6. Geomorphology

Abstract

The Skagit River delta has evolved over time due to both human and natural processes. Human activities such as construction of dikes and levees have influenced the spatial location, distribution, and function of distributaries that deliver most of the sediments and river flow to the delta, disconnecting numerous large historical distributaries in the Skagit River from riverine and tidal influence. Today, remaining distributaries are located at the outlet of the North and South Forks of the Skagit River. Sediment transported to the outlet of the North and South Forks has resulted in marsh accretion in these areas and the development of new (or altered) distributaries, though marsh accretion shifted to the North Fork after the dominant flow was shifted from the South Fork to the North Fork due to channel adjustments in 1937. Sediment supply and transport in the basin has been influenced by human activities such as logging and road construction that have increased sediment loads in the Skagit River. Clearing of large log jams have increased sediment transport capacity in the lower river, and dams have trapped sediments, reducing overall sediment supply from the headwaters. Human modification of the river channel has also altered sediment transport to the delta. Sediment reaching the delta largely bypasses the shoreline and tidal flats and accumulates on the face of the delta in deeper waters. Fine sediments mostly bypass the delta and are transported offshore (predominantly to the north) by surface currents. The offshore transport of fine sediments impacts important nearshore habitats through abrasion, fragmentation, substrate burial, and the effects of increased turbidity in the water column.

Sediment loads would be expected to increase in the Skagit River due to climate change-related changes in glacier retreat, loss of interannual snowpack, and projected increases in flooding. Climate change is also expected to increase coastal erosion due to sea level rise, although it is uncertain whether these effects would deliver additional sediment to the Skagit River delta or not. A key uncertainty in projecting future conditions is whether expected increases in sediment loads will lead to sufficient marsh accretion to keep pace with projected sea level rise, or whether sea level rise will ultimately result in a net loss of tidal marsh. Initial studies estimating net loss of

salt marsh and estuarine beaches using relatively simple models suggest net losses in these nearshore features.

6.1 Background

Geomorphology is the study of changing landforms, including how landscapes have evolved historically, and the biophysical processes that shape or control such changes (Woodroffe, 2002). Understanding these changing processes is important in the context of managing coastal resources that are vulnerable to climate change due to sea level rise, changes in rivers, or other factors (Woodroffe, 2002). River deltas in particular are affected by changing sea level, rising or falling land surface, changing river flow, retreating glaciers, changing sediment transport regimes, changing delivery of nutrients, debris, and related biological interactions among vegetation and animal behavior (Hood 2007 & 2010a). One of the most important factors controlling or shaping delta landforms is the geometry of the distributaries (river channels which cut through the delta and deliver flow and sediment) (Hood, 2007 & 2010a). In addition to delivering sediments and fresh water, river distributaries deliver nutrients, debris, and other aquatic organisms to estuarine and coastal wetlands along the distributaries (Hood, 2007 & 2010a).

6.2 Morphology of the Skagit River Delta

As mentioned in Chapter 1, more than 90 % of the Skagit delta has been isolated from riverine and tidal influence by dikes and converted to farmland or other uses following non-native settlement in the 19th century. As a result of these changes, numerous large historical distributary channels have been disconnected from the river (Collins et al., 2003). These changes have continued sporadically through the 20th century. Historical distributary sloughs across Fir Island, between the North and South Forks for the Skagit River, for example, were disconnected from the river as recently as the 1950s in order to reduce dike maintenance costs and breaching risk (see Figure 6.1) (Collins, 1998; Collins et al., 2003; Hood, 2007 & 2010a). The remaining two distributaries in the Skagit delta are located at the outlet of the North and South Forks

(Figure 6.1). Due to these changes in the delta, direct fluvial delivery of freshwater and sediment to the bay fringe of Fir Island no longer occurs, although nearshore circulation may at times convey limited freshwater and sediment to the bayfront (Erik Grossman, personal communication). Consequently the bay fringe area is largely sediment starved and is experiencing marsh erosion, resulting in significantly lower tidal channel density in the bay fringe marshes (Collins, 1998; Hood, 2007 & 2010a; Beamer et al., 2005).

