Habitat Monitoring Strategy for the Tidal Skagit Delta

Integrating Landscape and Site-scale Perspectives

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1. Problem Statement

The Skagit Chinook Recovery Plan (SRSC & WDFW 2005) notes that tidal rearing habitat in the Skagit Delta is a limiting factor in Chinook recovery. Consequently, the recovery plan evaluates the potential for restoring 2700 acres of tidal marsh in the delta to recover Skagit Chinook populations, although the actual acreage necessary for Chinook recovery will depend on the quality of individual restoration project results, the landscape context and connectivity of the projects, and indirect and cumulative effects of landscape management—including the restoration actions themselves. The Skagit Chinook Recovery Plan describes a monitoring plan to relate the distribution, abundance, productivity, and migration timing of juvenile Chinook salmon in tidal marshes and nearshore habitats to habitat restoration (Greene & Beamer 2005). This Chinook monitoring plan is a rare example of validation monitoring (sensu Roni 2005, Roni et al. 2005) of Chinook habitat restoration that also addresses important questions about the effects of landscape structure and cumulative effects. Likewise, the recovery plan describes ongoing monitoring of returning adult salmon of all species, an activity central to harvest management as well as restoration monitoring.

Because Chinook salmon are the focus of habitat restoration in the Skagit Delta, it is logical to monitor them to evaluate their response to management actions taken on their behalf. However, only monitoring salmon is not enough, because this provides limited insight into what habitat restoration means; how or why a restoration project is a success or failure; or how restoration should be done most effectively. There are many environmental factors which affect salmon use of habitat (water temperature, dissolved oxygen content, salinity, depth, velocity; prey production within tidal channels or in habitat adjacent to channels; predation from other fish or birds; and the spatial distribution of habitat and migration corridors). Each of these factors is affected by a network of other environmental interactions. Failure to restore any one of the network links can impair the value of a presumably restored site. Consequently, additional monitoring of other system parameters is required to understand how or whether a particular restoration site, or suite of restoration sites benefits salmon. Ideally, habitat and Chinook population monitoring should be integrated to mechanistically link habitat restoration to salmon ecology. Elucidating the intervening links between restoration actions, habitat development, and salmon response will make restoration more effective and predictable. Consequently, what follows is a habitat monitoring plan, not a plan to monitor faunal populations of management interest such as Chinook salmon, waterfowl, shorebirds, Dungeness crabs, etc. If habitat quality and quantity limit population viability then habitat itself must be evaluated through monitoring to assess the need and potential for habitat protection and restoration, and to subsequently assess the efficacy of habitat protection and restoration actions. This will require integrating monitoring over a variety of scales and include effectiveness, validation, baseline, and status and trends monitoring (Roni 2005, Roni et al. 2005).

The monitoring strategy described here is habitat-centric rather than centered on any particular taxon. Chinook salmon's legal and ecological status as a threatened species provides considerable social and political impetus to habitat restoration. However, their habitat needs often overlap with those of many other species of management interest, including other salmon, waterfowl, shorebirds, beaver, and many others. This is particularly true when Chinook habitat is viewed from a broad systemic perspective, rather than the narrow perspective of direct physical occupancy. For example, juvenile Chinook salmon directly occupy tidal channels. However, those channels cannot provide maximal rearing opportunity without being maintained by the tidal prism provided by tidal marsh drainage basins. Nor can tidal channels provide maximal trophic support without detrital inputs from the tidal marsh vegetation growing in their drainage basins. Thus, tidal channels cannot be considered in artificial isolation from the tidal marsh matrix in which they are contained—just as streams and lakes cannot be sensibly separated hydrologically, geologically or ecologically from their watersheds, floodplains or littoral zones (Hynes 1975, Wetzel 1990). Habitat must be considered from a systemic perspective as well as a local perspective. Doing so allows habitat restoration to benefit a community of organisms dependent on that habitat rather than merely benefiting one or a few management targets.

2. Goals

The Skagit Delta Tidal Habitat Monitoring Strategy described here does not provide a prescription for required monitoring methodologies. Methodological guidance is available in the relevant primary literature (e.g., Neckles et al. 2002) and is broadly reviewed in several useful reference books and reports (e.g., Greig-Smith 1983, Bonham 1989, Elzinga et al. 2001, Zedler 2001, Bartone 2005, Rice et al. 2005, Roegner et al. 2008). The choice of monitoring methodologies is often dependent on circumstances, e.g., the purpose and goals of the monitoring effort, the variables to be monitored, site constraints, scale, available funds, new technology, and others, which makes narrow prescription hazardous. Furthermore, a focus on methodology often detracts from a more important focus on the purpose and goals of monitoring. The Skagit Delta Tidal Habitat Monitoring Strategy focuses on developing a rationale for a particular set of monitoring goals and questions that will direct monitoring effort in the Skagit marshes. Appropriate methodology will be chosen in the course of particular monitoring efforts with guidance from the scientific literature.

The goals of the Skagit Delta Tidal Habitat Monitoring Strategy are:

Goal 1: Produce and evaluate design, planning, and engineering tools for restoration.
Goal 2: Evaluate success of individual restoration sites.
Goal 3: Evaluate reference conditions and landscape context of restoration sites.
Goal 4: Evaluate system trends, e.g., effects of climate change, cumulative effects of restoration.
Goal 5: Evaluate success of a suite of restoration sites collectively (i.e., interactions, synergies, indirect effects, cumulative effects).
Goal 6: Evaluate system resilience.
Goal 7: Improve understanding of ecosystem patterns and processes.

Monitoring is often categorized as implementation, effectiveness, validation, baseline, and status and trends monitoring (Roni 2005, Roni et al. 2005). While such categorization can be useful, it can also be limiting if narrowly followed. The Skagit Habitat Monitoring Strategy is driven first and foremost by a desire to test particular monitoring hypotheses (described later) and to develop restoration design and planning tools. Many of the strategy's goals can be addressed by one of these monitoring categories, but they are best addressed by integrating and synthesizing several monitoring categories. For example, goal 2 is usually addressed by effectiveness monitoring, but optimal statistical design (e.g., Underwood 1994) requires baseline and status and trends monitoring as well. Although, goal 3 could be addressed only by baseline monitoring, and goal 4 only by status and trends monitoring, the remaining goals should be addressed by a combination of validation, baseline, and status and trends monitoring.

Several terms in the goal statement require definition, which follows:

2.1 **Definition:** *Success*

Success in the context of habitat restoration is generally considered achievement of restoration project goals. Each project may have a variety of goals, some of which will be common to all projects. This habitat monitoring plan focuses on in-common project goals and anticipates two categories of goals: [1] restoration of natural physical processes (e.g., riverine and tidal flooding, sediment transport/storage, distributary dynamics) that sustainably and resiliently drive ecosystem patterns and processes, i.e., form and maintain habitat structure, processes, and functions; and [2] restoration of sustainable and resilient natural or reference ecological patterns and processes (e.g., vegetation zonation, primary and secondary production, decomposition, competition, herbivory, predation, etc.).

Success in the context of landscape-scale evaluation of restoration is rarely considered, because habitat restoration is usually a site-focused activity. Goals are rarely developed on a landscape-scale, except to determine a target acreage or a potential footprint. For this monitoring plan, landscape-scale success will be defined by the degree to which natural landscape-scale physical processes and synergies (e.g., distributary dynamics, sediment routing, allometry of tidal prism and channel geometry [Hood 2007a]) as well as landscape-scale ecological patterns and processes (e.g., habitat zonation or gradients, habitat diversity, juvenile salmon migration routes and salmon distribution) are restored to a reference condition.

Finally, it should be noted that success is not necessarily a binary concept. There are degrees of success and there are qualified successes (Zedler & Callaway 2000). Nevertheless, one should not be shy about declaring failure and taking corrective action.

2.2 **Definition:** *Reference condition*

Restoration goals and success need to be evaluated with reference to a standard, i.e., a reference condition. Reference conditions are usually an ecologically healthy historical state from which a currently dysfunctional system has deteriorated. However, healthy historical ecosystem conditions are often poorly understood because they no longer exist and were poorly documented when they did exist. Incomplete knowledge of past ecological conditions can lead to a “shifting baseline” understanding of reference conditions. The apparent baseline condition may, in fact, not be the true baseline historical condition, so that standards for restoration may often be too low because the magnitude of system deterioration is not fully appreciated (Jackson et al. 2001). It is important to have an accurate baseline against which to evaluate the deterioration of the current system, to develop appropriate restoration goals, and to measure system recovery.

Ecological legacies of historical system management are pervasive, profound, and likely unrecognized in many situations (e.g., Jackson et al. 2001, Hood 2002a, Walter & Merritts 2008). Recently, several such hidden legacies have been revealed in the Skagit

Delta (Hood 2004, 2007). Consequently, we cannot rely solely on apparently natural habitat remnants to provide reference standards for habitat restoration—this apparent baseline has likely shifted. Instead we must refine our understanding of historical reference conditions by using information acquired through a combination of sources, including paleoecology, archaeology, historical archival materials, remnant habitat, basic understanding of system processes, and measurements of ecosystem condition across a wide range of natural and anthropogenically altered conditions. As a result of the dynamic nature of the scientific process, our understanding of historical reference conditions will constantly evolve as new information and tools become available.

3. Conceptual Model of Restoration/Amelioration

During the Pleistocene (1.8 million yrs bp-12,000 yrs bp) cycles of cool global climate and widespread glaciation controlled planetary ecology and geomorphology. During the Holocene (~12,000 yrs bp to ~1800 CE) warming climate, retreating glaciers, and rising sea-levels controlled global ecology and geomorphology. We currently live in a period of planetary history which geologists are now calling the Anthropocene, because humans are now the dominant climatic, geomorphological, and ecological agent on the planet (Syvitski & Milliman 2007, Zalasiewicz et al. 2008). While the current consensus dates the Anthropocene from ~1800 CE (the approximate start of the industrial revolution) to the present, a significant dissenting view would argue for an earlier date (Ruddiman 2003), because humans have caused large-scale and irreversible ecosystem change in antiquity (Redman 1999, Alroy 2001, Jackson et al. 2001).

"Ecological restoration" has been defined by the Society for Ecological Restoration as "*…the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed.*" This definition is vague because is begs the question: degraded, damaged, or destroyed compared to what standard? A common connotation for ecological restoration is return of an ecosystem (or a significant part of the system) or a threatened population to a pre-industrial or pre-Anthropocene reference condition. Although sensible, this conception of "restoration" is problematic. We live irretrievably in the Anthropocene, and the physical momentum which has already accumulated in the planetary climate system and biosphere since the industrial revolution cannot be reversed for at least several centuries (e.g., Rahmstorf 2007). Additionally, there are significant socio-economic barriers to large-scale restoration of systems to pre-Anthropocene conditions. We must admit that we can restore few, if any, ecosystems to pre-Anthropocene conditions. We can only ameliorate ecosystems, particularly in areas like Puget Sound where the ecological footprint of civilization has profoundly altered ecological structures and processes throughout the region.

Ecosystem amelioration often focuses on recovering desirable ecosystem functions, such as sufficient production of wild Chinook salmon to support sustainable commercial harvest. This practical goal falls well short of restoring Chinook populations to their historical, pre-industrial abundance. System restoration or amelioration should also focus on restoring or increasing inherent system properties of self-sustainability and resilience to disturbance while the system exists in a desirable condition. Thus, while we cannot return an entire system to a pre-Anthropocene reference condition, we can strive to return significant portions of the system to a condition resembling such a reference condition, i.e., sufficiently restoring system processes and structure to sustainably and resiliently recover important ecosystem functions.

3.1 **Definition:** *Resilience*

The concept of resilience is critical to system management, especially with regard to restoration or amelioration (for reviews see Gunderson 2000, Folke et al. 2004). Resilience is related to [1] the magnitude of disturbance a system can absorb while remaining within a given desirable state, i.e., maintaining desired structure, functions, and feedbacks; [2] the degree to which the system is capable of self-organization (versus organization forced by external factors like human infrastructure); and [3] the degree to which the system can build capacity for learning and adaptation, e.g., through monitoring, research, and adaptive management (Folke et al. 2004). Note that degraded systems can also exhibit resilience to change and remain in an undesirable condition despite attempts to restore the system to a pre-existing desirable condition. However, the concept of resilience is usually applied with reference to the desired system state.

Threshold effects and hysteresis are central to the concept of resilience in multi-state systems. These are illustrated through a well studied example, cultural eutrophication of shallow lakes (Figs. 1 and 2). As agricultural or urban development increase nutrient inputs to a lake, phytoplankton blooms occur which increase system turbidity and reduce the amount of light reaching submerged aquatic vegetation (SAV). As vegetation consequently dies off, lake sediments and sediment-bound phosphate are more easily resuspended by waves. This positive feedback further increases nutrient concentrations and phytoplankton biomass in the water column and leads to a stable (but undesirable) system of high turbidity, low SAV, low fish abundance/diversity, and low waterfowl abundance/diversity (Scheffer et al. 1993). The system exhibits hysteresis because the nutrient threshold above which the system converts from SAV-present to SAV-absent is different from the threshold below which it reverts to SAV-present from SAV-absent. Even if the nutrient load is reduced to values well below those at which system collapse occurred, shallow lakes tend to remain in a highly turbid, eutrophic state.

