

2009 EPA Tribal Implementation Grant (PA-00J15001)



**Monitoring and Adaptive Management of the Nisqually Delta after Tidal Marsh Restoration:  
Restoring Ecosystem Function for Salmon**

Final Summary Report

Prepared By Christopher Ellings, Nisqually Indian Tribe

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Nisqually Delta Research and Monitoring Core Team (Team)

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## Introduction

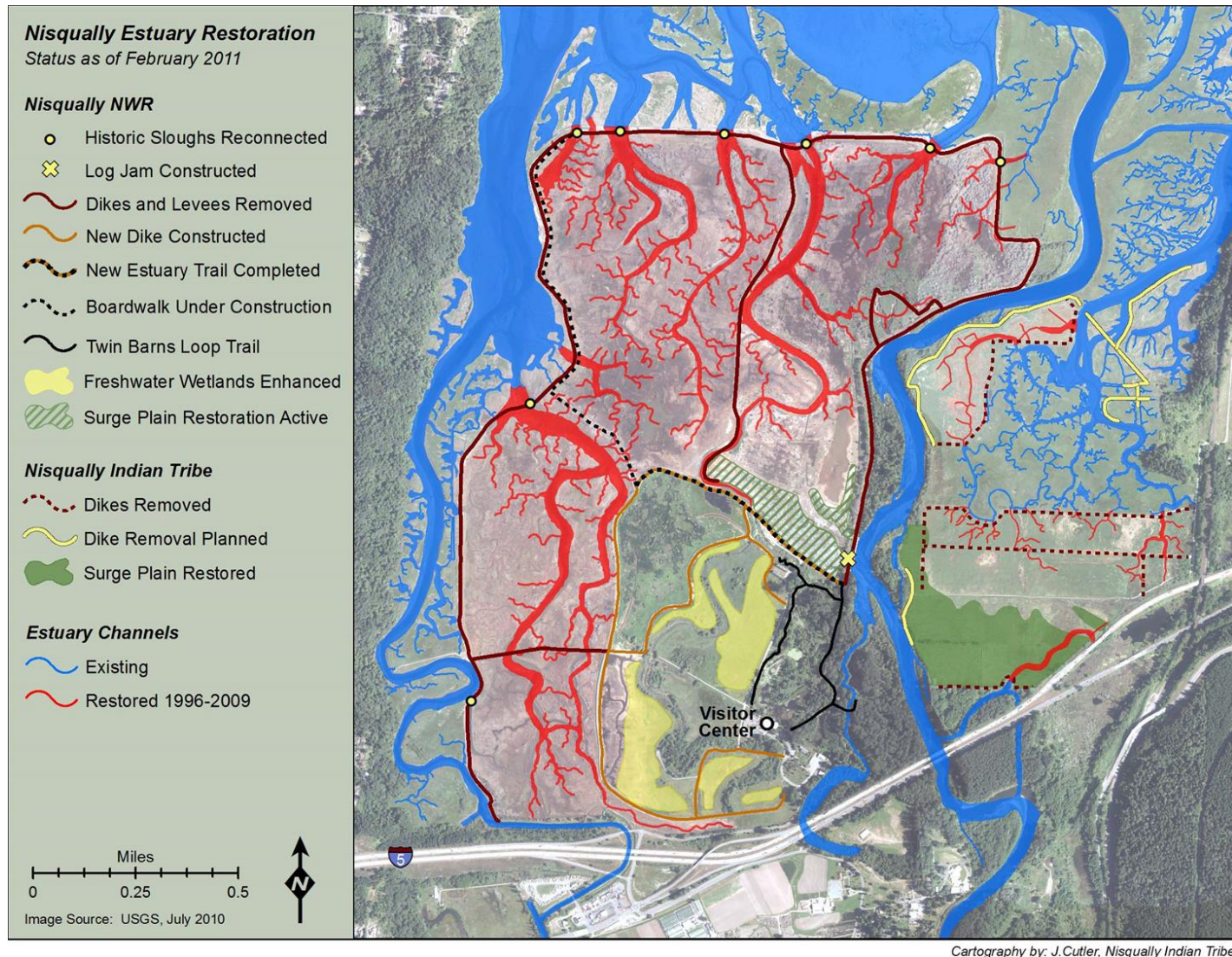
The return of tidal inundation to over 750 acres of the U. S. Fish and Wildlife Service Nisqually National Wildlife Refuge (Nisqually NWR) in fall of 2009 was the crowning moment in the effort to protect and restore the Nisqually Delta (Map 1). The Nisqually NWR project complemented three earlier restoration projects completed by the Nisqually Indian Tribe on tribal property. Over 900 acres of the estuary has been restored, representing the largest estuary restoration project in the Pacific Northwest and one of the most significant advances to date towards the recovery of Puget Sound. However, it remains uncertain how the Delta will respond to this new inundation in light of many altered physical processes (river flow control, reduced sediment inputs) and the 100-year history of subsidence and freshwater peat development since initial diking. The Nisqually Delta restoration projects were decades and many millions of dollars in the making. Thus, the need for project monitoring and research as the magnitude of the Nisqually Delta restoration project makes its potential contribution to restoration science unprecedented in Puget Sound.

The purpose of this project was to conduct cutting-edge research by the Nisqually Indian Tribe, three U.S. Geological Survey partners, and others (Team) focused on assessing the effectiveness of the Delta projects at restoring estuarine processes, habitats, and ultimately the capacity of the Delta in support of Chinook salmon and other fishes. Restoration effectiveness information from this project will support the implementation of Puget Sound estuary restoration efforts by Tribes and others. An additional outcome of the project is the advancement of adaptive management indicators for management of the Nisqually Delta by the Nisqually Indian Tribe and Nisqually National Wildlife Refuge.

The Nisqually Fall Chinook stock is one of the 27 stocks in the Puget Sound evolutionarily significant unit listed as threatened under the federal Endangered Species Act (NCRT 2001 and Ellings and Hodgson 2007)). Our project explored some of the Process-Structure-Function linkages presented by the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) (Simenstad et al. 2006; Gelfenbaum et al. 2006) to ultimately determine the 'success' of the Nisqually Delta restoration effort. These linkages are: 1) sediment delivery to the delta via the Nisqually River; 2) hydrodynamics affecting sediment transport and estuarine mixing; 3) geomorphic change; 4) vegetation community colonization and succession; 5) insect, benthic, and neustonic invertebrate community response; 6) Chinook salmon functional response to process and structure changes as expressed by their distribution and relative abundance, feeding ecology, estuarine and delta residence time and growth, and their life history diversity.

The Nisqually Indian Tribe and USGS team were able to generate additional resources via grants, internal funding, and cost savings in order to build off of the initial EPA award of \$600,000 to cover multi-disciplinary studies from 2010-2013. Our collective research is being captured in manuscripts, graduate theses, technical documents, and other formats. We have also presented much of our work at the 2011 and 2014 Salish Sea Ecosystem Conferences. This report contains summaries of our findings related to the specific outputs in our 2009 proposal to the EPA.