In contrast, the deltas near the outlets of the North and South Forks (which currently receive more flow and sediment) have substantially prograded (increased in area) since at least 1889 (Collins, 1998; Hood, 2007). As a result, new marsh and minor distributaries have developed in the outlets of the North and South Forks. Between 1889 and 1937, for example, significant amounts of marsh had accreted in the South Fork while there was little change in the North Fork marsh. After the dominant flow of water and sediment was shifted from the South Fork to the North fork around 1937 (due to human changes to the river channel), marsh accretion shifted from the South Fork to the North Fork (Collins, 1998; Hood 2010a) (Figure 6.2). As sediment was deposited at the outlet of the North Fork, smaller distributary tidal channels were also formed at the outlet of the North Fork (Hood, 2006 & 2010a). Some of the distributaries were blocked by more sediment at the upstream end of the channel to form blind tidal channels (typically tidal channels with an open downstream channel but no upstream inlet) (Hood, 2006 & 2010a). For example, the channel labeled C_1 in Figure 6.2 is one of several blind tidal channels that have formed (Hood, 2010a). Tidal channels (particularly blind tidal channels) provide important rearing habitat for juvenile Chinook salmon, and other aquatic species (Hood, 2007). It is important to note, however, that these recently formed areas of favorable delta habitat are very small in comparison with the salmon habitat lost due to historical isolation of the river from its floodplain. Also, recent formation of blind channels has been quite localized, whereas historically these kinds of habitat were spread evenly across a much larger area with a range of salinity gradients, thereby creating diverse habitat for the continuum of early life-history stages for Chinook.

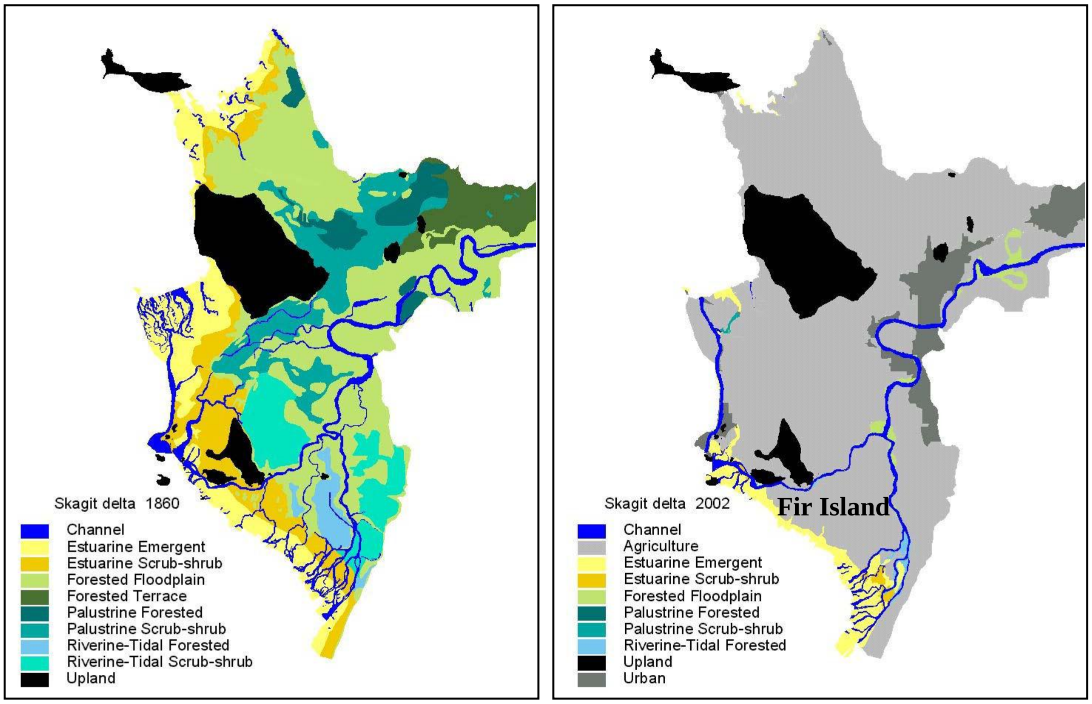

Figure 6.1 The mid-19th century (1860, left panel) and current (2002, right panel) channel conditions in the Skagit delta (Source: Collins et al. 2003; Hood, 2009).