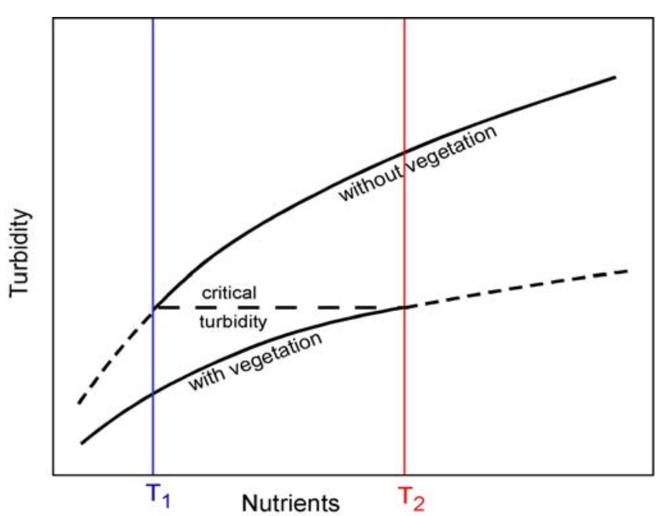

Figure 1. Alternative-equilibrium states of shallow lakes. Presence of submerged aquatic vegetation (SAV) depends on whether critical nutrient and turbidity thresholds are exceeded. There are three critical thresholds in this system, a turbidity threshold above which SAV cannot exist, a nutrient threshold above which phytoplankton populations explode (T_2), and another nutrient threshold below which phytoplankton populations crash (T_1). Figure modified from Scheffer et al. 1993.

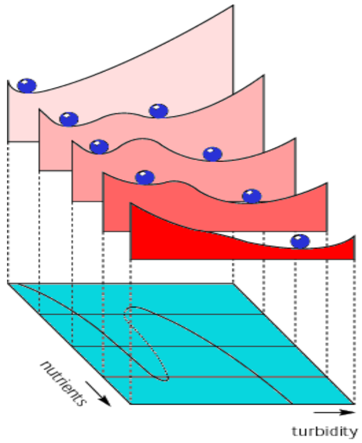

Figure 2. "Marble-in-a-cup" representation of the stability properties of lakes at five different levels of nutrient loading (Scheffer et al. 1993). The system, like a rolling ball, will be attracted to stability valleys, corresponding to stable parts of the folded curve on the bottom plan; hilltops represent the unstable disequilibrium threshold turbidity, i.e., the dashed middle section of the curve on the bottom plan.

Below and above the two nutrient thresholds, the system has two stable alternative states—with and without SAV. Within the two thresholds the system is vulnerable to disturbance and flipping to the alternate state. For example, an SAV-present system with nutrient levels between T_1 and T_2 would be vulnerable to strong wind storms that could generate waves capable of resuspending lake sediments and associated phosphate; the closer to the T_2 threshold, the more vulnerable the system, e.g., a less powerful storm could be competent to flip the system. More resilient systems can absorb greater disturbances or imposed change without changing in fundamental ways. When massive transformation is inevitable, resilient systems can reorganize without sacrificing the provision of ecosystem services.

Threshold effects and multiple stable states have been demonstrated in a wide variety of ecosystems (Resilience Alliance & Santa Fe Institute 2004). Variables involved in system thresholds and that influence resilience are invariably those that are large-scale and slowly-changing such as landscape processes and legacies which control smaller scale and faster ecological processes. Consequently, resilience derives from landscape-scale processes and patterns that often can be restored only slowly, such as reservoirs of soil nutrients, heterogeneity of ecosystems on a landscape, or genotype and species diversity (Folke et al. 2004).

Resilience, thresholds, and hysteresis are determined by the nature and extent of feedback loops in the system. Feedback loops are an essential aspect of system self-organization. Negative feedback loops result in homeostasis. Positive feedback loops permit threshold effects and hysteresis. The more self-organizing the system, the fewer feedbacks need to be introduced by managers. If the system is strongly self-organizing, those feedbacks that do need to be built in by managers are not "delicate" or "sensitive," i.e., there can be significant error in the management feedback without the system deviating from the desired behavior (Walker et al. 2002).

Adaptive management is essential for socio-ecosystem resilience. It forms a feedback loop between management and the ecosystem that can increase system predictability and resilience (Fig. 3). The design of management experiments is key to developing reliable and actionable new knowledge. "Adaptive management" and "experimental management" are synonymous (Walters 1997, Ralph & Poole 2003). "*Adaptive management views policy as hypothesis…most policies are really questions masquerading as answers*" (Gunderson 1999). Implementation of adaptive management is often problematic because it requires a long-term commitment to monitoring. After extreme interventions, like restoration, ecological systems generally require many years to decades before they reach a dynamic equilibrium state which can be evaluated with reference to restoration goals. The time lag between initial management action, system equilibration, and later corrective reaction (if necessary) to monitoring results can challenge agencies that are pressed to demonstrate positive short-term results, and thus weaken their commitment to long-term investment in monitoring/adaptive management.

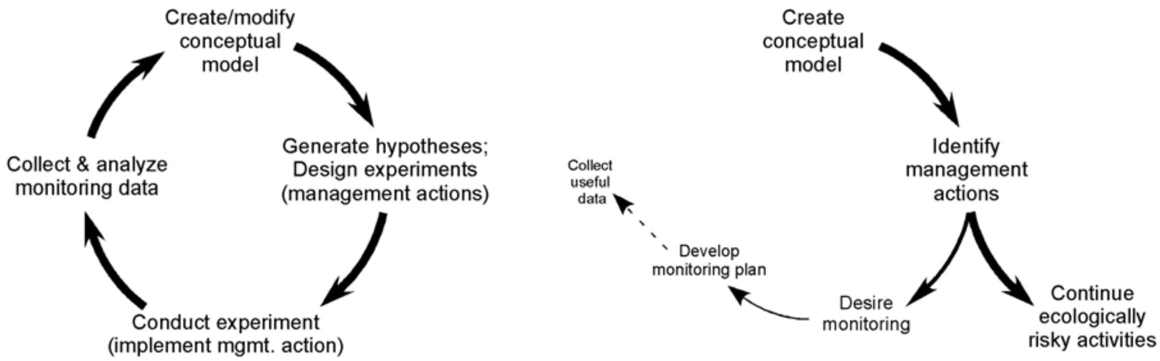

Figure 3. Representation of adaptive management feedback in its ideal form (left) and in its common realization (right). Adaptive management fails to occur when the feedback loop between restoration and monitoring is broken. This typically occurs because there is insufficient programmatic commitment to monitoring. Modified from Ralph & Poole (2003).

Resilience is difficult to measure and more difficult to predict. It has usually been demonstrated post-hoc in relatively simple ecosystems, often as a post-mortem examination of management mistakes. Nevertheless, the conceptual model of resilience and the known case studies of resilience illustrate [1] the scope of the dangers that can result from poor management, e.g., refractory alternate and undesirable stable system states; [2] the rationale for fundamentally sound approaches to management, e.g., focusing on maintaining or restoring natural ecosystem processes that structure habitat, and focusing on system-scale, rather than merely site-scale, management.

A focus on restoring a desirable ecosystem state (i.e., one that provides valued historical functions) that exhibits system resilience (i.e., resistance to disturbance and management error, and capacity for self-organization and sustainability) leads to a focus on restoring system relationships and processes. This contrasts with management that focuses on a single species or on merely recreating habitat structure or imposing structural controls. Single-species management or management that relies on rigid imposed control mechanisms to create short-term predictability lead to long-term system degradation and instability (Folke et al. 2004, Pikitch et al. 2004). Resilience restoration requires understanding the network of system relationships involved in forming ecosystem processes and patterns. This requires initial synthesis of existing system understanding into a conceptual ecosystem model.

4. Conceptual Ecosystem Model

A conceptual ecosystem model for the Skagit Delta (Fig. 4) serves several functions: [1] it provides a framework for organizing, synthesizing, and prioritizing existing knowledge of the ecosystem; [2] it illustrates the complexity of the system, even though the model shown below is a simplification of reality and shows little detail; [3] it illustrates landscape-scale linkages between parts of the network, e.g., watershed management (river and land management) profoundly affect delta geomorphology and ecology through their influences on river discharge, sediment supply, and nutrient inputs; [4] it illustrates the potential for feedback loops in the system that may facilitate either homeostasis or multistable-state dynamics; and [5] it provides a tool for communicating

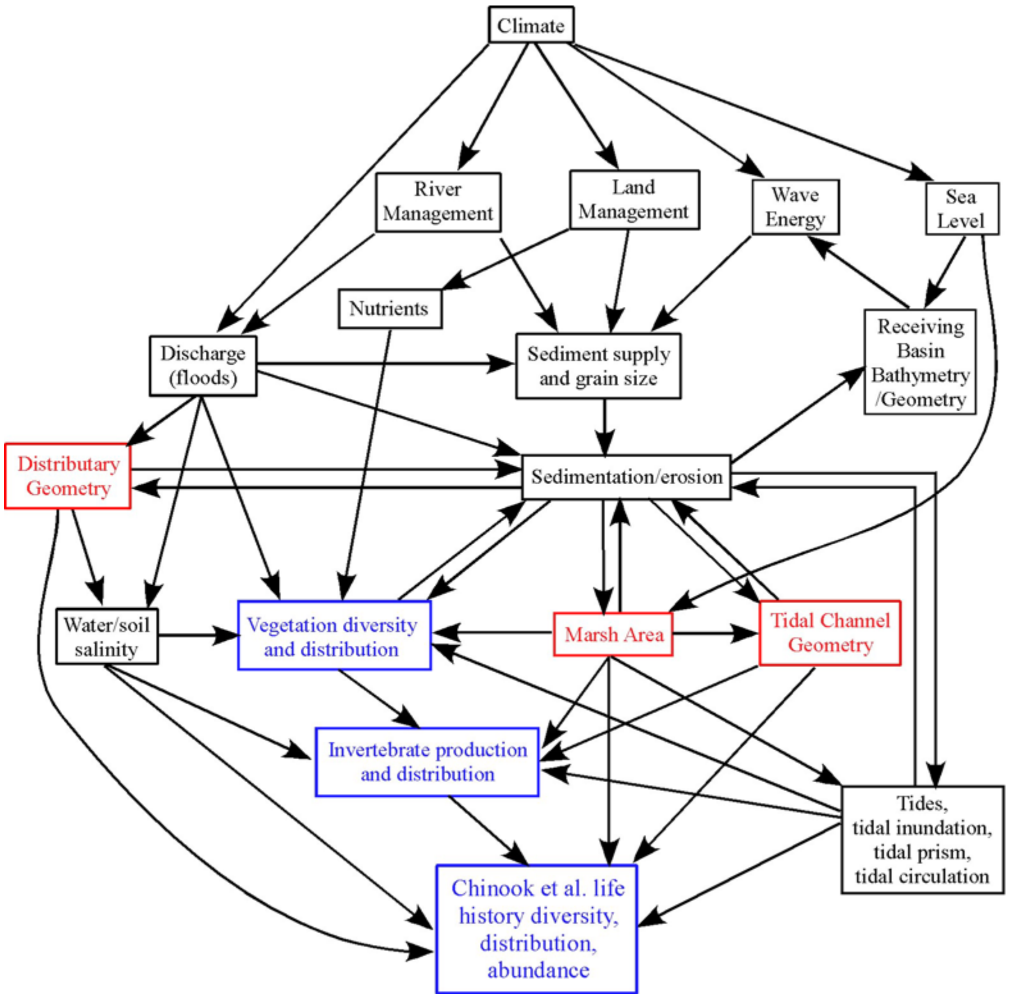

Figure 4. Simplified representation of Skagit Delta system network. Arrows are cause (base) and effect (arrowhead) linkages between system components. Red boxes are components that are often directly modified by estuarine habitat restoration actions through dike breaching/removal or channel excavation. Blue boxes are often ecological management objectives.

our understanding of the system to other scientists, managers, and the general public (Ogden et al. 2005).

The conceptual model presented here provides only a low-resolution overview of the system. For example, ducks, geese, shorebirds, herons, beaver and other fish and wildlife have been omitted in this version, as have significant processes like nutrient cycling. Similarly, different plant species are not distinguished, nor are benthic, epibenthic, or pelagic invertebrate species or functional groups. River management could be further resolved into different categories of management such as dam operation, levee and riprap maintenance/construction/removal, floodplain occupation/restoration, water withdrawals. Land management could be further resolved into types of development, use, or regulation. In addition, the model does not show whether relationships are positive, negative, or conditional. It does not show rates. It is not spatially explicit. In other words, model resolution is low. Nevertheless, the model is a useful starting point from which one can selectively increase the detail of sub-system models, depending on management objectives (e.g., section 6.4).

5. Monitoring Philosophy/Rationale

5.1 Hypothesis Testing & Tool Development

Restoration monitoring has typically focused on evaluating the structural similarity and/or functional equivalence of a restored site compared to natural reference sites. The more a restored site resembles reference conditions the greater the restoration success. Comparisons can be made over an endless variety of structural and functional parameters (e.g., Neckles et al. 2002). Generally, the greater the number of parameters evaluated the greater the confidence in the evaluation (Ruiz-Jaen & Aide 2005). However, there are diminishing returns with this approach because even reference sites differ from each other due to natural environmental heterogeneity, and the probability of finding differences increases with the number of parameters compared. Monitoring costs also increase with increasing parameters evaluated. This has led to a desire to prioritize the parameters to be evaluated. Prioritization should be based on the strength of the link between the monitored parameter and the management target (i.e., is the linkage direct or indirect, is there a cause-and-effect linkage or merely a correlation, is the linkage quantitative or qualitative) and the cost of monitoring the parameter.