**Map 1. Nisqually Delta Restoration.**

## Proposed Outputs

Key outputs proposed by the Team included:

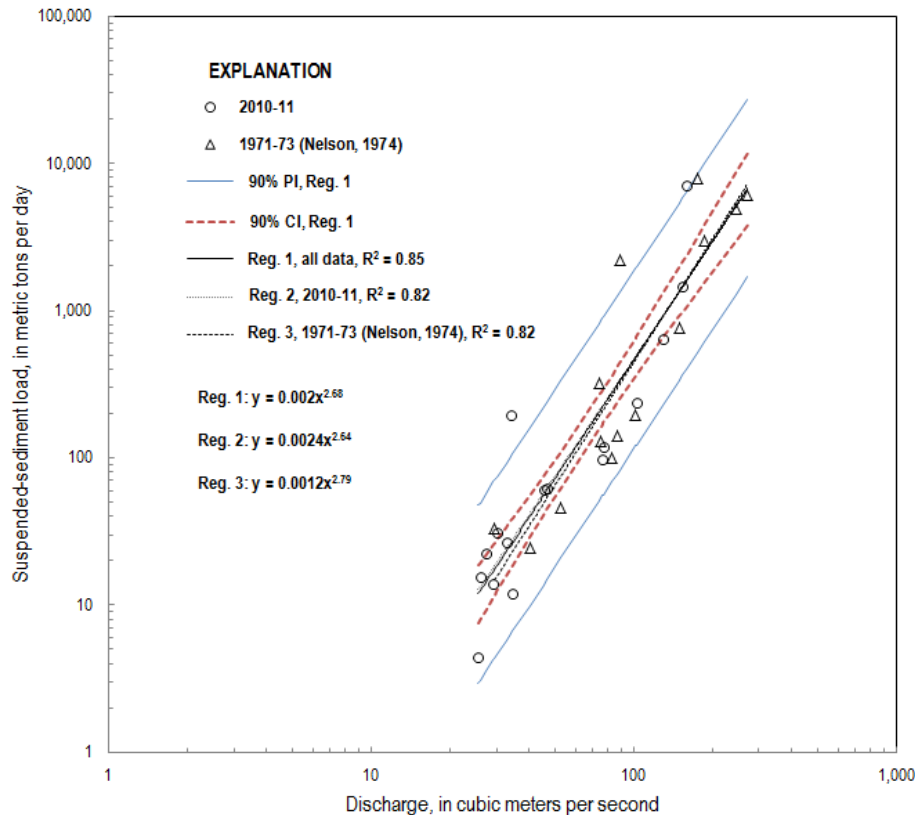
- A. Continuous and synoptic measurements of river flow and sediment load to develop a quantitative sediment rating curve for Nisqually River above the delta and for select stations across the estuarine mixing zone and tidal flats;
- B. A robust rating curve will be developed for suspended sediment load relative to river discharge;
- C. Numerical modeling and field studies of nearshore hydrodynamics to develop a better understanding of nearshore circulation surrounding Nisqually Delta and the mixing/fate of freshwater and particulate matter;
- D. Post-restoration vegetation composition and development with comparison between restoring and reference marsh;
- E. Post-restoration invertebrate community composition and abundance with comparison between restoring and reference sites;
- F. A refined model of the distribution, abundance, and timing of Chinook and other fishes in freshwater, estuary, mud flats, and nearshore habitats;
- G. Chinook and other fish presence in restored and reference sloughs;
- H. Chinook diet composition comparisons between restored and reference sloughs;
- I. Chinook otoliths analyzed to quantify Chinook residency, growth, and life history diversity across multiple habitats.

## Results Summary

*Output A (and B): Continuous and synoptic measurements of river flow and sediment load to develop a quantitative sediment rating curve for Nisqually River above the delta and for select stations across the estuarine mixing zone and tidal flats.*

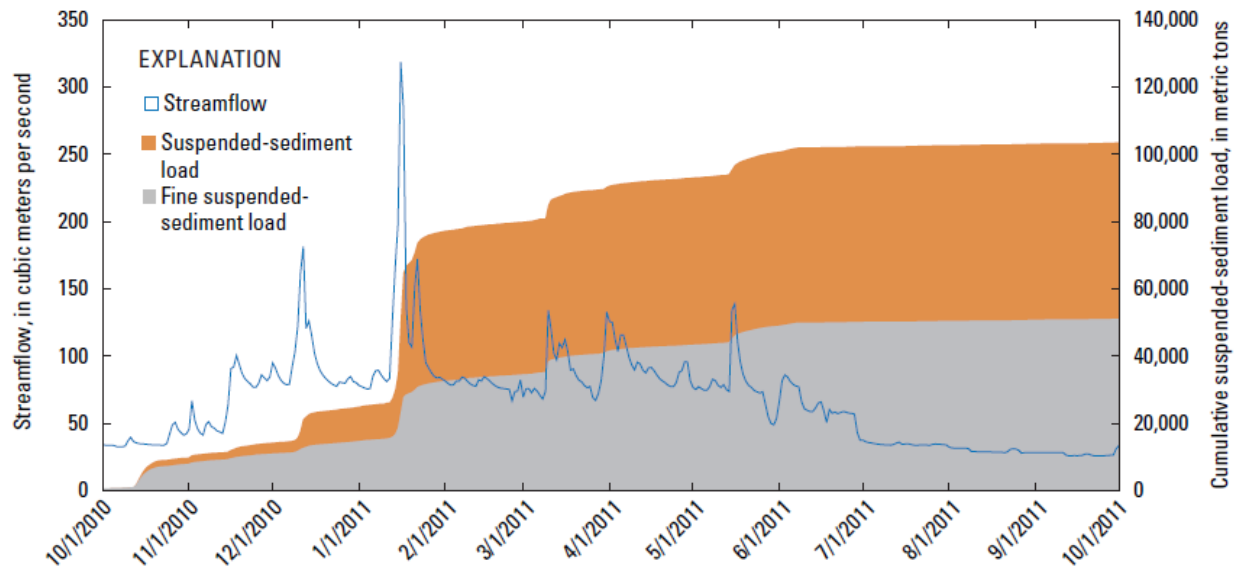
### ***Fluvial Sediment Transport***

A year and a half (July 2010 to December 2011) of continuous and synoptic measurements of fluvial discharge and suspended sediment flux were made above tidal influence to quantify flow conditions and the sediment load to Puget Sound following standard USGS stream gaging and sediment sampling protocols (Figure A1). Sixteen cross-section samples of suspended sediment collected over a range of flow conditions during 2010 and 2011 that quantify suspended sediment concentrations (used for load estimates) and that are used to model suspended sediment flux with concurrent turbidity monitoring and rating relationships, revealed that on average  $99,000 \pm 20,000$  metric tons per year of suspended sediment are delivered by Nisqually River to Puget Sound. Our results are in close agreement with data collected in 1971-73 using similar methods (Nelson 1974). These results imply that downstream of Alder and La Grande reservoirs, the relation between suspended-sediment load and discharge has remained consistent over time, likely due to sediment trapping in reservoirs which have limited downstream supply (Czuba, 2012).



**Figure A1. Suspended-sediment transport curve for the Nisqually River near Yelm, WA**

For the 2011 water year (Oct.1-Sep.30), daily sediment and continuous turbidity data were used to determine that 103,000 metric tons of suspended sediment were delivered to Puget Sound, and 39 percent of this load occurred during a single winter storm (Figure A2). The mean discharge in the Nisqually River for the 2011 water year was about 30 percent greater than average and largely the result of greater than normal spring runoff from snowmelt (March-June). Of the total suspended-sediment load calculated for the 2011 water year, 52 percent was sand (particle size >0.063 mm) and the remainder (48 percent) was silt and clay. The magnitude of some high-flow events in the lower Nisqually River is muted by flow regulation, and relative to other free-flowing, glacier-influenced rivers in Puget Sound, less sediment proportionally is delivered by the Nisqually River to Puget Sound during the late summer due to upstream sediment trapping. The results of this portion of the study are reported in a U.S. Geological Survey Open-File Report currently in Review (Curran and Grossman, In Review).