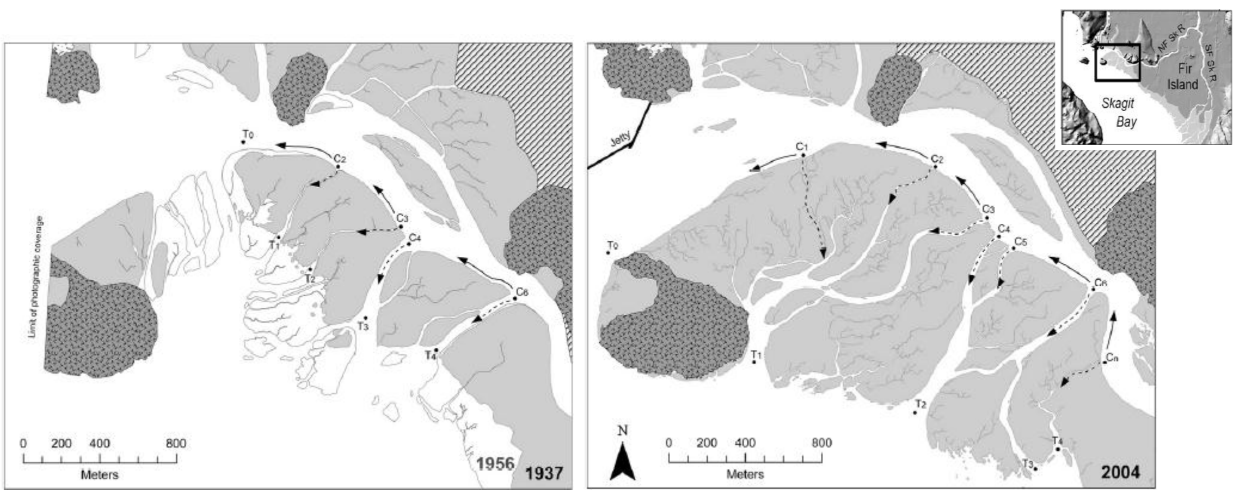

Figure 6.2 Planforms of the North Fork marsh/distributary system. Cross-hatched areas are farmland, checked areas are bedrock outcrops, light gray is tidal marsh in 1937 (left panel) and 2004 (right penal), gray outline indicates 1956 tidal marsh (left panel), white areas are channels and bay. T_0 is the river terminus and T_1–T_4 are the termini for distributaries of the North Fork of the Skagit River. C_1–C_6 are the distributary channel bifurcation points (Source: Hood, 2010a).

Channelization of the lower Skagit river, disconnection from the natural floodplain, and a reduction in the number of distributaries in the Skagit delta have resulted in strongly altered sediment transport processes in the Skagit delta. Channelization of the entire flow of the river through its two present outlets of the North and South Forks focused freshwater and sediment and likely increased flow velocities and sediment carrying capacity in the lower river. Bathymetric change analyses across the Skagit tidal flats and examination of sediment cores indicate that a significant change in substrate and habitat occurred beginning in 1850 as the entire tidal flats that were once muddy were replaced by 1-2 m thick sand (Grossman et al., in press). The sands show evidence of cross-bedding which is indicative of sediments bypassing the delta and suggest that tidal flats also changed from a relatively calm environment where muds used to accumulate to a more energetic tidal flat characterized by braided, meandering, sand-filled channels (Grossman et al., in press).

Several recent studies have established that sediments delivered to the delta (primarily sands, which constitute 50-60% of the total sediment load—Curran et al. in review) mostly bypass the shoreline and tidal flats and are instead accumulating along the delta front (Grossman et al. in press and in review). The fine sediments that in pre-settlement times were deposited in the delta as mud, are now largely lost from the delta, swept away by surface currents that show a net northward transport direction (Grossman et al. 2007). These fine sediments that bypass the delta also impact near-shore habitats and eelgrass beds through abrasion, fragmentation, burial, and by increasing turbid conditions that block light and may affect fish gills.

6.3 Sediment Supply and Transport in the Skagit River

Sediment supply and transport in the Skagit River basin has also been significantly influenced by human activities. The clearing of log jams up to a mile long in the Mount Vernon area, logging of streamside forests, forest road construction, and dredging of the lower river have been identified as probable causes of increased sediment supply to the Skagit River and sediment transport to the delta (Collins, 1998; Beamer et al., 2005). At the same time, dam construction on the Baker River and Skagit River, which impound flow and sediment from about 47% of the basin, have both reduced natural peak flood flows in the lower river (by about 50%) and trapped sediments. However, because of different geology and sediment production regimes, the contribution of sediment to the Skagit River from the watersheds above these impoundments in comparison with undammed tributaries (particularly the Sauk and Cascade Rivers that drain Glacier Peak) remains uncertain. It also remains uncertain as to whether there has been a net increase or reduction of sediment delivery to the delta due to the cumulative effect of these different historical changes.