The Skagit Delta Monitoring Plan advocates an alternative approach to monitoring, focused on testing predictive models and the underlying hypotheses upon which the models are based. This approach prioritizes monitoring parameters that are essential to model inputs and outputs. It also produces a planning and design tool (the predictive model) that can be used by planners, resource managers, scientists, and engineers involved in habitat restoration. Predictive tools are needed to provide greater certainty and guidance to the likely outcomes of potential restoration actions, and to inform policy. These tools can be either quantitative models or more general conceptual models. Restoration monitoring can test the accuracy and utility of these models, while comparing restoration/reference similarity (i.e., restoration success). It also provides a direct and necessary feedback to the engineering/planning tool development process, and such feedbacks are central to adaptive management.

Prediction is fundamental to the scientific process. Hypothesis testing involves making predictions based on available evidence and theoretical understanding, and testing those predictions against experiments or other observations. Science-based habitat restoration likewise depends on making and testing (i.e., monitoring) predictions of the outcome of a proposed restoration.

5.2 Monitoring Sequencing

Restoration monitoring often occurs only after a restoration project is implemented, but strong monitoring design also calls for pre-restoration (baseline) monitoring to allow before/after-control/impact paired series comparisons (BACIPS design; Stewart-Oaten et al. 1986, Stewart-Oaten 1996), preferably with replication of reference conditions (Underwood 1994). When baseline monitoring does occur, it is often hastily implemented, perhaps a year before restoration begins, so that often little insight is acquired into site characteristics, relevant system processes, the relationship of a site to its landscape context, or system variability and dynamics.

Baseline monitoring can include historical reconstruction of habitat conditions, quantification of current conditions, trend/threshold detection, evaluation of rates of change, and hypothesis testing. Baseline monitoring plays a vital role in precisely identifying and quantifying the extent of the ecological problem to be solved by restoration, e.g., the degree to which habitat has been lost, the type of habitat loss that has occurred, and the causes of the habitat loss. Restoration feasibility studies can sometimes provide some of this baseline information, but the scope of feasibility studies is often limited to the site scale and consequently provides limited information. Larger scale baseline monitoring often reveals hidden historical legacies that impact system function; provides landscape-scale and project-scale insight into system processes; may be used to evaluate system resilience; and informs and supports the appropriate solutions of the problem by suggesting proper restoration goals and design details (e.g., Hood & Hinton 2004, Hood 2004). Finally, it can be used to evaluate restoration as part of a BACIPS monitoring design. Thus, baseline monitoring is fundamentally necessary to restoration planning and evaluation. In this vein, the Intensively Monitored Watersheds (IMW) program is funding juvenile Chinook salmon monitoring on a landscape scale in the Skagit Delta. A spatially and temporally large-scale restoration plan, like the Skagit Chinook Recovery Plan, likewise requires large-scale baseline as well as post-project monitoring of restored and reference habitat.

6. Monitoring Questions/Priorities

There are a number of basic questions restoration project planners, designers, and engineers need answered to improve their ability to plan and design estuarine restoration. The questions occur at a variety of scales (treatment-scale, site-scale, and landscape-scale) and are described below. Treatment-scale questions are concerned with restoration tactics or techniques. Tactical questions can usually be addressed by project-scale restoration and monitoring design. Larger scale questions are concerned with restoration strategy and can be addressed in part by development of predictive models and/or long-term landscape monitoring.

Monitoring priorities for the Skagit Delta Monitoring Plan were set here by the relative importance of these questions, and by a qualitative assessment the complexity and likely cost of answering the questions. Cost was assumed to be highly correlated with complexity. Relative importance was determined by the experience, professional judgment, and limited expertise of the author, and by the relevance of the questions to the Skagit system and the Skagit River System Cooperative. Many of these questions are likely relevant to other systems. Nevertheless, other experts in other systems may reasonably quibble with how the questions were prioritized, and could readjust the priorities to fit their system's circumstances, their expertise and experience, and their monitoring resources.

6.1. Vegetation

Intertidal vegetation is the defining feature of a marsh. Healthy vegetation is critical to marsh persistence, particularly in the context of sea level rise or storm disturbance, because by stabilizing sediments and facilitating sedimentation it preserves marsh surface elevation within the tidal frame. Intertidal vegetation provides forage for ducks, geese, beaver and other herbivores. It also supports prey production (invertebrate herbivores and detritivores) for juvenile salmon, shorebirds, ducks and others. Prey production occurs on-site and off-site through tidal transport of organic material. Finally, marsh vegetation provides habitat structure (e.g., nests, cover) for wildlife.

6.1.1. The most common **treatment-scale** questions regarding restoration of estuarine wetland **vegetation** are listed below. There are many ancillary questions, but these are the most fundamental. They can be addressed by a combination of literature reviews, interviews with restoration practitioners, and treatment-scale experimentation during site restoration.

1. *Does vegetation need to be planted on a restoration site or can natural (passive) colonization be successful?*

There appears to be a growing consensus that passive colonization is feasible for restoration of most estuarine emergent marshes because there is generally a sufficient seed source. The first year of plant colonization is often dominated by relatively weedy annuals that are displaced in the second or third year by species typical of mature tidal marshes. Some exceptions may be in highly industrialized estuaries like the Duwamish or Puyallup where little marshland and few natural seed sources remain. Another exception may occur when there is a large competing non-native seed source, e.g., narrow leaf cattail (*Typha angustifolia*). In contrast, estuarine shrub and tidal forested (surge plain) wetlands will require planting to significantly accelerate development of these vegetation communities. There is some uncertainty surrounding this question, but it is relatively low, so this is a **low priority** for testing/monitoring.

2. *Are nurse logs necessary for woody species establishment (cf Hood 2007b) or can earthen mounds or site grading patterns provide substitute elevated platforms? Are nurse logs only necessary for seed germination, so that seedlings or cuttings can be transplanted directly on the site without site grading (depending on site salinity and elevation in the tidal frame)?*

The answer to these questions likely depends on the species involved. Sweetgale (*Myrica gale*) and willow (*Salix* spp.) are the most common shrubs found in the oligohaline portion of the Skagit tidal marshes. Willows are often found on tall channel berms, which suggests that elevation, rather than substrate (soil vs. wood) is the controlling factor. Sweetgale can be found on lower plains, but are disproportionately associated with large woody debris (LWD). Because, tidal shrub habitat has been devastated in the Puget Sound area, and in the Skagit Delta (Hood 2007b), greater attention to restoring this habitat type is likely warranted. This will require treatment-scale experimentation to answer the above questions. *In areas where tidal shrub restoration is appropriate*, this question should be a **high priority**.

3. *Does the site need to be prepped to enhance restoration rates or probability of establishing desirable species (e.g., discing the soil to break up roots of existing, non-target vegetation and reduce their competitive interaction with desired colonists; stripping the top-soil to remove the rhizomes and seed-bank of non-native species).*

Site preparation by discing vegetation into the soil seems a logical approach to facilitating site recovery. Stripping top-soil, while advocated by some restorationists, has the drawback of significantly reducing site elevation which directly affects vegetation colonization, tidal prism, and potentially drainage patterns. Another drawback is the additional restoration cost involved. There is relatively little experience with this suggested tactic. In situations where site preparation may be applicable (e.g., sites dominated by reed canarygrass [RCG, *Phalaris arundinacea*]), this question should be experimentally addressed and monitored. Few such sites exist in the Skagit Delta, because most potential restoration sites are agricultural areas that are already regularly plowed. However, the Wiley Slough site does have a few areas where RCG is established, and where this question could be addressed. In this case the question would be a **high priority** for investigation.

4. *How can non-native plant species be best controlled?*

The most common non-native plant species in the Skagit tidal marshes are: narrow-leaf cattail (*Typha angustifolia*), RCG, Japanese knotweed (*Polygonum japonicum*), purple loosestrife (*Lythrum salicarium*), and Spartina (*Spartina* spp.). By far the most common is narrow-leaf cattail. SRSC is currently engaged in a treatment-scale experiment to control narrow-leaf cattail in a 3-acre portion of the Deepwater Slough restoration site. However, this question runs the risk of focusing exclusively on treating a symptom (presence of exotic species) rather than the systemic cause of the problem, which may be nutrient pollution. Many studies have shown that nutrient enrichment in wetlands causes plant communities to change dramatically and species richness to decline (Bedford et al. 1999, Svengsouk & Mitsch 2001). Two uncertainties weaken the priority of this question: [1] Is the problem tractable—is there any hope of controlling widespread species like narrow-leaf cattail? [2] Can we address the root cause of non-native species invasion, which may be systemic nutrient pollution, the presence of established propagule sources, or another cause? These uncertainties need to be answered to determine the probability of achieving long-term control. **Priority = medium**.

6.1.2. The fundamental **site-scale vegetation** questions are:

1. *If tidal hydrology is restored to a site, will vegetation colonize the site, or will the site be an unvegetated tidal flat?* **Priority = high**.
2. *What species of vegetation will colonize? What determines which species will colonize and their spatial distribution?* **Priority = high**.
3. *Will vegetation persist in the face of anticipated sea-level rise?* **Priority = high**.
4. *How quickly will a tidal vegetation community develop?* **Priority = medium**.

Site-scale questions 1-2 can be addressed by a relatively simple model that uses site elevation (or tidal inundation frequency and duration) and salinity as independent variables and vegetation species presence as the response variable. Such a model is currently being developed and tested for the Skagit Delta (Figs. 5, 6) and could be relatively easily generalized to include the Snohomish Delta and other Puget Sound sub-systems. Further elaborations of the model could include sediment type and disturbance regimes as additional independent variables, and plant height, stem density, above-ground biomass, and below-ground biomass as additional response variables. Development and testing/monitoring of this predictive vegetation model is of the highest priority because of its fundamental utility for restoration planning and design. Persistence in the face of sea-level rise can be modeled from a combination of vegetation modeling (developed to address questions 1 and 2) and marsh accretion modeling. Such an effort is currently underway for the Skagit Delta. Trend monitoring will be essential to test model predictions and provide early detection of sea-level rise effects. The rate of vegetation community development cannot be easily modeled, but instead requires observational data from past, present, and future restoration monitoring efforts.

6.1.3. Important **landscape-scale vegetation** questions are:

1. *How do restoration projects interact with each other depending on their connectivity to each other (physical interactions [hydraulic effects, sediment routing] and ecological interactions [sources of recruitment, community composition, daily to seasonal migratory pathways of associated biota and their relationship to population productivity, trophic subsidies])?* **Priority = medium**

These lead to the following questions:

2. *What vegetation communities characterized the historical landscape?*

This question cannot be answered or tested by restoration and monitoring, but it can through research. This question has been answered, although not at high resolution, by Collins et al. (2003). For example, it is unclear which emergent marsh plant species have been displaced by the invasive non-native narrow-leaf cattail. Efforts are underway to reconstruct past presence and distribution of eelgrass by the USGS. **Priority = medium**

3. *Which of these communities are now rare in the landscape?*

This question has been answered in part by Collins et al. (2003) and Hood (2007b). Like question 3 it must be further pursued by research rather than restoration and monitoring. **Priority = medium**

4. *Has nutrient pollution (cultural eutrophication) from agricultural and urban development affected plant species composition and distribution in the Skagit Delta?*

Nutrient enrichment is associated with declines in species richness and displacement of native species by invasive non-natives. (Bedford et al. 1999, Svengsouk & Mitsch 2001). Cultural eutrophication in modern estuarine systems is nearly ubiquitous, especially near populous areas. It would be surprising if this were not a problem in the Skagit Delta and if it were not affecting vegetation distribution and community composition. However, it is possible that cultural eutrophication is modest due to the high proportion of the watershed that is forested (limiting nutrient inputs), the high discharge of the river (reducing nutrient concentrations, and perhaps low residence time in the marshes due to rapid river flushing to the bay and into deeper waters with active tidal circulation flowing through Deception Pass. **Priority = medium**

5. *How does the current connectivity between vegetation communities compare to the historical condition?*

This question has several contingencies. It depends on answers to questions 3 and 4, and the spatial and taxonomic resolution at which they are answered. It also depends on the resolution with which historical channel geometry can be resolved. Finally, it depends on the organism responding to habitat connectivity. Connectivity will be defined differently for plant propagules, fish, and waterfowl. We are not yet ready to propose relevant hypotheses that can be tested by landscape-scale habitat restoration, except with regard to juvenile Chinook salmon (*cf* Greene & Beamer 2005). **Priority = low**

6. *What ecological function has been lost as a consequence of reduced habitat diversity, abundance, and connectivity?*

Ongoing SRSC research (Hood, unpublished data) shows that beaver dams are associated with blind tidal channels in tidal shrub habitat, but not estuarine emergent habitat. Dams quadruple the amount of low tide pool habitat available to small fish (including juvenile Chinook) compared to channels without dams. Additionally, great blue heron are found foraging on fish only in the tidal emergent zone, probably because of shallower water (fewer low tide pools) and easier access to channels without overhanging shrub thickets. Fish densities (juvenile Chinook and three-spine stickleback [*Gasterosteus aculeatus*]) are 4-fold greater in low tide pools compared to shallows. Tidal shrub habitat is currently only 5% of what it was historically in the Skagit Delta (Hood 2007b). Almost 100% losses of this habitat type have occurred in the Stillaguamish and Snohomish River deltas (Collins et al. 2003). Thus, there has been a great loss of beaver habitat in the delta with likely significant impact to juvenile salmon production. These results suggest additional effort to restore tidal shrub habitat is warranted. They also suggest a specific case (i.e., tidal shrub-beaver-fish interactions) for testing this general hypothesis through restoration and monitoring. Further research is necessary on the ecological value of tidal shrub and other historical delta habitat types to other wildlife to generate additional versions of this hypothesis that can be tested by habitat restoration and monitoring. One can anticipate that restoration of former habitat diversity, abundance, and connectivity will increase species diversity with often unpredictable system benefits. Prediction of this issue would be a useful area of investigation. **Priority = high**