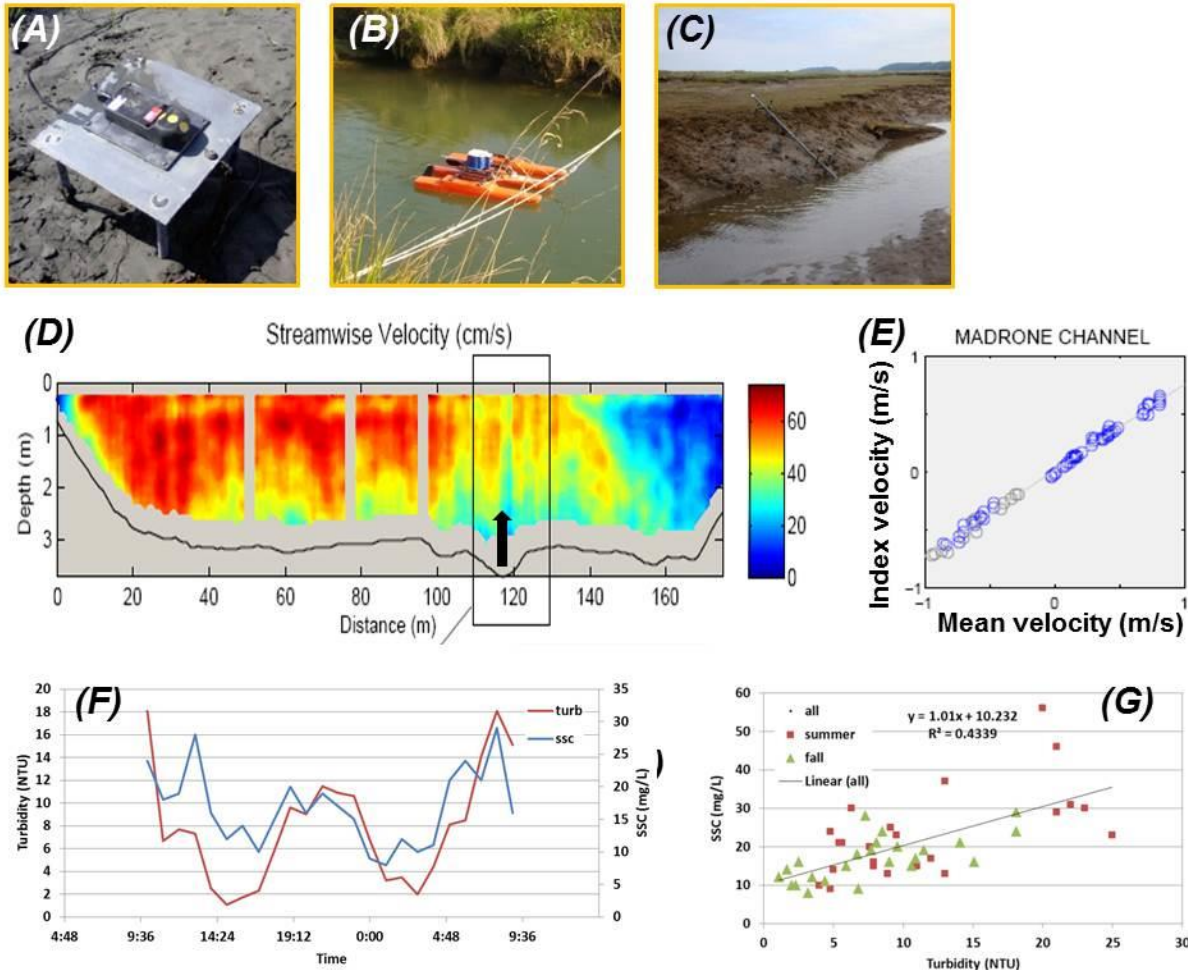


**Figure A2. Cumulative suspended sediment and fine sediment (size <0.063 mm) load delivered by Nisqually River to Puget Sound in 2011 water year (Oct.1, 2010 to Sep. 30, 2011)**

### ***Estuarine Hydrodynamics and Sediment Flux to Restoration Area***

Continuous and synoptic measurements of flow conditions including water levels (tides), current velocities and directions, and suspended sediment flux were made across the delta and estuary including all five channel connections to the restored marshes to quantify the budget of water and suspended sediment transported into and out of the restoration area (Figure A3). A6<sup>th</sup> instrument package was deployed in the nearshore to characterize general circulation patterns along the delta front. These information are important because sediment delivery to the restored marshes relies almost entirely on tidal processes to move river-derived sediment deposited on the tidal flats into the restored area as historic distributary pathways have not yet been restored. A small amount of sediment enter the restoration area over the river banks during floods, but this has not been observed yet since the restoration and it remains uncertain if the volume or spatial extent would significant to assist marsh accretion. Continuous measurements were made at the restored breaches of Leschi and Madrone Sloughs for 2 years and were concurrent with 3 months of monitoring at Area 1, Area 3 and McAllister Creek (Figure A4). At each channel breach site where instruments were deployed, synoptic measurements were made of cross-sectional area to develop a relationship between stage-area as the tides rise and fall. Also measurements of the cross-channel current velocities were made to quantify the mean current velocity across each slough relative to the “index” site where currents were continuously measured at one location. Finally suspended sediment samples were collected and analyzed to develop a rating between suspended sediment concentration and turbidity which was monitored continuously. Together these data sets allow for calculations of the flux of water and sediment into and out of the restored marshes.