Much of the sediment in the Skagit River basin is glacial in origin, and the estimated sediment transport rate is between 1.7 and 4.5 million tons per year (Collins, 1998; Curran et al., in review; Pacific International Engineering, 2008). As noted above, sediments deposited to the delta have provided important habitat for salmon by creating new distributary channels in some areas. On the other hand, increased sediment supply in some tributaries, mostly due to logging and road construction, has caused an increase in scour and fill of the channel bed in some areas, affecting salmon egg to fry survival as well as freshwater rearing (see Chapter 7) (SRSC and WDFW, 2005). This problem is exacerbated by accelerated sedimentation from glacial recession on Glacier Peak which exposes unstable slopes to erosion, and is observed to produce large quantities of fine sediment. For instance, glacier melt from Glacier Peak has deposited large amounts of silt downstream of the Suiattle River since 1991, reducing incubation survival (SRSC and WDFW, 2005). Beamer et al. (2000) reported that sediment supply is greater than 1.5 times the natural rate in many areas of the Skagit River basin. The area with the greatest sediment load is the lower Sauk River, which doesn't have any dams and is also impacted by receding glaciers (SRSC and WDFW, 2005).

6.4 Effects of Climate Change on Sedimentation

Sediment loads are likely to increase under climate change due to loss of snowpack and continued glacial recession (Chapter 4), which may expose additional and highly mobile sediment sources (Knight and Harrison, 2009; Lu et al., 2010), and increasing extreme peak flows (Chapter 5), which would move sediments downstream more rapidly. There is also evidence that sediment loads in glacial-fed watersheds could be elevated by geomorphic hazards associated with glacial retreat such as rock avalanche, debris flows and moraine dam failures (Moore et al., 2009; Lu et al., 2010; URLs 1, 2, & 3).

Thus continued glacier recession is hypothesized to result in increasing sediment loads in glacial-fed rivers at the time scales of years to decades, though the sediment loading rate could be reduced temporarily if glacial lakes trap and store sediment discharged by a glacier (at least until the lakes fill) (Moore et al., 2009; Lu et al., 2010). Fine, subglacial sediments would be flushed with meltwater resulting from strong summer ice mass loss from glaciers. Rapid glacier retreat also releases sediments stored in the ice near the terminus, near the bed of the glacier, and from recently deglaciated moraines and forefield deposits. These sources of fine sediment in late summer would presumably decrease with ongoing loss of glacial ice mass and reduced late summer melt water.

These hypothesized impact pathways related to changes in glaciers are supported by historical changes in other PNW rivers on the west slope of the Cascades, such as the Nisqually and White Rivers, which have experienced dramatic increases in sediment production and accretion in the headwaters (Lu et al., 2010; PALS, 2008). In the Nisqually and White River case studies, large amounts of sediment have been transported from steep, unvegetated slopes exposed by retreating glaciers. These sediments are then deposited downstream, increasing river bed elevation (a process called aggradation) and/or making a shallow, braided river system with multiple (and potentially more mobile) flow channels (Lu et al., 2010; PALS, 2008). For example, aggradation in glacial-fed rivers in Mount Rainier National Park has occurred at a rate of 6 to 14 inches per decade (URL 1). In the last decade, the rate of sediment buildup at Mount Rainier has dramatically increased (URL 2) due in part to high flow events and resulting debris flows, such as the flood of November 6 and 7, 2006. During that event, Mount Rainier received 18 inches of rain in 36 hours. Debris flows, which began with glacial outburst floods, increased the elevation of the riverbed near Nisqually Road by more than four feet (URL 1). The Nisqually River bed has in certain areas been elevated by 38 feet since 1910 (URLs 1 & 4). Debris flows have also increased damage to Mount Rainier National Park (URLs 1 & 3). Figure 6.3 shows some of the flood damage that occurred at Mount Rainier National Park during the 2006 flood. Impacts to the lower basin in the Nisqually case study are not clear, in part because intervening dams have trapped sediments before they reach the Nisqually delta. A current USGS study of sediments stored behind Alder dam in the Nisqually basin since about 1950 calculates that sediment loading at the delta has been reduced by about a factor of ten by the dam (E. Grossman, personal communication).

Physical drivers are similar in the glaciated headwaters of the Skagit River basin, and increased sediment loads are expected to accompany projected continued glacial recession (see Chapter 4) and loss of snowpack (Chapter 5), especially in undammed rivers like the Sauk.

Figure 6.3 The flood damage at Mount Rainier National Park in November 2006: the Nisqually River at Sunshine Point (left panel) and the broken edge of the Nisqually road (right panel) (URL 5).

In coastal environments, sediment loads are also expected to increase due to accelerated bluff erosion under climate change. Bluff erosion or collapse is usually caused by storms with large waves, especially when combined with high tides (Laevelle et al., 1986; Huppert et al., 2009). Projected sea level rise (Chapter 3) will increase the high tide level (Shipman, 2004; Huppert et al., 2009), potentially accelerating rates of erosion on unstable bluffs and increasing the frequency of landslides (Lavelle et al., 1986; Shipman, 2004; Huppert et al., 2009). It remains uncertain, however, whether sediment sourced from bluff erosion will be retained on beaches to help mitigate further effects of sea-level rise or be transported offshore by increased wave exposure near the shore under higher water levels.