7. *How do gradients in physical processes and patterns (e.g., tidal inundation [elevation], flooding disturbance, and salinity; channel avulsion, channel network topology, sediment dispersal, LWD recruitment, others) currently structure this landscape and its vegetation communities. How do historical processes compare?*

SRSC has investigated LWD influences on vegetation and is currently investigating the role of distributary networks via their influence on soil salinity. Examination of historical aerial photos suggests relatively sudden, flood-mediated changes in channel morphology have lasting effects on vegetation communities. All of these factors affect marsh vegetation spatial heterogeneity, and all have implications for predicting and testing habitat restoration effects in different parts of the delta. SRSC research is currently generating hypotheses that can guide and be tested by restoration. **Priority = high**

8. *Will marshes be resilient to sea-level rise? Does this vary spatially?*

SRSC is investigating this question in collaboration with research partners. Preliminary modeling suggests tidal shrub communities may be very vulnerable to sea-level rise, with disproportionate losses compared to tidal emergent vegetation. Spatial variation in vulnerability will guide restoration planning. A likely recommendation will be to reduce risk of climate uncertainty by spatially diversifying our delta restoration portfolio. Spatial diversity in restoration sites will maximize current habitat diversity, including habitats receiving little attention and whose ecology is poorly understood, e.g., tidal sweetgale communities, other tidal shrub and forest communities, delta-river surge plains, and deltaic beaver marshes. Spatial site diversity also maximizes future habitat diversity, and diversifies possible habitat responses to climate change. Trend monitoring of changes in marsh vegetation species and their distributions can address this question, although care will need to be taken to rule out other agents of change, e.g., changes in nutrient pollution or various types of natural disturbance. **Priority = high**

9. *What are the spatial patterns of exotic plant species distributions (in addition to the nearly ubiquitous narrow-leaf cattail)? What physical factors affect marsh resilience with respect to exotic species invasion? Are the number or abundance of exotic species changing over time?*

Surveys of exotic species abundance and distribution could be related to channel planform, topography, sediment type, salinity, etc. These could in turn be related to flood and storm disturbance, with the underlying hypothesis being that disturbance-prone areas are likely to have high numbers and abundance of exotic species. This information would also provide sampling guidance on trend monitoring. Results could be used to evaluate restoration site vulnerability to exotic species invasion. **Priority = medium**

6.1.4. Vegetation Summary.

Landscape-scale questions are probably best addressed through a combination of GIS models, hydrodynamic models, and conceptual models that include consideration of island biogeography theory, stepping-stone theory, meta-population theory, corridor theory, disturbance theory, landscape allometry, and others (Margules et al. 1982, Kareiva 1990, Johnson et al. 1992, Rosenberg et al. 1997, Hood 2007c). Predictive models on this scale are rare due to development costs and the rarity of intact reference systems (at this scale) necessary to parameterize and validate such models.

The highest priority (regarding vegetation) for the Skagit Delta Tidal Habitat Monitoring Plan is development and testing of a site-scale to region-scale predictive model of estuarine vegetation distribution. This will allow predictive vegetation mapping (Franklin 1995, Yost 2008) and help answer site-scale questions 1, 2, 3 and landscape-scale question 9, and provide a practical tool for ecologists, planners, and engineers. It will also contribute to the development of morphodynamic models that integrate the effects of and feedbacks between hydrodynamics, sediment transport, and vegetation, and to models that better predict the ecological effects of sea-level rise. Furthermore, the goal of developing such a model could be achieved within the next few years if sufficient funding and commitment were available. The current GIS-linked model (version 1.0) accounts only for the effects of elevation, i.e., tidal inundation depth and frequency. SRSC is currently working to include effects of soil salinity (version 2.0). Another likely factor affecting vegetation could be sediment grain size (version 3.0). Complicating factors that would contribute to model error could be flood disturbance frequency (although this might be accounted for by proximity to a distributary), nutrient effects, establishment history (pre-emption), and grazing by waterfowl, among others.

Predictions generated by version 1.0 of the model are currently being tested (Figs. 5, 6). The monitoring methodology involves taking GPS (<1m accuracy) point samples of vegetation species presence at ~5-m grid intervals. A species map is made from these point samples and compared to the predicted species occurrence. Model success is quantified by the proportion of correct predictions. If biomass (above-ground or below-ground), stem density, or productivity were being predicted the sampling methodology would change accordingly (*cf* Neckles et al. 2002).

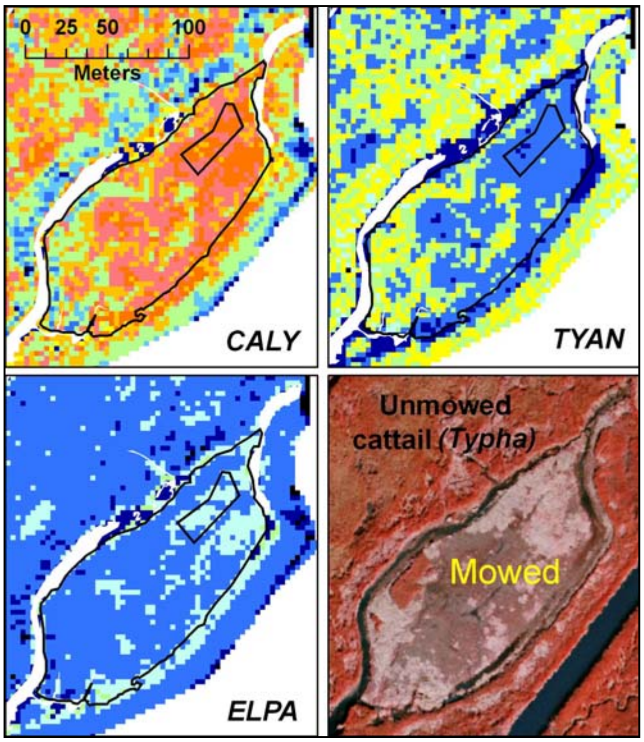

Figure 5. Predicted vegetation for part of the Deepwater Slough restoration site; CALY = *Carex lyngbyei* (sedge); TYAN = *Typha angustifolia* (cattail); ELPA = *Eleocharis palustris* (spike-rush); bottom right, infra-red aerial photo of the mowed site in 2006. An experimental 3-acre site was mowed over several years to remove pre-emptive competition from previously established non-native cattails. Cattails became established while the site was still diked, and were growing at an elevation that under normal tidal hydrology supports primarily sedge. Without pre-emptive competition, site elevation should be the primary determinant of vegetation distribution in this oligohaline site (soil salinity is 0-2 psu).The cool-to-warm color ramp represents low-to-high probability of species occurrence. Predictions were generated from species/elevation field surveys (n = 600) in oligohaline Skagit Delta reference marshes, which were then linked to lidar data.

6.2. Tidal channels

Estuarine tidal channels are conduits for water, sediment, nutrients, detritus, and aquatic organisms, and thus link the nearshore marine environment to highly productive tidal marshes (Simenstad 1983, Odum 1984, Rozas et al. 1988, Pethick 1992, French & Spencer 1993). Tidal channel geometry affects hydrodynamics (Rinaldo et al. 1999), sediment transport (French & Stoddart 1992), and the distribution and production of flora (Sanderson et al. 2000) and fauna (Levy & Northcote 1982, Halpin 1997, Williams & Zedler 1999, Hood 2002b). Consequently, understanding tidal channel geometry is key to understanding geophysical and ecological processes in tidal marshes and associated tidal flats.

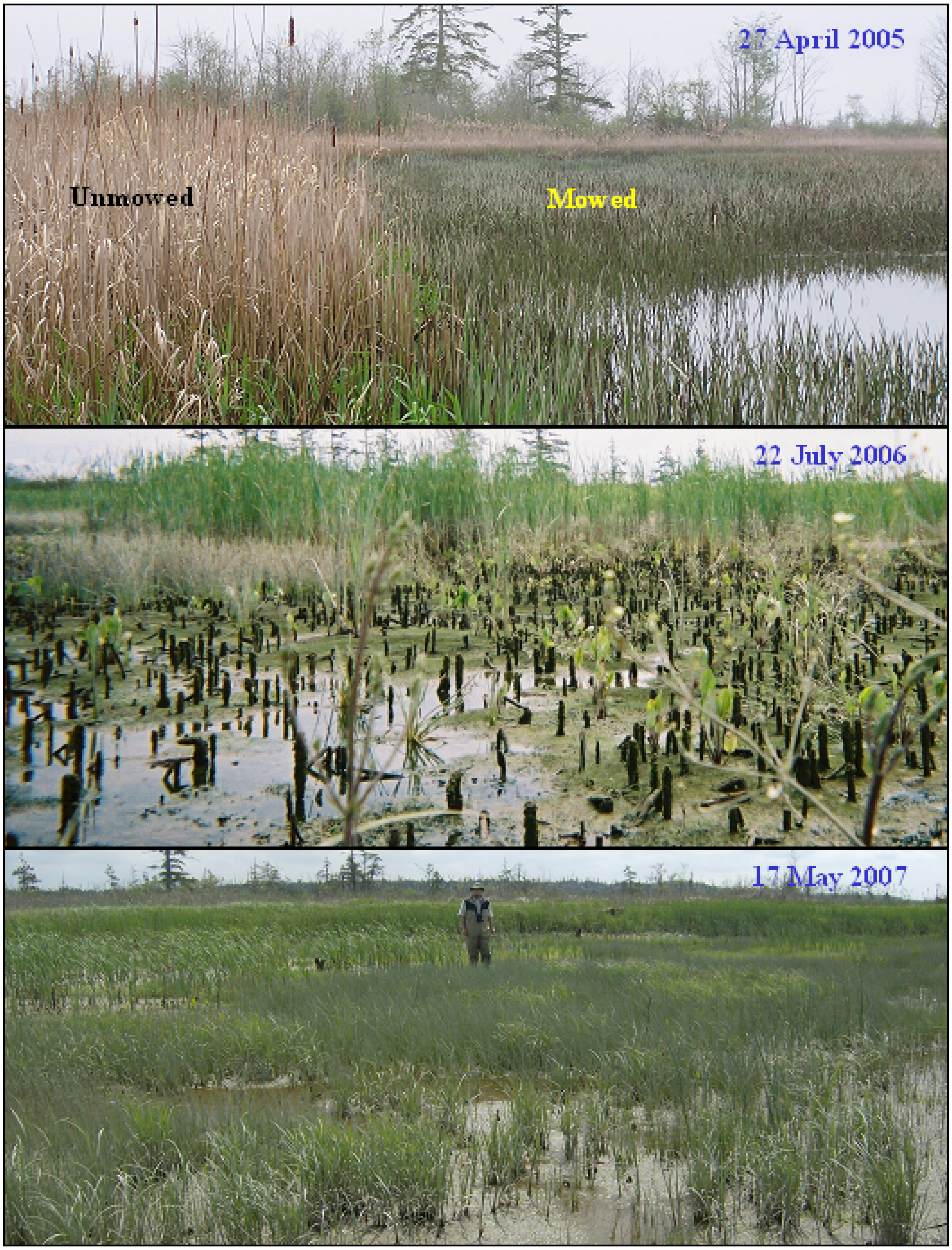

Figure 6. Site vegetation at various times during experimental treatment of the Deepwater Slough site in Figure 5. The top frame shows mowed and unmowed *Typha*, two years after the first mowing. The middle frame shows dead stumps of *Typha* in the foreground and colonizing *Alisma triviale*, which is normally uncommon in the reference marshes, occurring only in areas of low elevation and very low salinity. The bottom frame shows colonizing *Carex lyngbyei* and *Eleocharis palustris* in the foreground, and some *Typha* regrowth in the background.

6.2.1. Common **treatment-scale** questions regarding tidal channel restoration are:

1. *Should tidal channel networks be excavated or can they carve themselves through tidal erosion?*

This question can be addressed through restoration experiments, but may also be addressed through change analysis of historical photos of incidentally breached sites. Change analysis is underway for sites in the Skagit and Snohomish Deltas in a collaboration between SRSC and the Tulalip Natural Resources Dept., although the work is progressing slowly due to very limited funding. **Priority = high**.

2. *How quickly can tidal channels develop through tidal erosion?*

This question applies to channel developing *de novo* as well as excavated or pre-existing remnant channels, but which may elongate or develop tributary channels following tidal prism restoration. It can be addressed through change analysis of historical breaches and monitoring of current restoration. **Priority = high**.

3. *Will site prepping (e.g., discing to break up plant roots) accelerate passive erosional tidal channel development?* **Priority = high**.
4. *How much of a channel network should be excavated and how much can be allowed to erode?* **Priority = medium**.
5. *What size should the channels be if excavated? What size will they become if allowed to erode to a point of dynamic equilibrium?* **Priority = high**.
6. *Does channel sinuosity matter?* **Priority = high**.
7. *Will excavated tidal channels persist or will they fill with sediments?* **Priority = high**.
8. *Should borrow ditches and drainage ditches be filled during site restoration to promote natural channel formation and channel geometry?* **Priority = medium**.
9. *What is the ecological significance of tidal channel geometry?* **Priority = high**.

An important caveat should be mentioned regarding tidal channel experimentation at the treatment versus site scale. It can be challenging to hydraulically isolate tidal channels to create experimentally independent treatment and control sites (Hood 2006). Often the treatment scale and site scale must be the same, so that experimental replication will require multiple and independent sites.