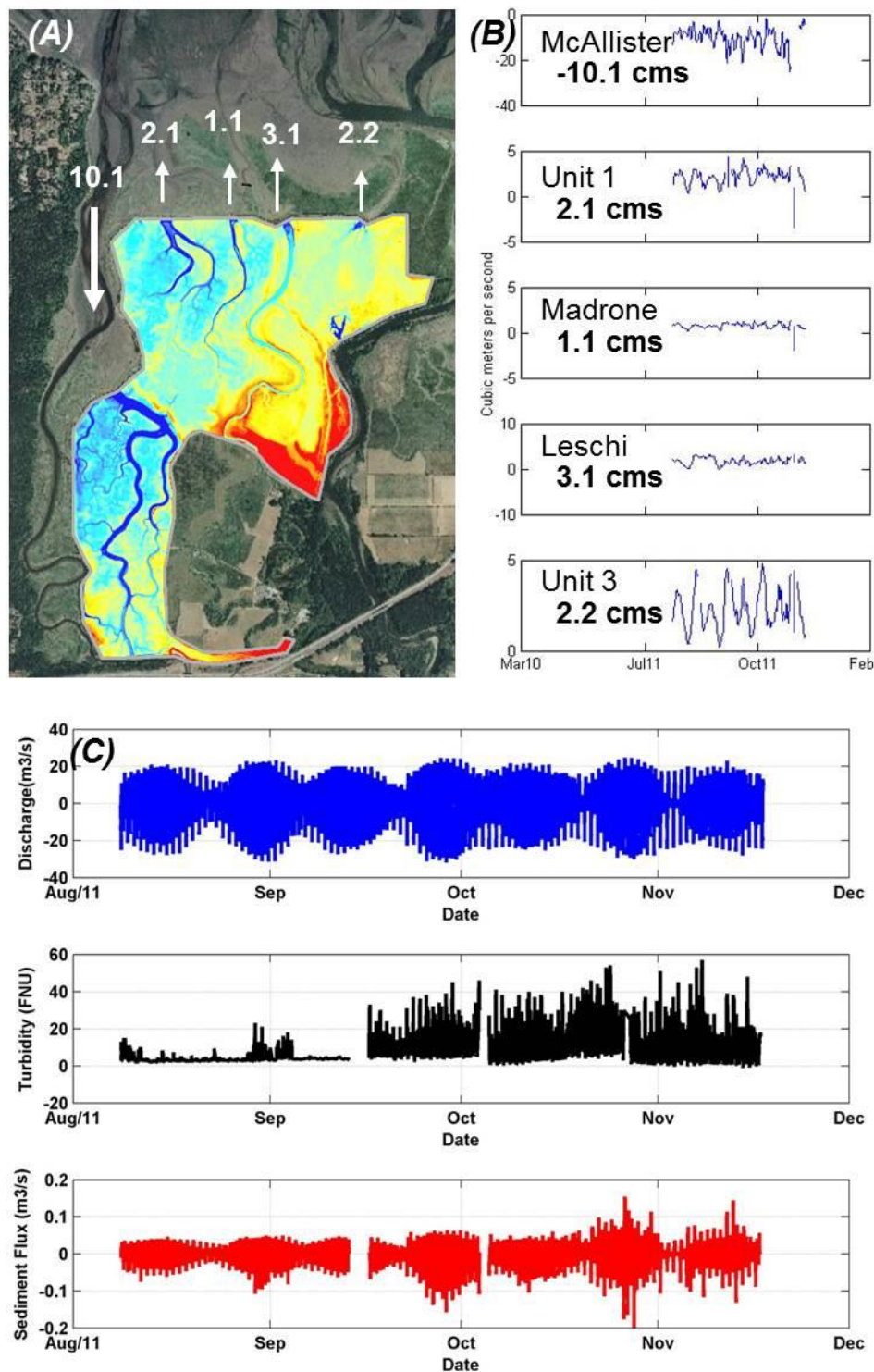


**Figure A3. (A) Uplooking Acoustic Doppler Current Profiler deployed at each channel entrance to gather time-series data of flow conditions and Index Velocity. (B) Acoustic Doppler Current Profiler used to characterize variations in velocity across channel and water levels (tides, river discharge). (C) Turbidity sensor deployed at each channel entrance to gather time series data of turbidity (discrete sediment samples gathered to rate turbidity to suspended sediment concentration). (D) Example cross-channel current velocity profile relative to Index Velocity measured at black arrow. (E) Mean channel velocity relationship to Index Velocity for a range of water levels (tides) for Madrone Channel. (F) Example of time series of turbidity and suspended sediment concentration for one period of sampling at Madrone Channel. (G) Rating curve between turbidity and suspended sediment concentration for Madrone Channel.**

Net water flow through the marsh channels was on average 1.6 cubic meters per second and ~6% of river flow with a majority related to flow through McAllister Creek and Shannon Slough. Turbidity monitored simultaneously in the river and sloughs showed that during periods of high fluvial turbidity (sediment concentrations), turbidity in the marshes on average was 40-50% of that in the river suggesting that fluvial derived suspended sediment is lost (or deposited) between the river and marshes. Turbidity can be high and even higher inside the marsh sloughs



than the river at times and is the result of redistribution of sediments within the restoration due to the restored tidal prism and geomorphic processes that continue to find equilibrium following the restoration. The net flux of sediment was into the marshes and governed by the strong asymmetry in flow through McAllister Creek (stronger flow into McAllister than the four other smaller marsh channels). The net flux of suspended sediment for water years 2010 and 2011 however, was relatively low and estimated to be  $370 \pm 80 \text{ m}^3/\text{yr}$ . Assuming this amount of sediment was deposited evenly across the restored marsh area at or above elevations where marsh vegetation occur ( $\sim 2.0 \text{ m}$ ) the potential annual sediment accretion rate would be  $0.12 \text{ mm/yr}$ . This is significantly lower than the rate of sea level rise ( $\sim 2.0\text{-}3.5 \text{ mm/yr}$ ) suggesting that the marsh is likely to have a challenging time recovering with the current sediment delivery regime given the historical  $1\text{ m}$  of subsidence it experienced since the dikes were emplaced in the late 1800s and recent acceleration of global sea level rise. The results of this portion of research documenting the flux of water and sediment through the restored marsh channels of the Nisqually Delta are being published in a U.S. Geological Survey Open-File Report currently in review, Grossman and Curran (In Review).



**Figure A4. (A) Map showing sampling sites (white arrow) and net water discharge results through each channel in cubic meters per second. (B) Plots of channel discharge time series results and net flux for each channel (positive offshore), revealing a net flow of water into the restoration area of 1.6 cubic meter per second, dominated by flow in through McAllister Creek and flow out of the four smaller channels. (C) Plots of total discharge, turbidity and**

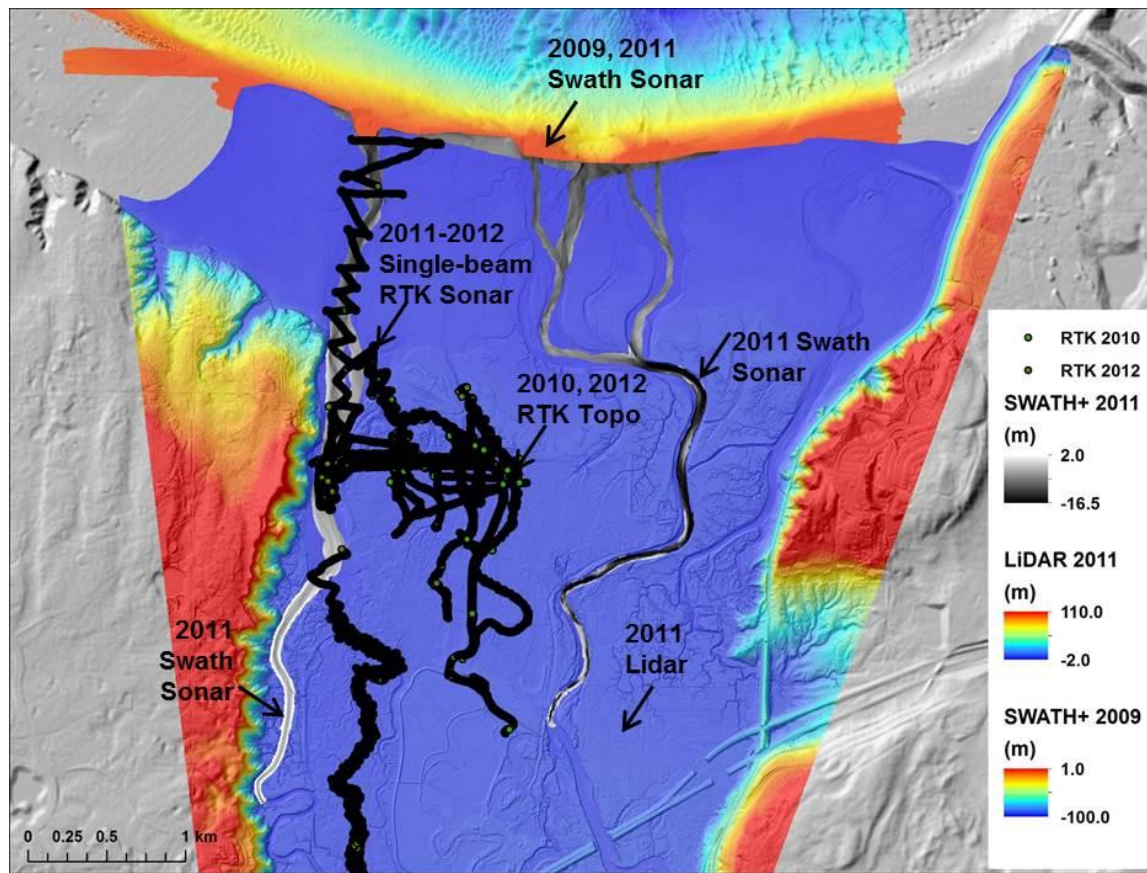
**resulting suspended sediment flux for all channels during the period August to December 2011 when all channels were simultaneously monitored. Resulting suspended sediment flux of  $370 \pm 80 \text{ m}^3/\text{yr}$  estimated from these data.**