6.5 Potential Climate Change Impacts on Delta Morphology

Fully integrated modeling studies that would result in a more comprehensive understanding of the impacts of climate change on the Skagit River delta are currently unavailable, however a number of well-formed hypotheses have developed based on historical impacts related to sea level rise and potential changes in sediment transport. Initial studies estimating net loss of salt marsh and estuarine beaches due to several competing factors suggest net losses in these near shore features.

As mentioned above, the salt marshes in both the South and North Forks of the Skagit River have prograded (increased in area due to sediment accumulation) until about 1980. Analysis of progradation rates in the Skagit delta as a whole using remote sensing techniques indicates that rates have been gradually slowing since 1937. The South Fork region has experienced more rapid declines in progradation rates than the North Fork (see Figure 6.4) (Hood, 2005) and in fact the South Fork marshes have probably been eroding since about 1980 (Beamer et al., 2005). This steady decline in progradation rates in the North Fork and the shift to steadily increasing erosion rates in the South Fork marshes may be the result of sea level rise over the past century (estimated to be about 20 cm in the global mean) or changes in the relative distribution of sediments between the N and S Forks. Therefore one hypothesis is that further declines in the progradation of the marsh (and/or increases in current erosion rates) would accompany projected sea level rise for the 21^{st} century, and would also result in associated decreases in the network of distributary channels and the habitat they provide. This hypothesis is supported by long-term geological records which show that regression (marsh translation landward) was the norm between 5,000 yr BP and 1850s in most areas of the world when sea level rise was 0.5 to 1.0 mm/yr (Stanley and Warne, 1994).

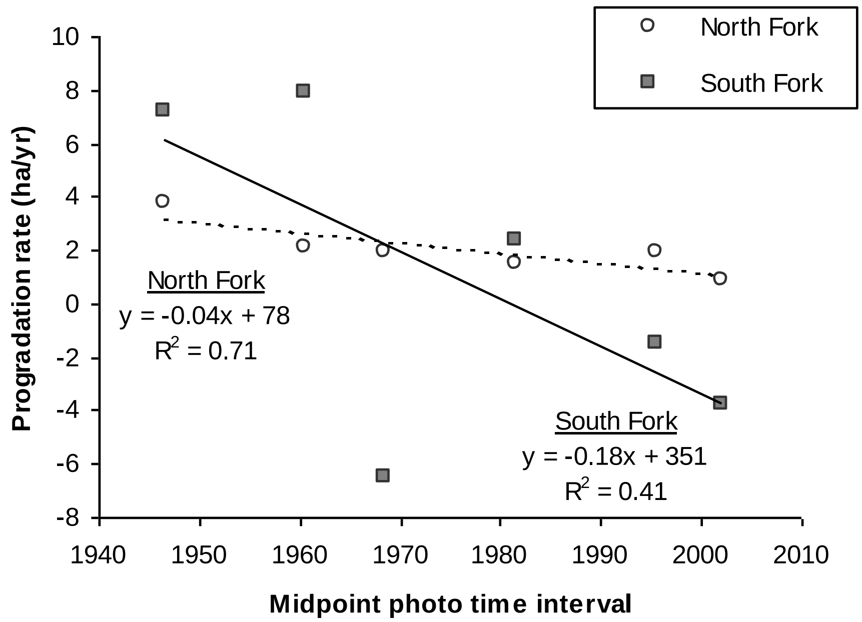

Figure 6.4 Average marsh progradation rates, calculated from GIS analysis of historical aerial photos. The North Fork trend is represented by a dashed line, the South Fork trend by a solid line. Negative values represent net marsh erosion rather than progradation (Source: Hood, 2005).

An alternate hypothesis, however, is that possible rapid increases in sediment deposition in the Skagit delta due to climate-change-related changes in glacial recession, increased flooding, erosion of bluffs due to sea level rise, or along-shore transport of sediment originating from other near-shore areas could result in accelerated rate of accretion and the development of new (or altered) distributaries. Thus a key question remains as to whether sea level rise will ultimately result in a net loss of tidal marsh or whether marsh accretion due to changes in these factors will ultimately be able to keep pace with an accelerating rate of sea level rise associated with global warming (Schweiger, 2007).