Treatment-scale questions 1 and 7 are currently unsettled and controversial (Hood 2006). Answers to the questions are probably contingent on local conditions, likewise for questions 2-5. Defining those conditions through restoration related experimentation would be useful. Question 2 can be answered in part by literature review (Hood 2006), but requires further restoration monitoring to better characterize variation in rates and the causes of that variation. Question 5 has been partially addressed in the Skagit marshes with a model of channel allometry (Hood 2007a). Question 6 has been investigated in the Skagit, but only with some pilot sampling of benthic invertebrates. Results, though preliminary, suggest meaningful relationship between sinuosity and benthic productivity (Hood, unpublished data). A consensus exists among regional and national experts on question 8, who argue from first principles that borrow ditches and drainage ditches should be filled, particularly if they orthogonally intersect natural drainage paths (Simenstad, University of Washington, personal communication). Nevertheless, it would be useful to test this recommendation. Some literature can answer question 9, but significantly more research is needed on this issue (reviewed in Hood 2007c).

6.2.2. Common **site-scale** questions regarding tidal channel restoration are:

1. *How many channels should one excavate or expect to develop through erosion?*
This question has been addressed in an empirical channel allometry model developed for the Skagit (Hood 2007a), but it requires testing through habitat restoration/monitoring. **Priority = high**.

2. *What size distribution of tidal channels should one expect or excavate?*
This could be addressed through extension of the Skagit channel allometry model. **Priority = high**.

3. *Are there differences in the resulting channel network geometry between dike breaches and dike removal?*
This analysis is underway for sites in the Skagit and Snohomish Deltas in a collaboration between SRSC and the Tulalip Natural Resources Dept., although the work is progressing slowly due to very limited funding. It will also depend on long-term monitoring of Deepwater Slough and Wiley Slough restoration sites where extensive dike removal has occurred (DS) or will occur (WS) in the near future. **Priority = high**.

4. *If dike breaching rather than dike removal is employed for restoration, how many breaches should be made and how wide should they be?*
Hydraulic geometry has been used to guide breach design (Williams et al. 2002). However, recent experience has shown that breaches can widen beyond expectations, which is problematic if bridges span the breach. One cause of the problem may be that changes in tidal prism are not anticipated as the site evolves. Another may be that hydraulic geometry predicts an equilibrial channel cross-section endpoint, but it does predict the evolutionary path that a channel may take to that equilibrium point. Self-restoring channels usually deepen beyond the predicted equilibrial endpoint, then widen and shoal again through bank failure. A better understanding is required, not only of equilibrial endpoint prediction, but also of the potentially non-linear evolutionary pathway towards that endpoint. **Priority = high**

5. *Are there differences in channel network geometry for sites where drainage/borrow ditches were filled vs. left unfilled?* **Priority = medium**.

6. *If there are differences (#3 and #4 above) are they ecologically significant?*
This question will require significant research effort. **Priority = high**.

In the last ten years, self-regulating tide-gates (SRTs) have been increasingly advocated as an engineering approach to habitat restoration that minimizes impacts to residential or agricultural landuse. SRTs close once the incoming (flood) tide reaches a pre-determined elevation. This allows controlled, only partial tidal filling of a drainage channel, and allows property adjacent to the drainage channel to remain dry. SRTs have been installed in Edison Slough and McElroy Creek in the northern end of the Skagit Delta, and in channel outlets that drain former tidelands on the northwest side of the Swinomish Channel. Because SRTs do not fully restore tidal inundation, tidal prism, or tidal flushing energy and because they allow little or no tidal marsh restoration, they ameliorate impacts to tidal channel habitat rather than actually restoring integrated marsh-channel ecosystems. While SRTs appear to be appealing because they seem to allow farms and salmon to co-exist, the ecological and geomorphological limitations and benefits of this approach are poorly understood. There is significant concern that by limiting restoration of tidal processes, SRTs will only allow limited geomorphological and ecological benefits. For example, natural tidal channel flood velocities typically peak when the tide rises above the adjacent marsh surface, while ebb tide velocities peak just as the tide drops below the adjacent marsh surface (Bayliss-Smith et al. 1979, French and Stoddart 1992, Friedrichs and Perry 2001). Because SRTs are designed to prevent tides from overtopping channel banks, SRT-controlled channel hydrodynamics will be dramatically altered and SRT-controlled tidal channels are likely to be characterized by significantly lower tidal velocities compared to fully restored channels. These altered hydrodynamics will likely have significant effects on sediment and detrital transport, with likely cascading effects on channel geometry, benthic invertebrate community structure and productivity, fish use, and perhaps water quality. Consequently, SRTs are a controversial compromise between competing visions of landuse. Several critical questions arise from the proposed use of SRTs.

7. *How does the equilibrium geometry of SRT-controlled tidal channels compare to that of natural tidal channels? How much channel habitat is actually restored by an SRT compared to what might be restored by full tidal flushing?*
8. *How do ebb and flood tidal velocities over the tidal cycle compare between SRT-controlled tidal channels and natural reference channels?*
9. *How does water quality compare between SRT-controlled tidal channels and natural reference channels: temperature, salinity, dissolved oxygen, agricultural or residential pollutants?*
10. *Is a vegetated (upland or wetland) buffer along an SRT-controlled tidal channel necessary for, or effective at, intercepting and filtering agricultural or residential pollutants?*
11. *How do detrital accumulation, sediment grain size, and benthic community structure compare between SRT-controlled tidal channels and natural reference channels?*
12. *How does SRT gate design affect passage by benthic vs. surficial fish? Do vertically vs. horizontally oriented gates differ in passability by different types of fish? How do culvert invert and top elevation relative to the tidal frame affect fish passage?*
13. *How does fish community structure, density and feeding compare between SRT-controlled tidal channels and natural reference channels?*
14. *To what extent do SRTs increase salinity intrusion and reduce the productivity of nearby agricultural fields?*

These SRT-related questions are all of **high priority.**

6.2.3. Important **landscape-scale** questions regarding tidal channel restoration are:

1. *Are there local or regional differences in tidal channel geometry (allometry)?*

This question has been addressed for local differences (between the South Fork, North Fork, and interdistributary marsh fringe of the Skagit Delta (Hood 2007a) and for some regional differences (Hood 2002a). Landscape-specific allometric relationships should be characterized for other marsh/tidal channel systems in Puget Sound to provide an important planning/design tool and to better understand the amount of landscape variability and its causes. This analysis is underway for the Snohomish Delta in a collaboration between SRSC and the Tulalip Natural Resources Dept., although the work is progressing slowly due to very limited funding. **Priority = high**.

2. *If there are local or regional differences in tidal channel allometry, what causes these differences? Can differences be diagnostic indicators of anthropogenic impacts?*

Some allometric studies have found local/regional differences, suggested potential causes for the differences, and provided examples for how they may be diagnostic of anthropogenic impacts, including previously unrecognized historical legacies (Hood 2002a, 2007a). However, these questions need to be explored in greater detail and with greater precision. **Priority = medium**.

6.2.4. Tidal Channel Summary.

The highest priority (regarding tidal channels) for the Skagit Delta Tidal Habitat Monitoring Plan is further development and testing (through restoration and monitoring) of local- to region-scale predictive models of tidal channel geometry. This will help answer treatment-scale question 5; site-scale questions 1-5; landscape-scale questions 1 and 2; and provide a practical predictive tool for ecologists, planners, and engineers. It will also contribute to increased understanding and predictability of cumulative effects. For example, Skagit Delta results (Fig. 7) show that total channel length, total channel surface area, and the surface of the largest channel draining a marsh island increase more rapidly than does island area, i.e., there is a non-linear response when $\beta \neq 1$ (β is the slope of the log-transformed regression). This suggests channel length and surface area can be maximized by restoring large contiguous areas rather than many fragmented parcels. For example, restoring a single 100-acre site will produce more tidal channel length and area than will restoring ten 10-acre sites.

Monitoring tidal channel geometry can be easily and efficiently accomplished through regular inventory by aerial photography and change analysis with GIS. Analysis of planform geometry is usually sufficient for restoration project evaluation, but collection of channel cross-sections and profiles should be encouraged. While this adds additional expense it provides information that can be linked to hydraulic models, better characterizes the nature of channel evolution, and provides more information with which to evaluate ecological implications of the restoration trajectory. Additionally, future elaborations of the channel allometry model will include depth-related parameters, and this may improve understanding of local and regional variation in allometries.

6.3. Distributary channels.

River distributary networks and their dynamics are central to understanding delta hydrodynamics, geomorphology, and ecology. A complicated set of feedbacks between distributary network geometry, the dispersal of river discharge, river sediments and nutrients, and the distribution of tidal vegetation governs system structure and dynamics. For example, large river distributaries carry more sediment than do small ones, consequently delta progradation is focused at the mouths of larger distributaries to a greater degree than smaller ones. However, as the delta progrades at the mouth of the larger distributaries, their gradient declines and flow switches to smaller and steeper distributaries, i.e., channel switching occurs. Perhaps the most dramatic local example of this phenomenon is the abandonment of the lower Stillaguamish River in favor of Hat Slough, which occurred within the past century. By affecting the spatial distribution of

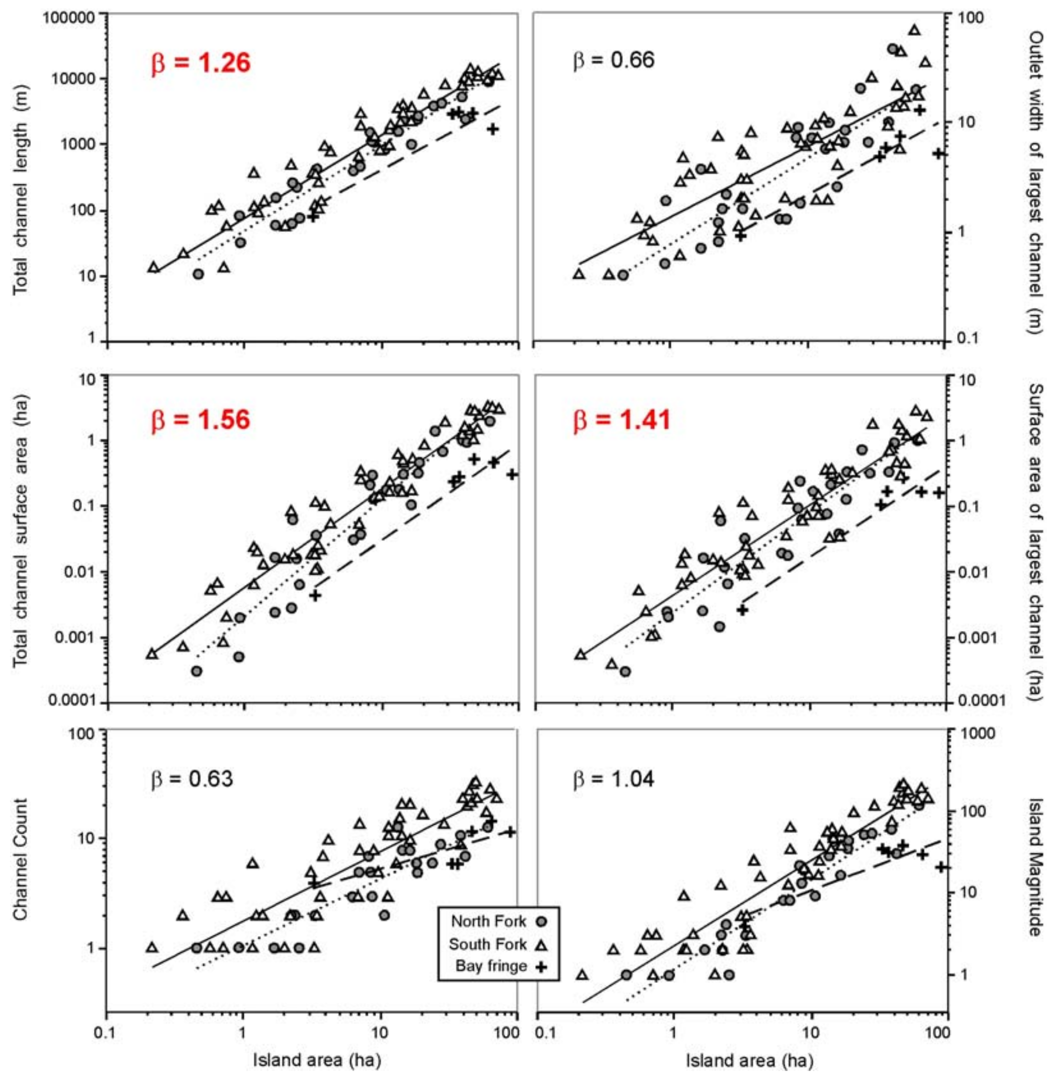

Figure 7. Skagit Delta tidal channel allometry (modified from Hood 2007a). When β, the slope of the log-transformed regression, is greater than 1 the response variable increases faster than marsh island area. When β < 1, the response variable increases more slowly than marsh island area. These relationships quantify local-scale non-linear cumulative effects of restoration.

river discharge, distributaries affect the spatial distribution of marsh salinities and thus the distribution of marsh plant species. Likewise, river distributaries affect the distribution of juvenile salmon and other marine fauna (Beamer et al. 2005).

There are significant lacunae in our understanding of river distributary networks that have implications for planning and predicting the effects of habitat restoration in river deltas. While the scaling signatures of the upper river basins are well understood (Rodriguez-Iturbe and Rinaldo 1997), distributary network structure in depositional deltas and fans is relatively poorly understood (Paola et al. 2006). There is even disagreement on whether distributary formation occurs primarily through bar development at distributary mouths, with subsequent channel splitting (Edmonds and Slingerland 2007) or whether sudden, and potentially less predictable, channel avulsion is the normative process (e.g., Swenson 2005, Vella et al. 2005). Evidently both process occur, but under which environmental conditions do they dominate? The answer is critical for safe and predictable system management, including habitat restoration.