*Output C - Numerical modeling and field studies of nearshore hydrodynamics to develop a better understanding of nearshore circulation surrounding Nisqually Delta and the mixing/fate of freshwater and particulate matter.*

A numerical hydrodynamic model of the Nisqually Delta was constructed using Delft3D and used to examine inundation frequency, habitat connectivity over different tides and river flows, and to examine sediment transport and retention. Sensitivity tests of modeled sediment transport to the influence of waves, tidal currents and four wetland vegetation types that attenuate (trap) sediment were conducted. To develop the Nisqually Delta Delft3D model, a new high-resolution, seamless onshore-offshore digital elevation model (DEM) was constructed. Along with accurate water level data collected as part of measuring hydrodynamics and sediment flux in and out of the restoration area (Output A), the DEM is a fundamental boundary condition for numerical hydrodynamic modeling.

### ***Digital Elevation Model***

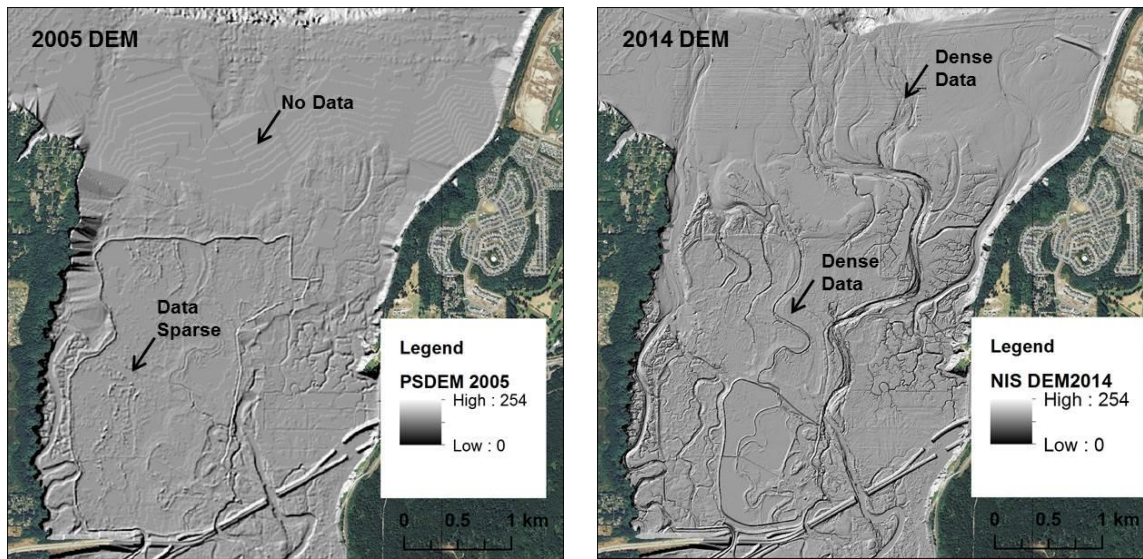
A new digital elevation model was constructed through collection, processing and integration of several new topographic and bathymetric mapping data sets. These were gathered through a 2011 topographic LiDAR survey, Swath (multibeam) sonar bathymetry surveys in 2009 and 2011, two high-resolution single beam sonar surveys in 2010 and 2011, and RTK-GPS topographic surveys during 2010, 2011, and 2012 (Figure C1 – below). Although these data span different time periods, most recent data are superimposed over older data and together they represent the best available data for the post-restoration elevation surface. Error among the data sets vary between 0.05-0.25m, with a final merged DEM error generally ranging 0.15m, except in the deeper channels within the restoration area that may reach 0.25m.



**Figure C1. Map showing data sources for new 2014 high resolution digital elevation model.**

The new Nisqually DEM (Figure C2, below) is a vast improvement over past available data, represented by the 2005 Puget Sound DEM (Finlayson, 2005). The 2005 DEM lacks elevation data in most intertidal areas of Puget Sound and therefore generated a surface by interpolating between moderately dense early generation LiDAR data onshore and generally sparse sonar data offshore. The new high density LiDAR data (>8 pulses per square meter) and continuous Swath sonar data capture significantly more detail of the geomorphology, substrate, vegetation, and habitats of the Nisqually Delta, characteristics particularly important for influencing water flow, circulation, and sediment transport.





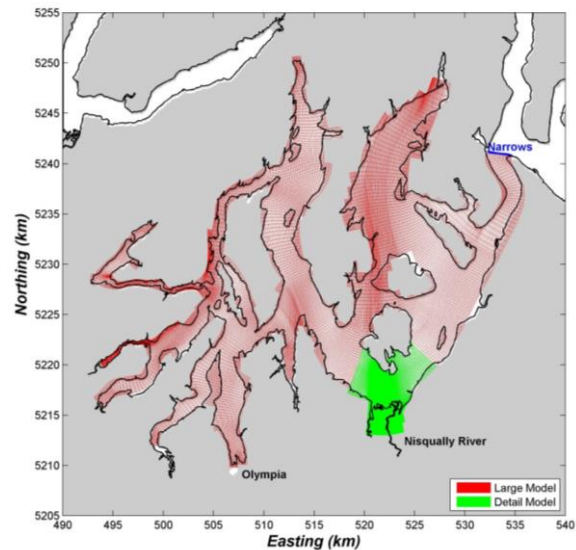
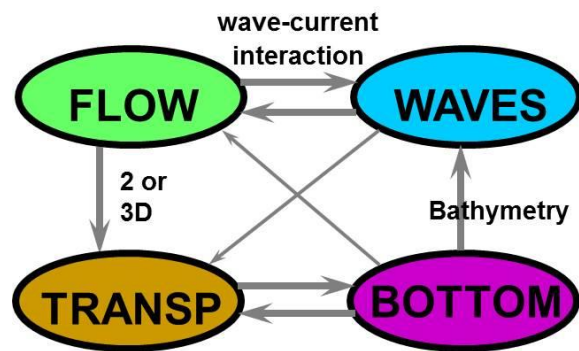
**Figure C2. Maps comparing details of the 2005 DEM (left) and 2014 high-resolution digital elevation model (right).**

### ***Hydrodynamic Model***

A hydrodynamic model of Nisqually Delta was constructed using Delft3D, an open source, set of modules that simulate and dynamically update the interaction of flows, waves, sediment transport and morphological evolution of the bed. Briefly, Delft 3D simulates the non-steady flow and transport of water, sediment or dissolved constituents from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary-fitted grid. D3D includes the effects of stratification, wetting and drying and nearshore wave transformations. The sediment transport module supports both bed-load and suspended load transport of non-cohesive sediment and suspended load transport of cohesive sediment. Exchange of sediment with the sediment bed causes changes in bed level in the form of erosion or accretion. Because these morphological processes take place on a larger time scale than the flow, a morphological factor can be applied to the bed level change to account for the shorter model time step. Of importance to Nisqually and similar wetland environments across Puget Sound, D3D has the ability to integrate friction effects of vegetation which influence circulation, waves and sedimentation. This project has advanced the integration of vegetation into estuarine sediment transport modeling but will not be described further here. More detailed information can be found in the Delft3D User Manual (*Deltares 2009*).