Based on the recent studies quantifying sediment transport processes in the delta cited above, establishing a physical environment where net accretion can take place will likely require re-connection of distributary channels to a larger area of the delta in order to spread sediments and river flow more evenly across areas being inundated by sea level rise. This is because a substantial portion of sediment delivered to the delta currently bypasses the shoreline and tidal flats and most fine sediments are lost offshore (Grossman et al., in press; Grossman et al., in review).

Without such structural changes, initial studies (using relatively simple models) support the first hypothesis that sea level rise will result in net loss of tidal marsh. Schweiger (2007) estimated the loss of tidal marshes and estuarine beaches for two sea level rise scenarios - 28 and 69 centimeters (11.2 and 27.3 inches) of sea level rise as shown in Figure 6.5, concluding: "Much of the dry land for this site is protected by dikes and is not subject to inundation. This means that brackish marshes and beaches that are trapped against seawalls may be especially subject to loss, largely through conversion to saltmarsh or tidal flat. By 2100, brackish marsh is projected to decline by 77 percent, and estuarine beach by 91 percent." (see Table 6.1 and upper panel in Figure 6.5). It should be noted that while the study considered changes in elevation of the delta due to estimates of current sedimentation and accretion rates as well as tectonic processes (subsidence and uplift) when investigating the impacts of sea level rise on tidal marsh habitats in the Skagit delta, potential systematic changes in sediment supplies, nutrient supplies, and other biological factors associated with climate change that may influence the delta were not considered. For reasons already discussed above, marshes in the South Fork were projected to be more vulnerable than those in the North Fork (Hood, 2005; Schweiger, 2007).

Lower panels in Figure 6.5 and Table 6.2, however, show simulations of the effects of removing the existing dikes. In this scenario there is a dramatic conversion of undeveloped dry land to salt marsh, transitional marsh, and tide flats. Thus one adaptive response to the losses of delta habitat projected in Table 6.1 and upper panels in Figure 6.5 may be to remove some of the existing diking (as has been done in the Nisqually Delta, for example). (This scenario also highlights the vulnerability of existing dry land areas to potential dike failures under conditions of elevated sea level).

