in the North Fork delta) reference channels showed no decrease in surface area over a 63-yr span. Hydraulic geometry theory (Renger and Partenscky 1974; Zeff 1988; Hume 1991; Friedrichs 1995) suggests that diking the upper reaches of tidal channels reduced the tidal prism for channel reaches downstream from the new dikes, and that this loss in tidal flushing resulted in re-sizing of the downstream tidal channels through sediment accumulation. The geomorphic trajectories shown in Fig. 7 are consistent with this theory.

Traditional parameters for quantifying hydraulic geometry include tidal prism, channel cross-sectional area, channel width, and channel depth. Of these, only width was measurable from aerial photographs. Tidal prism shapes the geometry of not only a particular channel cross-section, but also of every possible cross-section of a channel because it shapes the geometry of the channel as a whole. Integrating the equations for cross-sectional hydraulic geometry over the length of a channel produces an allometric relationship between tidal channel volume and surface area, and similarly between tidal channel surface area and perimeter (Hood 2002). An allometric approach to hydraulic geometry is useful because surface area and perimeter can be measured from aerial photographs using standard GIS techniques to indirectly evaluate the effects of tidal prism. More detailed and costly measurements of channel depth or cross-sectional area can be avoided, while the absence of historical cross-sectional information can be finessed through this indirect approach.

Tidal channel allometry follows from a more general fractal theory of landforms (Rodriguez-Iturbe and Rinaldo 1997), and the scaling of perimeter with surface area is a common reflection of landform fractal geometry (Mandelbrot 1983; Sugihara and May 1990). A wide variety of landforms have been shown to be allometric or, equivalently, self-affine fractals (Bull 1975; Church and Mark 1980; Ouchi and Matsushita 1992; Rodriguez-Iturbe and Rinaldo 1997). Like the traditional equations for hydraulic geometry, allometric and fractal relationships are described by power functions. A system is allometric when the relative rate of change of one part of a system (y) is proportional to the relative rate of change of another part of the system (x), or of the whole system, i.e.,

$$\frac{dy}{y}\frac{1}{dt} = b\frac{dx}{x}\frac{1}{dt}$$

where b is a proportionality constant (Woldenberg 1966). Multiplying by dt and integrating produces a power function, $y = ax^b$.

Dike construction in the Wiley Slough area between 1956 and 1965 may have had another indirect effect—reduction of channel sinuosity between 1956 and 2000 in the lower portion of Freshwater Slough, the primary distributary of the Sough Fork Skagit River. Removing 80 ha of marsh from the Freshwater Slough floodplain constrained flood flow to the distributary channel for an additional 1.2 km, rather than allowing it to disperse over the marsh surface. The constrained flow increased erosive forces during floods thereby leading to decreases in channel sinuosity more than twice as great in lower Freshwater Slough as in any other distributary. Because high sinuosity is associated with small channel width relative to depth (Leopold et al. 1964), the observed correlation between changes in sinuosity and in mean channel width suggests that distributary channel widths changed to a greater degree than channel depths. Greater adjustment in width relative to depth with changing discharge is consistent with hydraulic geometry theory (Leopold et al. 1964).

The observed changes in channel sinuosity and width could also be due to shifts in distributary flow regimes resulting from spatially heterogeneous patterns in marsh progradation. Marsh progradation causes local channels to lengthen, reducing their gradient and increasing sediment accumulation within the channels. The lower reach of Tom Moore Slough in the South Fork delta has become narrower since 1956 and it is also very shallow compared to other distributaries. Branch Slough, a distributary of lower Tom Moore Slough, has become wider and straighter during this time as normal river flow has been naturally diverted from lower Tom Moore Slough to Branch Slough. Similarly, in the late 19th century river discharge was greater in the South Fork than the North Fork of the Skagit River, while today the opposite is true. This regime shift has been ascribed to changes in channel gradient between the two forks (Collins 1998). Given these two examples, the small-scale regime shift between lower Tom Moore and Branch sloughs and the large-scale shift between the North and Sough Forks, it is possible that a similar medium-scale shift in flow occurred from upper Tom Moore to Freshwater Slough. Such a shift in flow could result in channel re-sizing (widening) with an associated decrease in sinuosity for lower Freshwater Slough. Upper Freshwater Slough would have had less opportunity for widening since it has been constrained by dikes on both banks for more than 100 yr. Both potential causes of channel widening and straightening in lower Freshwater Slough, indirect dike effects and distributary flow regime shifts, are not mutually exclusive, and they might have acted synergistically on lower Freshwater Slough.

Loss of channel sinuosity has likely resulted in decreased channel habitat diversity, e.g., loss of deep pools and areas of relatively low velocity flow, as well as point bars and their associated accumulations of large woody debris. Such habitat loss likely affects large pool-dwelling fish such as returning salmon, trout, and sturgeon, harbor seals that haul out on cut banks adjacent to deep pools, and wading birds and shorebirds that feed in the shallows over point bars (Hood personal observations). Although studies of the ecological role of tidal channel sinuosity are rare, dense populations of oysters (*Crassostrea virginica*) are associated with meander cut banks (Keck et al. 1973), while meander deposition bars are areas where small fish forage on abundant benthic prey and avoid predators (McIvor and Odum 1988).

Indirect (seaward) dike effects are often overlooked while direct (landward) effects are generally apparent and expected. Conditions landward of dikes are usually in stark visual contrast with seaward conditions. Land is lower in elevation landward of dikes versus seaward, and the vegetation and hydrology obviously differ from the undiked marsh. Marshes seaward of dikes look very natural; they support native marsh vegetation and experience the full range of tides and riverine floods, but when examined from a broad temporal perspective, indirect dike effects are evident in the superficially natural marsh.

Indirect dike effects have several implications for environmental management. Habitat loss in estuarine landscapes may often extend well beyond dike boundaries, particularly for species that are strongly dependent on tidal channel habitat. Quantification of habitat loss must account for indirect dike effects. Estuarine habitat restoration should include habitat seaward of dikes, truncated channels that have filled in with sediment, as well as landward of dikes. When dikes are removed, considerable restoration benefit may occur to areas seaward of dikes, especially if there is explicit planning for this possibility. Estuarine habitat restoration frequently involves mere breaching of dikes rather than complete removal. However, remnant dikes interfere significantly with tidal flow across the marsh surface (French and Stoddart 1992) and consequently with biogeophysical processes associated with tidal flooding of marshes, such as the movements of sediments, nutrients, detritus, large woody debris, and aquatic organisms. The present study indicates that remnant dikes could also interfere with external circulation patterns; for example, by confining flood flows and focusing their erosive energy dikes may reduce channel sinuosity of nearby delta distributaries. When areas are restored by removing dikes, most restoration monitoring ignores marsh areas seaward of the removed dikes, except to treat them as reference sites. Areas seaward of removed dikes are probably not appropriate reference sites, because they may be affected by restoration just as they were originally affected by dike construction, and should be treated as part of the restoration area. Reference sites should be judiciously selected to be away from the influence of the dike removal.

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