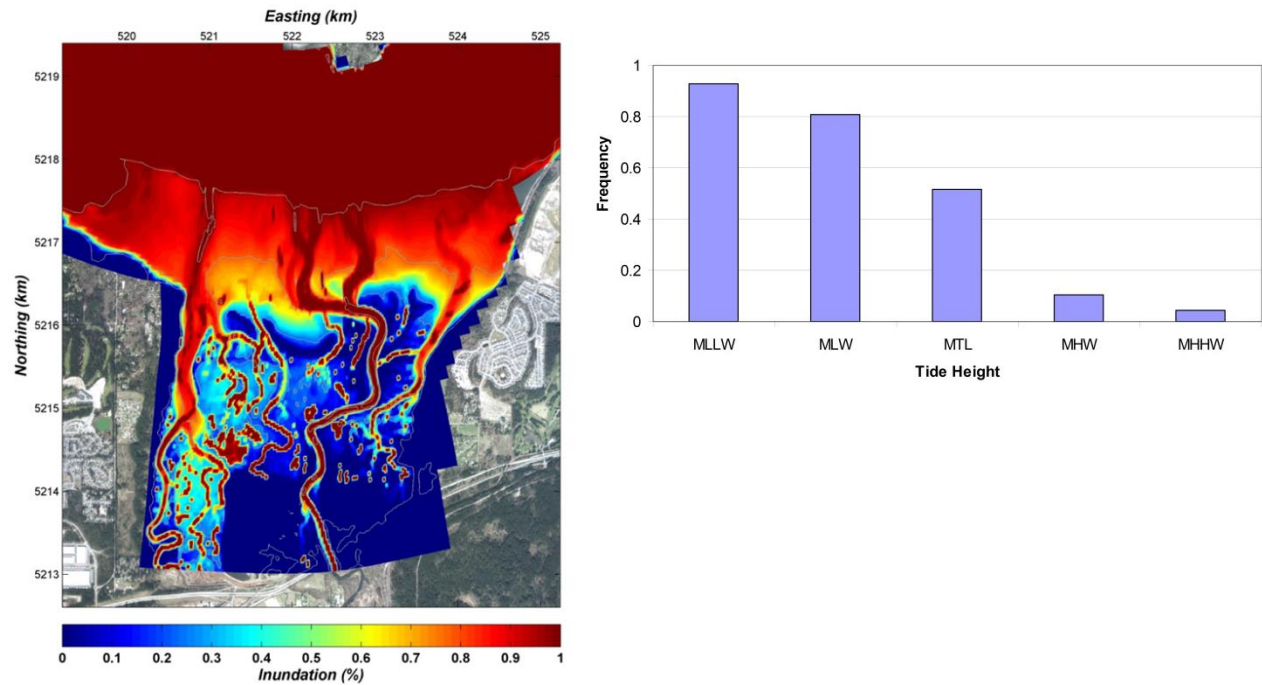
The Nisqually model developed includes a three part nested model framework. At the largest scale (smallest area) a detailed model covering the delta and tidal flats is forced at its boundaries by tide levels and current velocities modeled with a South Puget Sound hydrodynamic model, which is in turn forced at the Tacoma Narrows (Figure C3, below) by our USGS Salish Sea model. The Salish Sea model is forced by published tidal harmonics developed by NOAA at the west entrance of the Strait of Juan de Fuca and a continuously refined digital elevation model for the Salish Sea. Model predictions of tide levels and currents from the large

Salish Sea model and the South Puget Sound model are validated by measurements of water levels and tidal currents at various USGS study sites and where available data exist. For Nisqually, water level and current measurements made along the outer tidal flats test the accuracy of the South Puget Sound model and measurements made at the channel beaches and inside the restoration test the accuracy of the detailed Nisqually Delta model.



**Figure C3. Diagram showing the four primary Delft 3D modules used to simulate circulation and sediment transport (additional modules for example water quality also exist) and the South Puget Sound (forcing) and detailed, nested Nisqually Delta model grids.**

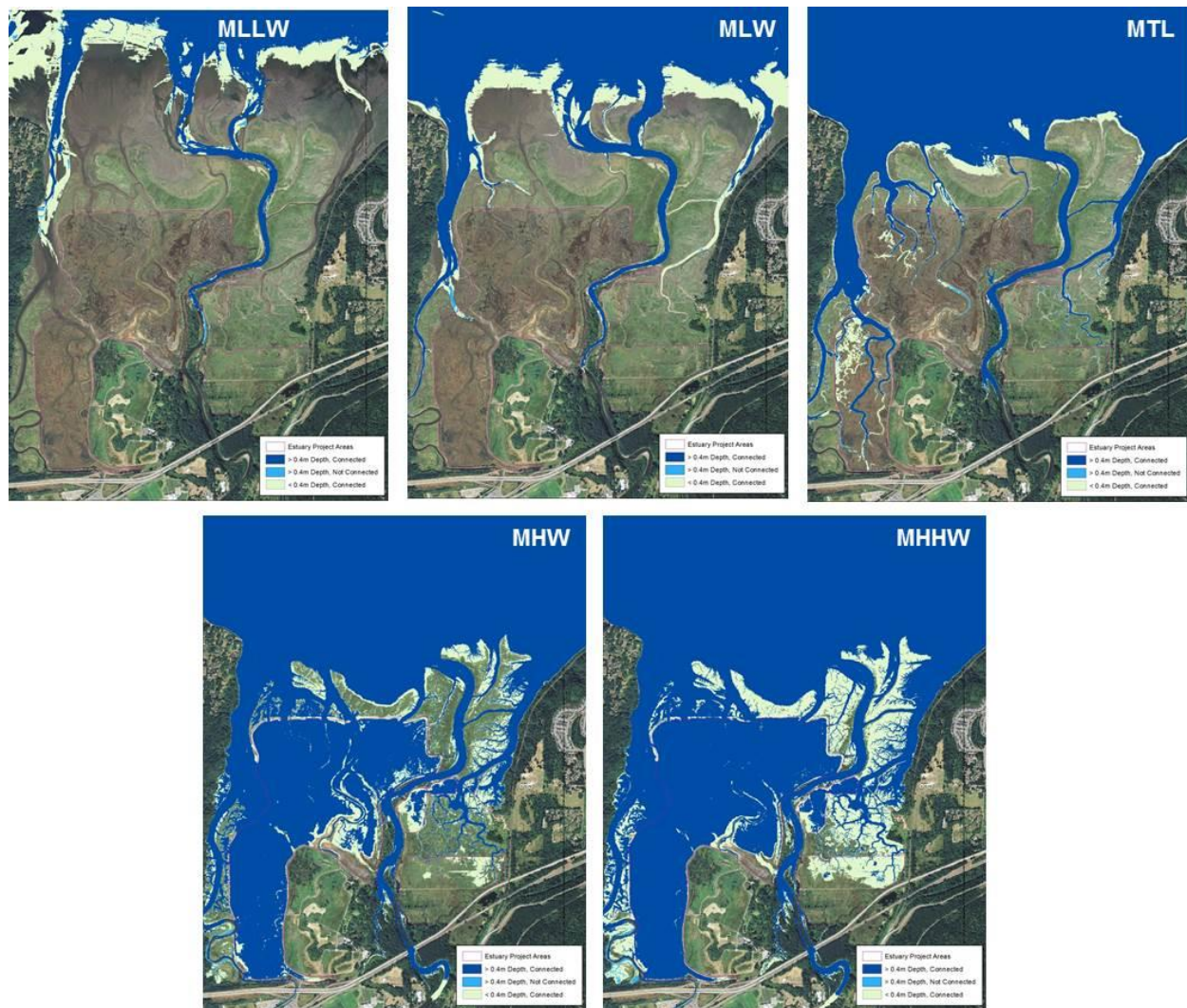
Model outputs of inundation frequency and habitat connectivity are validated with measurements of water levels throughout the restoration area. Inundation frequency within the restored area ranges 25-90% and is highest in the deeper channels (Figure C4, below). Inundation frequency is likely higher than planned given the historical subsidence of the area and lack of sedimentation within the restored area.