Habitat restoration can directly and indirectly affect the distributary network. For example, the Deepwater Slough distributary was restored in 2000 by breaching a pair of dikes that had blocked the distributary for nearly a century. Likewise, the Skagit Chinook Recovery Plan calls for restoration of a distributary across Fir Island (SRSC & WDFW 2005). Additionally, excavation of a new distributary was proposed just outside the dikes at the end of Rawlins Road, although benefits of this proposed action appear to be minimal, particularly in light of the natural development of a new North Fork distributary nearby. Finally, restoration of the historical West Branch of Freshwater Slough was considered during development of the Wiley Slough restoration plan, although it was abandoned due to project constraints. Dike removal may also affect distributary dynamics by reducing channel constriction, thereby reducing flood energy within the channel and allowing flood-borne sediment storage in the adjacent restored floodplain (Hood 2004). It is important to realize that distributaries within a network are likely tele-connected, i.e., changes in one part of a system, though spatially distant, will likely affect the rest of the system (e.g., Yang et al. 2009). For example, restoration of Deepwater Slough in the South Fork delta will very likely affect the geomorphology of Freshwater Slough which is its bifurcation sister. It will also, perhaps with less certainty or to a lesser degree, affect Tom Moore Slough and Steamboat Slough which share an upstream bifurcation point with Freshwater/Deepwater Slough near Conway. Furthermore, the North Fork and its distributaries may be affected by replumbing of the South Fork distributaries through consequent flow redistribution between the North and South Forks.

6.3.1. Important **treatment-scale** questions regarding distributary channel restoration are:

1. *When distributaries are restored, is an engineered structural control necessary to prevent avulsion?*

The answer to this question likely depends on the setting. Deepwater Slough was restored without any structural control because there was no significant infrastructure or human life at risk should Deepwater Slough grow to become the largest distributary in the South Fork marshes. In contrast, restoration of a Fir Island distributary would more likely require a control structure due to perceived risk to farmland, roads, and other infrastructure in the vicinity of the distributary should the restored distributary grow catastrophically to become the "Middle Fork" of the Skagit River. The answer in such a circumstance will depend as much on political as engineering or hydrodynamic considerations, with risk and liability being paramount concerns. **Priority = low**.

2. *What are the effects of structural anti-avulsion controls on fish passage or other aquatic fauna?*

Engineering fixes often cause as many problems as solutions, particularly with regard to their effects on ecosystems. **Priority = low**.

6.3.2. Important **site-scale** questions regarding distributary channel restoration are:

1. Can we predict how large a restored or newly developing distributary will become and how quickly this change will occur?

This is a critical question because its answer would provide guidance on whether structural controls are necessary to prevent avulsion. It is also important because of the need to predict restoration benefits that depend on distributary size, e.g., how many juvenile Chinook would pass through the distributary, how much sediment, how much freshwater (which affects system salinity), etc. There are two potentially complementary ways to answer this question: through complex hydrodynamic modeling and through development of simpler, empirical, statistical models. SRSC is currently developing a statistical model of the relatively simple distributary configuration in the North Fork to predict the fate of a naturally developing distributary, currently in early stages of growth.

Priority = high.

2. How do dike breaching vs. dike removal differentially affect the form and behavior of adjacent distributaries?

Answering this question will address a major controversy in estuarine restoration, i.e., should dikes be removed entirely, or can they merely be breached? As mentioned earlier, dike removal likely affects the morphology and behavior of adjacent distributaries (Hood 2004). Hydrodynamic modeling is probably the only way to predict likely effects while accounting for complex interactions with other independent changes in the system. For example, the Wiley Slough restoration project will remove dikes along Freshwater Slough and likely affect its geomorphology. However, restoration of Deepwater Slough in 2000 is also likely affecting Freshwater Slough morphology. These confounding effects prevent clean controlled experimental design or simple analysis.

Priority = medium.

6.3.3. Important **landscape-scale** questions regarding distributary channel restoration are:

1. Is there a limit to how many distributaries can be restored in a system? Can one only spatially rearrange distributaries? What is the normal size distribution of distributaries? Can that be altered by management—or do they simply become spatially rearranged? Can distributary network geometry be an indicator of system function or dysfunction?

This set of related questions cannot be easily answered by hydrodynamic models. A more promising approach is to use hydraulic geometry and other scaling relationships (allometric analysis) to generate predictive guidance. These questions are fundamental to characterizing the distributary network, and consequently the geomorphological and ecological behavior, of a delta. Hydraulic geometry suggests that there is an upper limit on distributary number, depending on basin discharge, because division of river flow into distributaries is constrained by the hydraulic threshold between sediment deposition and conveyance through a channel (Orton & Reading 1993). Observational data from deltas throughout the world show that [1] the number of distributary channels dissecting a delta scales with the maximum monthly discharge and inversely with the marine power; [2]

widths and lengths of distributary channels form a lognormal distribution, with the cumulative width of the river mouths directly related to the maximum discharge, tidal and wave energy; [3] distributary channel widths, depths, and lengths decrease nonlinearly and predictably with successive bifurcations; [4] for bifurcations up to fifth order, the width ratios are not equal but occur most frequently in the ratio of 1.7:1 rather than the more intuitive expectation of a 1:1 ratio; [5] average width and depth decrease with increasing bifurcation order because distributary channels are adjusting to a decreasing discharge (Edmonds & Slingerland 2007, Syvitski & Saito 2007). These results can be used to understand historical delta evolution, to predict the future evolution of river-dominated deltas, and to predict system responses to management actions—including restoration. The existing observational data has been generated from remote sensing data using relatively low resolution satellite imagery of some of the world's largest river deltas. We need higher resolution data for management of the Skagit Delta and we need information on distributary bathymetry or cross-sectional geometry. We also need to determine whether the Skagit Delta conforms broadly to other delta systems or if it is in a disequilibrium state. If it diverges from other system patterns, to what degree does it diverge what factors control this disequilibrium, and what are the management implications? **Priority = high**.

2. How does restoration or natural change in one distributary affect other distributaries in the network?

As mentioned earlier, river distributaries are tele-connected (Yang et al. 2009). Presumably indirect effects are related to proximity of system alteration. Short of hydrodynamic/morphodynamic modeling we currently have no way of quantitatively predicting tele-connected effects. **Priority = high**.

3. How does the distributary network configuration affect soil salinity, vegetation, sediment grain size, etc?

Data collected in the Skagit marshes indicates a strong and predictable relationship between distributary network geometry and soil salinity spatial pattern—this in turn affects vegetation patterns (Hood unpublished). Preliminary examination of historical aerial photos coupled with field observations also indicates that distributary dynamics spatially affect sediment sorting, which in turn affects vegetation distribution (Hood unpublished). Any alteration in distributary network geometry will very likely affect salinity patterns with concomitant effects on flora and fauna. **Priority = high**.

4. How does the distributary network configuration affect fish distribution—how will network changes influence fish distribution?

SRSC already has a model that describes the effect of distributary network configuration on juvenile Chinook salmon distribution (Beamer et al. 2005). This model can be experimentally tested through relevant distributary restoration projects. The IMW is currently funding fish monitoring on the landscape scale in the Skagit Delta to address this question. **Priority = high**.

5. What effect does distributary restoration have on upriver flood amelioration?

Minor distributary channels act as overflow conduits that during times of flood significantly increase in discharge compared to their mean value. This provides for a more reactive response than for the principal distributary channels (Syvitski et al. 2005). To what degree distributary restoration ameliorates upstream flood risk, and to what degree cumulative effects occur must be analyzed through hydrodynamic modeling.

Priority = medium.

6. *Where is erosion/progradation/infilling occurring, how is that related to distributary network geometry? What is the future trajectory of distributary-poor marshes? Can distributary restoration rehabilitate eroding marshes?*

Field observations, analysis of historical aerial photos, and allometric analysis of tidal channel geometry suggest the Fir Island bayfront between the North and South Fork marshes is eroding (Hood 2007a). Since the 1950s, this area has been isolated from distributaries that historically crossed Fir Island (e.g., Brown, Hall, Dry, McDonald, Claude O. Davis sloughs, and other smaller channels), and this has apparently led to sediment starvation of the marshes fringing Fir Island. Presumably, restoration of at least one cross-island distributary would replenish sediment to at least a portion of this area and improve marsh health (condition, resilience to storm erosion and sea-level rise, and sustainability). Interesting ancillary questions arise. For example, if a distributary is restored how will its form affect sediment deposition? Presumably, a distributary that is narrowly constrained by levees all the way to its mouth will have high jet momentum flux and carry sediments far into the bay, bypassing the sediment-starved marsh. While a distributary that is accompanied by a buffer of restored wetland along its length will have lower jet momentum flux and be more likely to deposit sediments within nearshore marshes. How wide should such a buffer be to maximize nearshore sediment replenishment? Is there greater depositional efficacy if the marsh buffer flares out toward the distributary outlet? Hydrodynamic modeling is necessary to address these questions.

Priority = high.

6.3.4. Distributary Summary.

Predicting distributary network responses to restoration actions principally requires two complementary types of models: hydrodynamic and allometric models. A critical foundation, and thus the highest priority, for developing these predictive models is an extensive morphological data set that describes distributary network bathymetry and planform geometry. This data set would not only parameterize the models it would also serve as a baseline from which to compare future system states following management actions or natural disturbances. It is essential that we acquire bathymetry on distributary bifurcations, preferably on the entire distributary network. This means, at a minimum, channel cross-sections above each bifurcation and below at each bifurcate channel, i.e., three cross-sections per bifurcation. Additionally, it would be important to collect bathymetric data (cross-sections at minimum) for each distributary mouth.

An additional priority is monitoring distributary bifurcations that are currently clearly out of equilibrium and undergoing relatively rapid change. Two such sites exist in the Skagit, the restored Deepwater Slough distributary and a naturally evolving distributary (arising through erosional migration of a North Fork meander bend into the head of a large blind tidal channel—i.e., a third mechanism for bifurcation formation that is dependent on neither avulsion or bar mouth formation). This monitoring will provide information on the rate and endpoint of distributary growth (i.e., site-scale question 1).

Again, we need to monitor the bifurcation sites in question (at a minimum three cross-sections), but we also need to monitor the mouths of each bifurcate pair of distributaries to detect likely indirect effects at their outlets. Additionally, we should monitor intervening bifurcations between the site bifurcation and the distributary mouths due to likely indirect effects on downstream bifurcations (i.e., landscape-scale question 2). This is more applicable to the Deepwater Slough restoration than the naturally evolving new North Fork distributary.

6.4. Sedimentation and Marsh Accretion.

Sedimentation and marsh accretion are important issues for tidal marsh restoration and protection for several reasons. Sea-level rise is accelerating due to anthropogenic forcing and this potentially threatens to drown tidal marshes; landuse is affecting sediment supply to and distribution in river deltas; and most former tidelands that are candidates for habitat restoration have subsided by a meter or more since conversion to agricultural use (Giosan et al. 2008). In the Skagit Delta, this subsidence is due primarily to oxidation and volatilization of the organic portion of the former marsh soils, soil erosion due to agricultural practices, and soil compaction by heavy machinery.

Sedimentation and accretion are central to marsh morphodynamics and to sustaining tidal marsh vegetation communities. Given sufficient sediment supply, tidal marshes can generally keep pace with sea-level rise. Moreover, salt marshes can respond rapidly to changes in forcing and are consequently generally near or progressing rapidly toward dynamic morphological equilibrium with sediment supply, vegetative growth, and relative sea level (Friedrichs & Perry 2001). The corollary to this natural responsiveness is that engineered marshes which are not initially in dynamic equilibrium with physical forcing may very rapidly (years to decades) evolve away from their initial design.

6.4.1. <u>Marsh Surface Elevation</u>. Inorganic sediment deposition in tidal marshes is dependent on marsh elevation (which directly controls inundation period), the type of vegetation present, tidal channel geometry, and sediment supply. The more water over the marsh surface, the more suspended sediment is available for deposition (Friedrichs & Perry 2001). Consequently, marshes lower in the tidal frame have higher sedimentation rates than those higher in the tidal frame. As a result of this stabilizing negative feedback loop, marshes tend toward an asymptotic elevation near mean higher high water (MHHW). Likewise, when sediment supply is not limiting, inorganic accretion tends to increase with increasing rates of sea level rise, and marsh elevation within the tidal frame is maintained. For organic accretion, however, the feedback loop between hydroperiod and accretion rate is positive and destabilizing (Fig. 8). Increased hydroperiod increases stress on vegetation which then reduces the production of organic material. This decreases organic accretion which further increases hydroperiod (Friedrichs & Perry 2001). Conversely, reduced hydroperiod reduces plant stress and increases production. However, above MHHW accumulation of organic detritus declines due to increased aerobic decomposition, so marshes again asymptote to a stable elevation.