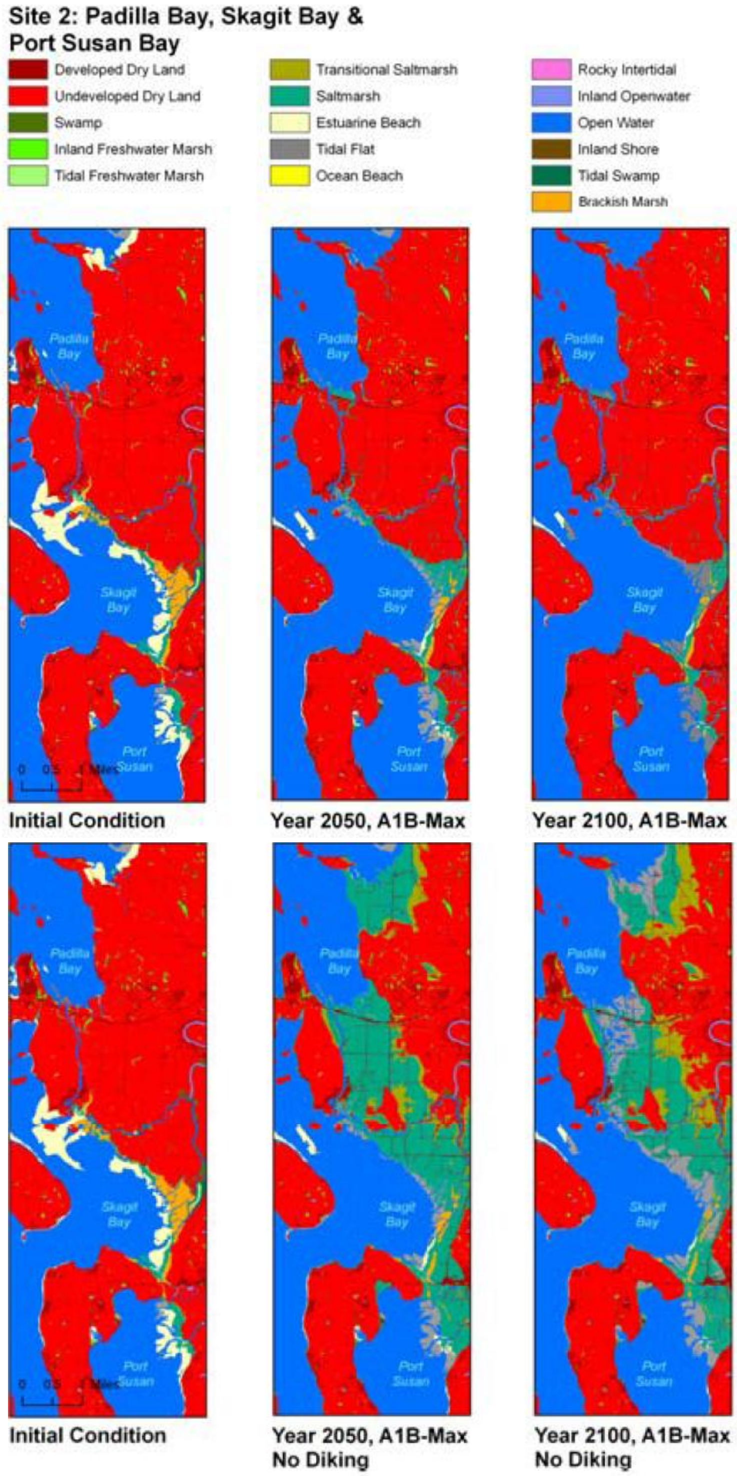

Figure 6.5 Projections of Habitat Changes for a projected 29 cm (2050) and 69 cm (2100) of sea level rise, accounting for current sediment deposition rates and vertical motion with diking (upper panels) and without diking (lower panels) (Source: Schweiger, 2007).

Table 6.1 Changes in the near coastal environment resulting from estimated sea level rise for 2050 and 2100 in the Skagit Delta and surrounding near-shore areas with existing dikes intact (see upper panels Figure 6.5). (Source: Table 10, Schwieger, 2007).

Table 10. Projections of Habitat Changes for Site 2
[A1B Max for 2050, 2100 and 1.5 Meters for 2100]

	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals for This Site)		
	Initial Condition	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+1.5 meters/59.1 inches)**	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+ 1.5 meters/59.1 inches)**
Undeveloped Dry Land	45,482 (112,388)	43,800 (108,232)	43,606 (107,753)	43,480 (107,441)	4% loss	4% loss	4% loss
Developed	4,215 (10,415)	4,215 (10,415)	4,215 (10,415)	4,215 (10,415)	No change	No change	No change
Swamp	485 (1,198)	362 (895)	328 (811)	283 (699)	25% loss	32% loss	42% loss
Inland Fresh Marsh	665 (1,643)	504 (1,245)	491 (1,213)	481 (1,189)	24% loss	26% loss	28% loss
Tidal Fresh Marsh	76 (188)	12 (30)	11 (27)	10 (25)	84% loss	85% loss	87% loss
Transitional Marsh	29 (72)	406 (1,003)	468 (1,156)	243 (600)	1,313% expansion	1,531% expansion	747% expansion
Saltmarsh	931 (2,301)	2917 (7,208)	1,854 (4,581)	1,315 (3,249)	213% expansion	96% expansion	41% expansion
Estuarine Beach	3,670 (9,069)	597 (1,475)	329 (813)	44 (109)	84% loss	91% loss	99% loss
Tidal Flat	289 (714)	1,618 (3,998)	2,061 (5,093)	2,801 (6,921)	460% expansion	613% expansion	869% expansion
Ocean Beach	0 (0)	3 (7)	0 (0)	0 (0)	NA	NA	NA
Inland Open Water	342 (845)	291 (719)	281 (694)	269 (665)	15% loss	18% loss	21% loss
Estuarine Open Water	33,546 (82,894)	35,976 (88,899)	36,892 (91,162)	37,695 (93,146)	7% expansion	10% expansion	12% expansion
Open Ocean	875 (2,162)	1,178 (2,911)	1,482 (3,662)	1,500 (3,707)	35% expansion	70% expansion	71% expansion
Brackish Marsh	1,414 (3,494)	432 (1,067)	332 (820)	41 (101)	69% loss	77% loss	97% loss
Inland Shore	30 (74)	27 (67)	27 (67)	27 (67)	10% loss	10% loss	10% loss
Tidal Swamp	202 (499)	34 (84)	22 (54)	10 (25)	83% loss	89% loss	95% loss
Rocky Intertidal	1 (2)	<1 (<2)	<1 (<2)	<1 (<2)	4% loss	12% loss	27% loss
Riverine Tidal	278 (687)	155 (383)	126 (311)	114 (282)	44% loss	55% loss	59% loss

Table 6.2 Changes in the near-coastal environment resulting from estimated sea level rise for 2100 in the Skagit Delta and surrounding near-shore areas without existing dikes (see lower panels in Figure 6.5). (Source: Table 11, Schwieger, 2007)