**Figure C4. Map showing model results of monthly mean inundation frequency across the restored Nisqually Delta (left). Bar plot showing frequency of inundation by tidal height (right).**

Habitat connectivity outputs showing connections between the river and Puget Sound marine waters and the marshes have been produced for both pre- and post-restoration to examine the increase in capacity and opportunity for restoration and fish habitat use. Examples showing the connectivity over the monthly tide cycle help to show how water, sediment, fish and other organic and inorganic material can be moved as water depth changes over the Nisqually Delta topography Figure C5, below.

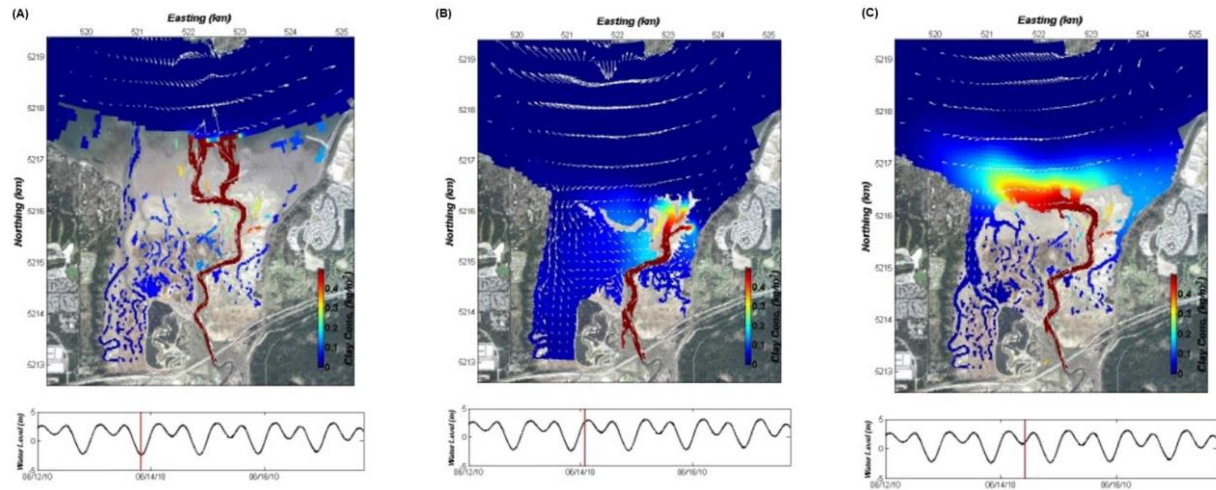




**Figure C5. Map showing results of habitat connectivity modeling at select water levels as the tides inundate the restored Nisqually Delta.**

Simulations of sediment transport between the river and restored marshes and scenarios of potential future geomorphic evolution of the delta have been conducted. Results are being prepared for a USGS report and peer-reviewed manuscripts. An example illustrated here presents a snap-shot in time of the (1) stream and nearshore current velocity and direction vectors (white arrows) and (2) concentration of suspended sediment ranging 0 to  $0.4 \text{ kg/m}^3$  (rainbow colors) emanating from the Nisqually River plume and across the Nisqually Reach for a modest high tide (Figure C6, below). The outputs of this simulation reveal that under average flood conditions when suspended sediment is delivered to the Sound, connectivity of the sediment-laden river plume to the restored marshes is limited to a brief period of time during high tides and that only a fraction of the total river sediment load reaches the restored area. The results agree with the comprehensive measurements made as part of Output A.





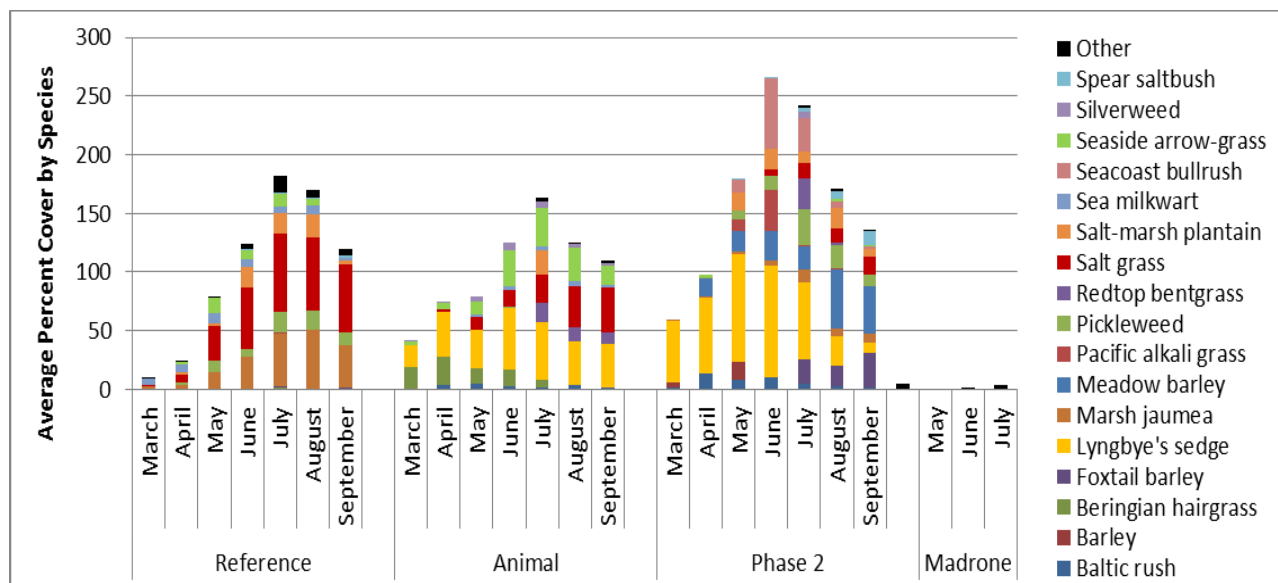
**Figure C6. Delft3D model outputs of simulated transport of suspended sediment emanating from the Nisqually River. At low tides, most suspended sediment is advected offshore of the tidal flats (left). During the first high tide of the diurnal tides, the suspended sediment of the Nisqually River Plume is generally pushed back into the river before it has a chance to connect with the restored marshes (center). The only appreciable period of time that the sediment-laden Nisqually River plume is connected to the restored marshes is during a small fraction of the time (~15-20%) that the 2<sup>nd</sup> diurnal high tide transports the pooled turbidity plume into the restored area.**

*Output D. Post-restoration vegetation composition and development with comparison between restoring and reference marsh*

A vegetation quadrat  $0.25\text{m}^2$ , was placed in the emergent marsh associated with the location of the insect fallout traps in close proximity to the slough at four intensively monitored channels (Map 2). Veg quadrats were surveyed monthly in 2010 for % cover and density to relate to the insect community. Percent cover was recorded for each species so that in areas with multi-species canopy cover, total percent cover will exceed 100%. Average percent cover by species increased through the growing season and peaked in July for Reference Marshes (Reference and Animal Slough) while percent vegetative cover peaked in June for Restoration Marsh, Phase 2 (restored in 2006; Fig D1). Madrone Marsh, which was recently restored in 2009, had very little plant cover throughout the spring-summer.