6.4.2. <u>Vegetation</u>. The energy of tidal flow within marsh grass or sedges typically decreases by an order of magnitude or more relative to unvegetated areas, and wind wave energy is similarly dissipated under most conditions (Friedrichs & Perry 2001). Consequently, marsh grasses and sedges can increase sediment deposition rates five-fold over unvegetated areas. The accretion rate of inorganic sediment increases with grass stem density, because greater stem density further reduces flow velocity. Because stem density varies by species, as does canopy architecture, it is likely spatial heterogeneity in vegetation composition contributes to spatial heterogeneity in sedimentation. Similarly, some species of marsh grass collect suspended sediment on the stems and leaves

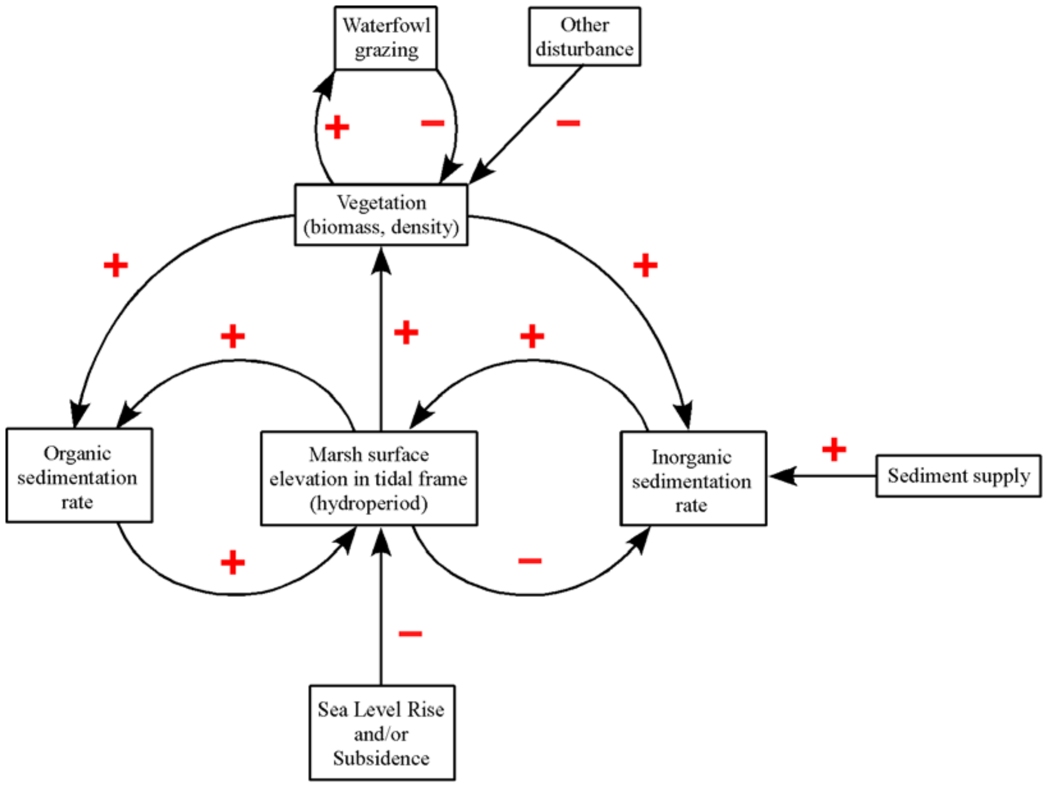

Figure 8. Conceptual model of marsh accretion. +/- signs denote positive or negative correlation between variables. Network loops have a positive or negative feedback depending on the product of the signs in the loop path. Positive feedback loops indicate system vulnerability to multiple stable states and associated hysteresis. See Figure 4 for factors affecting sediment supply. Note, threshold elevation effects (Fagherazzi et al. 2006) are not detailed here.

themselves, enhancing mineral sediment deposition by ~50% compared to other species (Friedrichs & Perry 2001).

Morphodynamic modeling suggests temporary disturbance to vegetation can facilitate rapid and widespread marsh degradation (Kirwan et al. 2008). Vertical accretion slows in disturbed areas, allowing localized submergence of the marsh platform (by normal marsh sediment compaction and sea level rise), tidal prism enlargement, and permanent channel network expansion. Rapid degradation of a healthy marsh can occur even when accretion otherwise keeps pace with sea level rise in undisturbed marsh areas. For example, vegetation disturbance by snow goose grazing appears to be causing local marsh loss on the actively prograding Fraser River delta in British Columbia. Long term accretion rates exceed sea level rise in many portions of the delta, though marshes on Westham Island, a protected bird sanctuary, are actively eroding. Geese exclusion experiments indicate herbivory reduces vegetation productivity in these marshes by at least 60%. Geese herbivory removes below-ground accumulation of organic material and bioturbates the soil, both of which reduce accretion rates. Sites protected from geese accrete faster than sea level rise, but unprotected sites erode by 1 cm/yr (Kirwan et al. 2008).

Significantly, marshes are more vulnerable to disturbance at high sea level rise rates and low suspended sediment concentrations (Kirwan et al. 2008). Marshes that formed and are stable under a low sea level rise rates or high sediment supply may become vulnerable to grazing or other vegetation disturbances under high sea level rise rates or decreased sediment supply. In these marshes, moderate vegetation disturbance may have led only to slight channel widening and dissection in the past because favorable sea level rise rates and sediment supply allowed rapid vegetation recovery. However, even without a change in disturbance regime, these marshes may become much more dissected and inundated under scenarios of accelerated sea level rise or reduced sediment supply. These issues are relevant to the Skagit Delta because snow geese and dabbling ducks extensively graze sedge (*Carex lyngbyei*) and dig up bulrush rhizomes (*Schoenoplectus americanus* and *S. tabernaemontani*) throughout the Skagit marshes. This suggests areas in the Skagit marshes dominated by sedges and bulrushes might be more vulnerable to sea level rise impacts than areas dominated by cattails and shrubs. Other modeling suggests shrubs will be the most vulnerable due to salinity and general inundation impacts (Hood, unpublished data). Perhaps marshes will suffer the worst of both worlds and climate change will leave us with exclusively cattail marshes.

6.4.3. <u>Tidal Channel Geometry</u>. Flow speed within the canopy is inversely related to distance from the tidal channel edge (Friedrichs & Perry 2001). Consequently, there is a rapid decrease in suspended sediment concentration and deposition rate with distance from the sediment source (the tidal channel), so that tidally dominated marshes exhibit patterns of inorganic accretion largely controlled by the distribution of marsh tidal channels. Strong gradients in sediment deposition rates are seen adjacent to creeks over distances of only a few 10s of meters (Friedrichs & Perry 2001). Rapid deposition immediately adjacent to tidal channels causes topographically higher marsh levees to form, paralleling the sides of the marsh creeks. Thus, at smaller scales immediately adjacent to the marsh creeks, the larger scale relationship between marsh elevation and accretion rate may be reversed with locally higher elevations directly correlated with higher rates of deposition. Additionally, the grain size of inorganic marsh sediment also generally decreases with distance from it source in tidal creeks. Marsh levees are typically characterized by fine sand and coarse silt, while fine silt and clay are more typical of the inner marsh. On very high tides and storms, the tide overtops the entire marsh and tidal channels no longer provide a first order control on hydrodynamics or sedimentation patterns (Friedrichs & Perry 2001).

Most of the preceding review assumes tidal marshes are dominated by tides rather than river flow or waves. However, the Skagit marshes and those of many other river deltas are dominated by river flow. Consequently, river distributaries play an important role in distributing river sediment in the marshes. Additionally, some parts of the undiked tidally influenced delta may exist above MHHW but nevertheless receive sediment during river floods. These tidally influenced floodplains are sometimes known as surge plains. River distributaries, blind tidal channels, variation in vegetation composition all interact to produce spatial heterogeneity in sediment supply, accretion rates and topography with feedback to channel geometry and vegetation productivity.

6.4.4. Monitoring Questions. We need to develop predictive models of marsh accretion for use in habitat restoration project planning and design, planning for sea-level rise impacts, and planning for other aspects of landscape management, e.g., dam management, flood control initiatives, water diversion, etc. Scientists at the Pacific Northwest National Laboratory (PNNL) have developed a model framework for the Skagit Delta and other areas in the Whidbey Basin using the Finite Volume Coastal Ocean Model (FVCOM) developed by University of Massachusetts (Chen et al. 2003). FVCOM is a three-dimensional (3-D) hydrodynamic model that can simulate wetting-drying, tide- and density-driven circulation, and sedimentation in an unstructured, finite element framework. A different, perhaps complementary approach would be to link simpler 1-D models to GIS to provide spatially explicit accretion estimates (Rybczyk & Callaway, in review). The advantage of 1-D models is that they incorporate vegetation effects on accretion, including organic accretion, while the 3-D models do not yet do so (although this capacity is under development for Delft 3D). They may also be more cost-effective for small-scale or pilot studies because they do not require super-computing facilities, but can be run on desktop computers. Finally, 1-D models may be more easily and economically parameterized.

Whatever model is chosen, each needs to be parameterized and validated. This can be accomplished through baseline and post-project monitoring. Monitoring questions include those that address model parameterization needs, those that test restoration tactics and strategies, and those that provide better system understanding.

6.4.4.1. Important **treatment-scale** questions regarding sediment accretion are:

1. *How does dike breaching vs dike removal affect sediment routing and spatial patterns of marsh accretion? How does it affect on-site sedimentation and how does it affect off-site sedimentation?*

This question can be predicted by 3-D hydrodynamic modeling and tested by monitoring.
Priority = medium

2. *What are the consequences of excavating or not excavating tidal channels on site accretion patterns and rates?* **Priority = low**
3. *How does channel density influence accretion rates? How much channel should one excavate?* **Priority = low**

Questions 2 and 3 could be addressed either by 1-D or 3-D modeling, with associated monitoring for model validation and testing.

6.4.4.2. Important **site-scale** questions regarding sediment accretion are:

1. *How do inorganic sedimentation rates vary by vegetation species—after accounting for elevation/hydroperiod and channel network effects?*
2. *How do organic sedimentation rates and in situ organic production and accumulation vary by vegetation species?*

These questions are of interest because they affect prediction of marsh resilience to sea level rise and can affect restoration site recovery trajectories. Currently questions 1 and 2 must be addressed by basic field measurements. They can be incorporated into 1-D models relatively easily, but 3-D models do not yet account for vegetation effects, although this capacity is under development. **Priority = medium**

3. *What is the relative importance of flood vs tides (i.e., normal or low river flow) in providing sediment to a site? How does this vary with flood intensity? how does this vary quantitatively over the landscape, i.e., relative to proximity to a distributary and to the size of the distributary?* **Priority = medium**

6.4.4.3. Important **landscape-scale** questions regarding sediment accretion are:

1. *How does sediment supply vary with river discharge?*

We have a very limited sediment rating curve for the Skagit (Grossman, USGS, personal communication). We need more data, particularly at higher river discharges, on this issue. We also need to account for storm sequence effects, i.e., a large storm/flood will produce a large pulse of sediment, while subsequent smaller storms may produce progressively less sediment because stored in-channel sediment may have already been flushed from the system. In contrast, a series of smaller storms may produce a steady discharge of sediment. A sediment rating curve is essential information for any modeling effort. **Priority = high**.

2. *How does sediment supply vary seasonally with glacier melt?*

The Chocolate Glacier frequently contributes a significant sediment load to the Skagit River at the end of summer, even at very low river discharge. This sediment load should be quantified and its effects on marsh accretion and progradation, as well as on eelgrass production in Skagit Bay, should be evaluated. **Priority = medium**.

3. *How is river discharge and sediment load partitioned among the river distributaries? How does this vary with total river discharge?*

We currently have very limited information on this issue. We only know that under average flow conditions flow is partitioned approximately 60:40 to 70:30 between the North and South Forks of the Skagit River (Grossman, USGS, personal communication). We have no idea how flow or sediment load is further partitioned. This information is critical to any modeling of sediment routing and accretion in the Skagit system. **Priority = high**.

4. *How do storms affect sedimentation patterns in the Skagit marshes?*

It is likely that storm winds from the south, coupled with north-south fetch, results in distinct storm effects on sediment accretion in the North Fork vs South Fork marshes. However, compared to other questions this one is currently **Low Priority.**

5. *Are there spatial differences (North Fork vs South Fork vs Bay Fringe marshes) in accretion rates, and if so, what controls those differences?*

This question is related to questions 3 and 4. River discharge/sediment partitioning and storm effects likely affect marsh accretion patterns on a broad spatial scale. This is suggested by research results on tidal channel geometry differences between these three areas of the Skagit Delta (Hood 2007a). Differences in marsh area relative to river discharge and distributary geometry may also affect spatial patterns in accretion. The South Fork marshes are three times larger than those of the North Fork, but they receive less river flow and sediment and what they do receive is more evenly distributed by a much larger network of river distributaries. **Priority = medium**

6. *What are accretion rates in various parts of the Skagit Delta—how do elevation, vegetation communities, and river distributaries interact on a landscape scale to predictably affect spatial heterogeneity in accretion rates.*

This question is related to question 5, but it considers the question at a finer spatial resolution. While the priority for this question is medium, because there is a more pressing need for other more basic information, this is nevertheless a critically important question that is essential to our understanding of system function and restoration and management planning. **Priority = medium**

7. *How do different vegetation types, including invasives like* Spartina, *impact sedimentation rates? How does their removal impact rates?* **Priority = medium**

8. *Is goose and duck grazing on sedge and bulrush vegetation significantly affecting sedimentation rates in the Skagit marshes?*

See discussion above. **Priority = medium**

9. *Is current system management, i.e., floodplain, surge plain, and marsh plain occupancy, impacting eelgrass in Skagit Bay?*

Levees and dikes currently prevent floods from depositing and storing sediments in delta and river floodplains. Instead, this sediment is bypassing normal storage areas and being delivered very efficiently to Skagit Bay where it is likely burying eelgrass with concomitant ecological impacts. Studies are underway by the USGS to determine the amount and fate of sediment bypassing the delta (e.g. deposition centers, accumulation rates, transport processes, and changes to substrate) to guide restoration planning aimed at redistributing sediments to the marshes. **Priority = medium**

6.4.5. Sedimentation/Accretion Summary.

Development of a robust sediment rating curve is a necessity for any morphodynamics modeling effort. We also need a better understanding of distributary network geometry and bathymetry to understand how river sediments are partitioned in the delta. Finally, we need spatial and temporal characterization of accretion, linked to distributary and blind tidal channel geometry, vegetation patterns (species distribution and canopy structure), and flood timing. Tidal marsh resilience to vegetation disturbance is threatened by climate change forcing of sea-level rise (Kirwan et al. 2008). System management that affects sediment supply and distribution will likely have significant consequences on the spatial variation in marsh health and sustainability.