Table 11. Projections for Habitat Changes for Site 2 with No Dikes (A1B Max for 2100)

	Area of Habitat Type in Hectares (Acres)		Percentage Change (Relative to Totals for This Site)
	Initial Condition	**2100 (+0.69 meters/27.3 inches)**	**2100 (+0.69 meters/27.3 inches)**
Undeveloped Dry Land	45,482 (112,388)	27,361 (67,611)	40% loss
Developed	4,215 (10,415)	4,215 (10,415)	No change
Swamp	485 (1,198)	315 (778)	35% loss
Inland Fresh Marsh	665 (1,643)	476 (1,176)	28% loss
Tidal Fresh Marsh	76 (188)	11 (27)	85% loss
Transitional Marsh	29 (72)	4,147 (10,247)	14,346% expansion
Saltmarsh	931 (2,301)	11,331 (28,000)	1,115% expansion
Estuarine Beach	3,670 (9,069)	329 (813)	91% loss
Tidal Flat	289 (714)	4,793 (11,844)	1,559% expansion
Ocean Beach	0 (0)	3 (7)	NA
Inland Open Water	342 (845)	270 (667)	21% loss
Estuarine Open Water	33,546 (82,894)	37,371 (92,346)	11% expansion
Open Ocean	875 (2,162)	1,483 (3,665)	70% expansion
Brackish Marsh	1,414 (3,494)	332 (820)	77% loss
Inland Shore	30 (74)	27 (67)	10% loss
Tidal Swamp	202 (499)	22 (54)	89% loss
Rocky Intertidal	1 (2)	1 (2)	12% loss
Riverine Tidal	278 (687)	41 (101)	85% loss

6.6 Summary and Conclusions

Human activities such as clearing of log jams, logging, diking, and construction of levees, dams and roads, and dredging have influenced the flow and sediment transport of the Skagit River, changing distributary channels and related sediment transport processes in the Skagit estuary. The delta area is likely to be influenced by human induced climate change due to impacts on sea level, glacial recession, changing flood magnitude, and resulting changes in sediment sources and transport processes, but many uncertainties about the direction of change are present. Key findings on historical and projected changes in geomorphology in the Skagit River include the following:

- Dikes and levees have isolated numerous distributaries in the Skagit River from the riverine environment. As a result, the remaining distributaries are located at the outlet of the North and South Forks of the Skagit River. Sedimentation in the outlet of the North and South Forks has resulted in progradation and the formation of new (or altered) tidal channels, although since the 1940s it appears the a majority of the sediment delivered to the delta has largely bypassed the shore and tidal flats, This represents a lost resource to the delta that would help to mitigate the impacts of sea level rise. The redirection of fine sediment offshore has impacted habitats via offshore burying, formation of fragmenting sea grass complexes and changing substrate conditions for invertebrates, plants and fish.
- Following a shift in the dominant flow path from the South to the North Fork, the progradation rate of the South Fork declined in comparison with the North Fork. Since about 1980, the South Fork marshes may have actually started to erode. The cause of this decline of progradation rates is not clear but one suspected cause is sea level rise associated with post-1970 climate change.
- Human activities have influenced sediment supply to the Skagit River. Sediment supply and transport in the basin has been increased by the clearing of logjams, dredging, logging, and road construction. Dam construction has trapped sediments in the headwaters. Sediment loads have also increased due to glacier retreat, particularly in the Sauk and Cascade River basins.

- Increased sediment loads would be expected in the Skagit River due to ongoing glacier retreat and associated geomorphic hazards such as rock avalanche, debris flows and moraine dam failures. Sediment loads would also be increased by accelerated bluff erosion or collapse resulted from storms with large waves especially when combined with high tides, although it is unclear if these increased sediment resources would ultimately contribute to delta formation or be redirected offshore.
- These historical impacts and case studies simulating the effects of sea level rise with current diking in place suggest future decreases in the areal extent of freshwater and tidal marsh. An alternative hypothesis, however, is that rapidly increasing sediment supply from glacier recession and more intense peak flows could potentially mitigate some of these losses by rebuilding the delta as sea levels rise. Results from one case study also show that removal of existing dikes has the potential to dramatically increase transitional and salt marsh habitat under sea level rise scenarios due to flooding of undeveloped land. These changes also highlight the vulnerability of the near-shore environment behind the dikes to sea level rise.

URL 1: http://www.nps.gov/mora/parknews/upload/TahomaSum07pgs5,6.pdf

URL 2: http://www.theolympian.com/2010/12/05/1463622_rocks-on-the-move.html

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