7. Summary

The long list of questions in section 6 is not exhaustive, but it nevertheless illustrates how little is known about tidal marsh restoration. It also shows why a simple, faith-based, “build it and they will come” approach to restoration does not advance the science or technology of restoration. Systematic learning requires integrating restoration and monitoring to test hypotheses—including predictive models and conceptual models implicit to particular restoration tactics and strategies. Predictive models are useful planning and design tools. They also provide a framework with which to analyze system trends and organize other baseline information.

Science-based habitat restoration depends on making and testing (i.e., monitoring) predictions of the outcome of a proposed restoration. To this end several predictive models are currently being developed for the Skagit Delta system. They include: [1] a predictive model of tidal marsh vegetation, based on elevation (hydroperiod), soil salinity, and sediment grain size, with the possibility of relating these variables to blind and distributary tidal channel geometry; [2] a predictive model of blind tidal channel allometry that provides insight into cumulative effects, historical anthropogenic legacies, and design guidance, with potential use as an indicator of system function or dysfunction (Hood 2007a); and [3] a sophisticated 3-D hydrodynamic model of the system that will allow prediction of water quality, sedimentation/erosion, and particle transport (e.g., juvenile Chinook salmon movement). Further elaboration and validation (including restoration monitoring) of these models is a high priority. Likewise development and testing of predictive/descriptive models of distributary network geometry, and development and testing of marsh accretion models that account for vegetation effects are also high priorities. These models will be used to guide restoration planning and design, restoration monitoring and evaluation, baseline monitoring/system characterization, and system trend monitoring. Restoration monitoring is essential to evaluate restoration tactics and strategies, as well as newly developed design tools (i.e., predictive models). Trend monitoring allows change detection relevant to broader management concerns such as climate change impacts, basin-scale flood management, or urban sprawl.

Due to anticipated programmatic and financial constraints the monitoring strategy described here has limited itself to a few priority areas of effort. Important issues have been omitted that in an ideal funding environment would have been included, e.g., developing and testing predictive models of prey production for juvenile Chinook salmon such as benthic detritivores and herbivores. Understanding and quantitatively predicting prey relationships to habitat variables would be useful not only to better understand and design habitat restoration for juvenile Chinook salmon, but also for other predators on these organisms, such as waterfowl and shorebirds. Waterfowl and shorebird monitoring has also been omitted even though there is a great need for better understanding of their ecology in Pacific Northwest coastal systems and considerable societal interest in their management. Nutrient geochemistry has been neglected because this issue is beyond the expertise of the author of this monitoring strategy.

The monitoring strategy presented here will require periodic updating as new information is acquired, models are improved, goals change, or funding improves. It is not meant to support inflexible prescription or proscription of monitoring or research effort in the Skagit Delta or elsewhere. Rather it provides guidance and a rationale for the monitoring and research directions that are currently being pursued or should be pursued in the Skagit Delta.

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APPENDIX I: SUMMARY OF MONITORING QUESTIONS

Monitoring Questions	**Scale**	**Relative Importance**	**Complexity and Cost**	**Priority**
6.1 Vegetation				
6.1.1-1 Does vegetation need to be planted on a restoration site or can natural (passive) colonization be successful?	Treatment	Low	Low	Low
6.1.1-2 Are nurse logs necessary for woody species establishment or can earthen mounds or site grading patterns provide substitute elevated platforms? Are nurse logs only necessary for seed germination, so that seedlings or cuttings can be transplanted directly…?	Treatment	Medium-High	Low	High
6.1.1-3 Does the site need to be prepped to enhance restoration rates or probability of establishing desirable species (e.g., discing the soil to break up roots of existing, non-target vegetation…; stripping the top-soil to remove the rhizomes and seed-bank of non-native species).	Treatment	Variable, depending on presence of exotic species and site elevation	Medium	Variable, depending on conditions
6.1.1-4 How can non-native plant species be best controlled?	Treatment	Medium	Medium	Medium
6.1.2-1 If tidal hydrology is restored to a site, will vegetation colonize the site, or will be the site be an unvegetated tidal flat?	Site	High	Low	High
6.1.2-2 What species of vegetation will colonize? What determines which species will colonize and their spatial distribution?	Site	High	Low-Medium	High
6.1.2-3 Will vegetation persist in the face of future sea-level rise?	Site	High	Medium-High	High
6.1.2-4 How quickly will a tidal vegetation community develop?	Site	Medium	Low	Medium
6.1.3-1 How do restoration projects interact with each other depending on their connectivity to each other (physical interactions [hydraulic effects, sediment routing] and ecological interactions [community composition, daily to seasonal migratory pathways of associated biota and their relationship to population productivity])?	Landscape	High	High	Medium
6.1.3-2,3 What vegetation communities characterized the historical landscape? Which are now rare in the landscape?	Landscape	High	Medium-High	Medium
6.1.3-4 Has nutrient pollution from agricultural and urban development affected plant species composition and distribution in the Skagit Delta?	Landscape	Medium	Medium-High	Medium

6.1.3-5 How does the current connectivity between vegetation communities compare to the historical condition?	Landscape	Low-Medium	Medium-High	Low
6.1.3-6 What ecological function has been lost as a consequence of reduced habitat diversity, abundance, and connectivity?	Landscape	High	Medium-High	High
6.1.3-7 How do gradients in physical processes and patterns (e.g., tidal inundation, flooding disturbance, channel avulsion…) currently structure the landscape and its vegetation communities. How do historical processes compare?	Landscape	High	Medium-High	High
6.1.3-8 Will marshes be resilient to sea-level rise?	Landscape	High	High	High
6.1.3-9 What are the spatial patterns of exotic plant species distributions? What physical factors affect marsh resilience with respect to exotic species invasion? Is the number or abundance of exotic species changing over time?	Landscape	Medium	Low	Medium
6.2 Tidal channels				
6.2.1-1 Should tidal channel networks be excavated or can they carve themselves through tidal erosion?	Treatment	High	Low-Medium	High
6.2.1-2 How quickly can channels develop through tidal erosion?	Treatment	High	Low	High
6.2.1-3 Will site prepping (e.g., discing to break up plant roots) accelerate passive erosional tidal channel development?	Treatment	High	Medium	High
6.2.1-4 How much of a channel network should be excavated and how much can be allowed to erode?	Treatment	Medium	Medium	Medium
6.2.1-5 What size should channels be if excavated? What size will they become if allowed to erode to a point of dynamic equilibrium?	Treatment	High	Low	High
6.2.1-6 Does channel sinuosity matter?	Treatment	High	Low-Medium	High
6.2.1-7 Will excavated tidal channels persist or fill with sediments?	Treatment	High	Low	High
6.2.1-8 Should borrow and drainage ditches be filled during site restoration to promote natural channel formation and geometry?	Treatment	Medium	Medium	Medium
6.2.1-9 What is the ecological significance of tidal channel geometry?	Treatment	High	Medium-High	High
6.2.2-1 How many channels should one excavate or will develop through erosion?	Site	High	Low	High
6.2.2-2 What size distribution of tidal channels should one expect or excavate?	Site	High	Low	High

6.2.2-3 Are there differences in the resulting channel network geometry between dike breaches and dike removal?	Site	High	Low	High
6.2.2-4 If dike breaching rather than dike removal is employed, how many breaches should be made; how wide should they be?	Site	High	Medium	High
6.2.2-5 Are there differences in channel geometry for sites where drainage/borrow ditches were filled vs. left unfilled?	Site	Medium	Medium	Medium
6.2.2-6 What is the ecological significance of channel geometry?	Site	High	Medium-High	High
6.2.2-7 How does the equilibrium geometry of SRT-controlled tidal channels compare to that of natural tidal channels?	Site	High	Low	High
6.2.2-8 How do ebb and flood tidal velocities over the tidal cycle compare between SRT-controlled vs natural reference channels?	Site	High	Medium	High
6.2.2-9 How does water quality compare between SRT-controlled vs natural reference channels: temperature, salinity, DO, agricultural or residential pollutants?	Site	High	Low-Medium	High
6.2.2-10 Is a vegetated (upland or wetland) buffer along an SRT-controlled tidal channel necessary for, or effective at, intercepting and filtering agricultural or residential pollutants?	Site	High	Medium-High	High
6.2.2-11 How do detrital accumulation, sediment grain size, and benthic communities compare between SRT-controlled vs natural reference channels?	Site	High	Low-Medium	High
6.2.2-12 How does SRT gate design affect passage by benthic vs. surficial fish? Do vertically vs. horizontally oriented gates differ in fish passability? How do culvert invert and top elevation relative to the tidal frame affect fish passage?	Site	High	Low-Medium	High
6.2.2-13 How does fish community structure, density and feeding compare between SRT-controlled tidal channels and natural reference channels?	Site	High	Low-Medium	High
6.2.2-14 To what extent do SRTs increase salinity intrusion and reduce the productivity of nearby agricultural fields?	Site	High	Low-Medium	High
6.2.3-1 Are there local or regional differences in tidal channel geometry?	Landscape	High	Low-Medium	High
6.2.3-2 If there are local or regional differences in tidal channel allometry; if so why? Can differences be diagnostic indicators of anthropogenic impacts?	Landscape	Medium-High	Medium-High	Medium

6.3 Distributary channels				
6.3.1-1 When distributaries are restored, is an engineered structural control necessary to prevent avulsion?	Treatment	Low	High	Low
6.3.1-2 What are the effects of structural anti-avulsion controls on fish passage or other aquatic fauna?	Treatment	Low	High	Low
6.3.2-1 Can we predict how large a restored or newly developing distributary will become and how quickly this change will occur?	Site	High	Low-Medium	High
6.3.2-2 How do dike breaching vs. dike removal differentially affect the form and behavior of adjacent distributaries?	Site	Medium	Medium	Medium
6.3.3-1 Is there a limit to how many distributaries can be restored? What is the normal size distribution of distributaries? Can that be altered by management—or are they only spatially rearranged? Is distributary network geometry an indicator of system function or dysfunction?	Landscape	High	Low-Medium	High
6.3.3-2 How does restoration or natural change in one distributary affect other distributaries in the network?	Landscape	High	Medium-High	High
6.3.3-3 How does the distributary network configuration affect soil salinity, vegetation, sediment grain size, etc.?	Landscape	High	Low-Medium	High
6.3.3-4 How does the distributary network configuration affect fish distribution—how will network changes change fish distribution?	Landscape	High	Medium-High	High
6.3.3-5 What effect does distributary restoration have on upriver flood amelioration?	Landscape	Medium	Medium-High	Medium
6.3.3-6 Where is erosion/progradation/ infilling occurring, how is that related to distributary network geometry? What is the future trajectory of distributary-poor marshes? Can distributary restoration rehabilitate eroding marshes?	Landscape	High	Medium	High
6.4. Sedimentation & Marsh Accretion				
6.4.4.1-1 How does dike breaching vs dike removal affect sediment routing and spatial patterns of marsh accretion? How does it affect on-site sedimentation and how does it affect off-site sedimentation?	Treatment	High	High	Medium
6.4.4.1-2 What are the consequences of excavating or not excavating tidal channels on site accretion patterns and rates?	Treatment	Low-Medium	Medium	Low

6.4.4.1-3 How does channel density influence accretion rates? How much channel should one excavate?	Treatment	Low	Medium	Low
6.4.4.2-1 How do inorganic sedimentation rates vary by vegetation species—after accounting for elevation/hydroperiod and channel network effects?	Site	Medium-High	Medium	Medium
6.4.4.2-2 How do organic sedimentation rates and in situ organic production and accumulation vary by vegetation species?	Site	Medium-High	Medium	Medium
6.4.4.2-3 What is the relative importance of floods vs tides in providing sediment to a site? How does this vary with flood intensity? How does this vary over the landscape, i.e., relative to distributary proximity and size?	Site	Medium-High	Medium-High	Medium
6.4.4.3-1 How does sediment supply vary with river discharge?	Landscape	High	Medium-High	High
6.4.4.3-2 How does sediment supply vary seasonally with glacier melt?	Landscape	Medium	Medium	Medium
6.4.4.3-3 How is river discharge and sediment load partitioned among distributaries? How does this vary with total river discharge?	Landscape	High	Medium-High	High
6.4.4.3-4 How do storms affect sedimentation patterns in the marshes?	Landscape	Low	High	Low
6.4.4.3-5 Are there spatial differences (North Fork vs. South Fork vs. Bay Fringe marshes) in accretion rates, and if so, what controls those differences?	Landscape	Medium	Medium	Medium
6.4.4.3-6 What are accretion rates in a various parts of the Skagit Delta—how do elevation, vegetation communities, and river distributaries interact on a landscape scale to predictably affect spatial heterogeneity in accretion rates?	Landscape	Medium	Medium-High	Medium
6.4.4.3-7 How do different vegetation types, including invasives like Spartina, impact sedimentation rates? How does their removal impact rates?	Landscape	Medium	Low-Medium	Medium
6.4.4.3-8 Is goose/duck grazing on sedge and bulrush vegetation affecting sedimentation rates in the Skagit marshes?	Landscape	Medium	Low-Medium	Medium
6.4.4.3-9 Is current system management, i.e., floodplain, surge plain, and marsh plain occupancy, impacting eelgrass in Skagit Bay?	Landscape	Medium	Medium	Medium