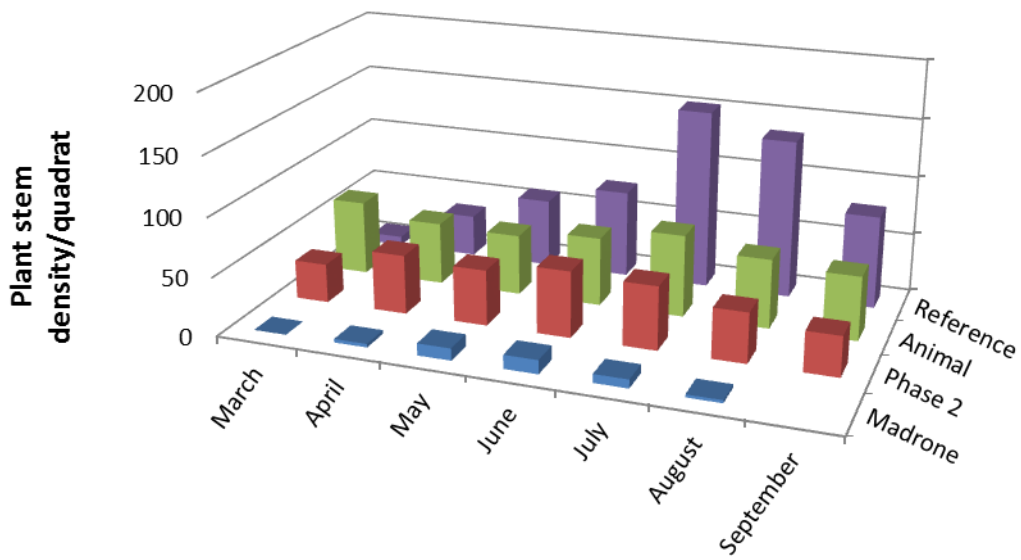


**Map 2. Nisqually Delta intensively monitored channels.**

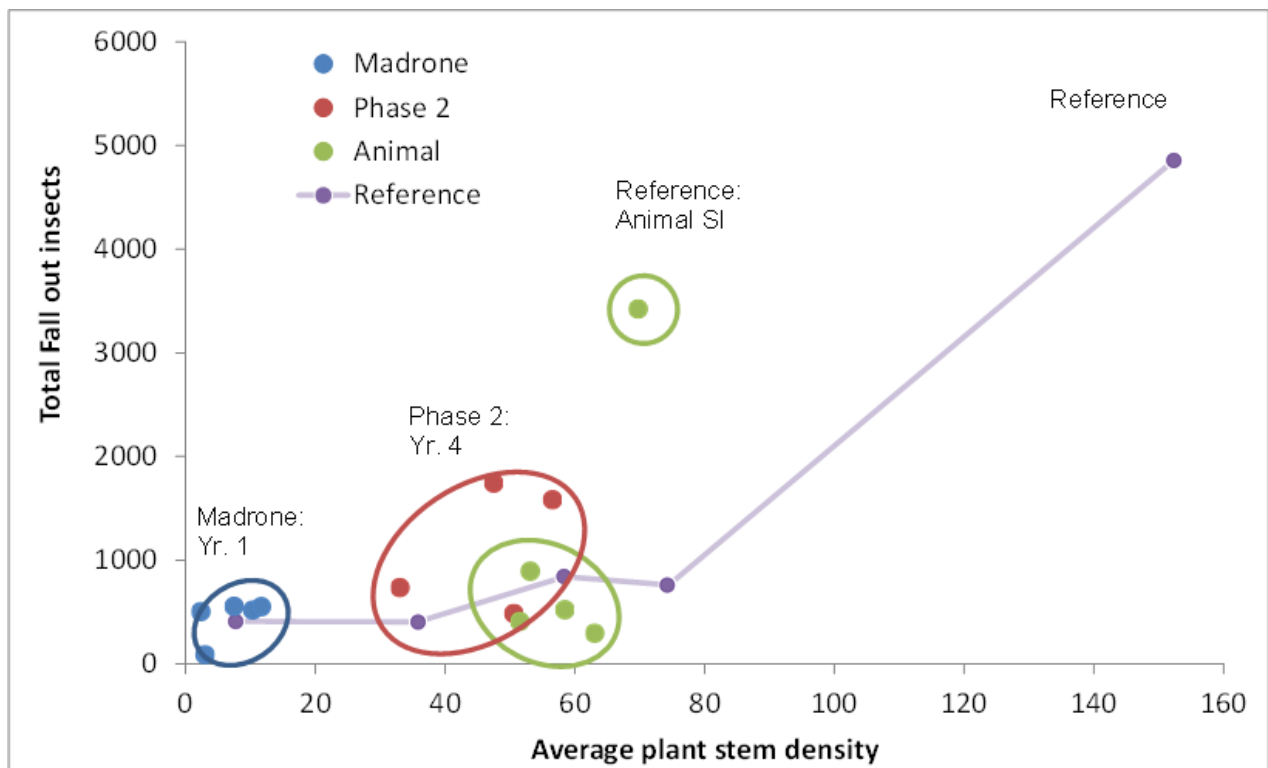


**Figure D1. Average percent cover by species in Reference Marshes (Reference and Animal) compared to Restoring Marshes (Phase 2 restored in 2006 and Madrone restored in 2009) across the growing season (March-Sept 2010). In instances with multi-species canopies, total percent cover exceeds 100%.**

Overall plant stem density increased over the growing season and was greatest at Reference Marshes (Reference and Animal Slough) with a maximum of 152 stems/quadrat in July in Reference Marsh. Phase 2 Restoration Marsh also had stem densities similar to Animal Slough Marsh; however Madrone, which was restored in 2009, had low stem densities with a maximum density of <12stems/quadrat (Figure D2). We related total insect fallout abundance with average stem density and points were somewhat clustered by site such that Madrone Marsh consistently had low stem density and low insect abundance over the entire season. Phase 2, Animal Slough, and Reference marshes were clustered together with stem densities ranging from 33-63/quadrat and with 300-1,750 insect abundance (Figure D3). The greatest abundance of insects we sampled occurred in the Reference marshes. We detected 3,423 insects associated with 70 plant stems at Animal Slough and 4,857 insects associated with 152 plant stems. These points represent the restoration potential for increasing insect numbers in relation to stem densities and insect habitat found in reference marshes.



**Figure D2.** Total plant stem density per 0.25m<sup>2</sup> quadrat in Reference Marshes (Reference and Animal) compared to Restoring Marshes (Phase 2 restored in 2006 and Madrone restored in 2009) across the growing season (March-Sept 2010).



**Figure D3.** Total insect abundance from fallout traps in relation to average plant stem density in Reference Marshes (Reference and Animal) compared to Restoring Marshes (Phase 2 restored in 2006 and Madrone restored in 2009).



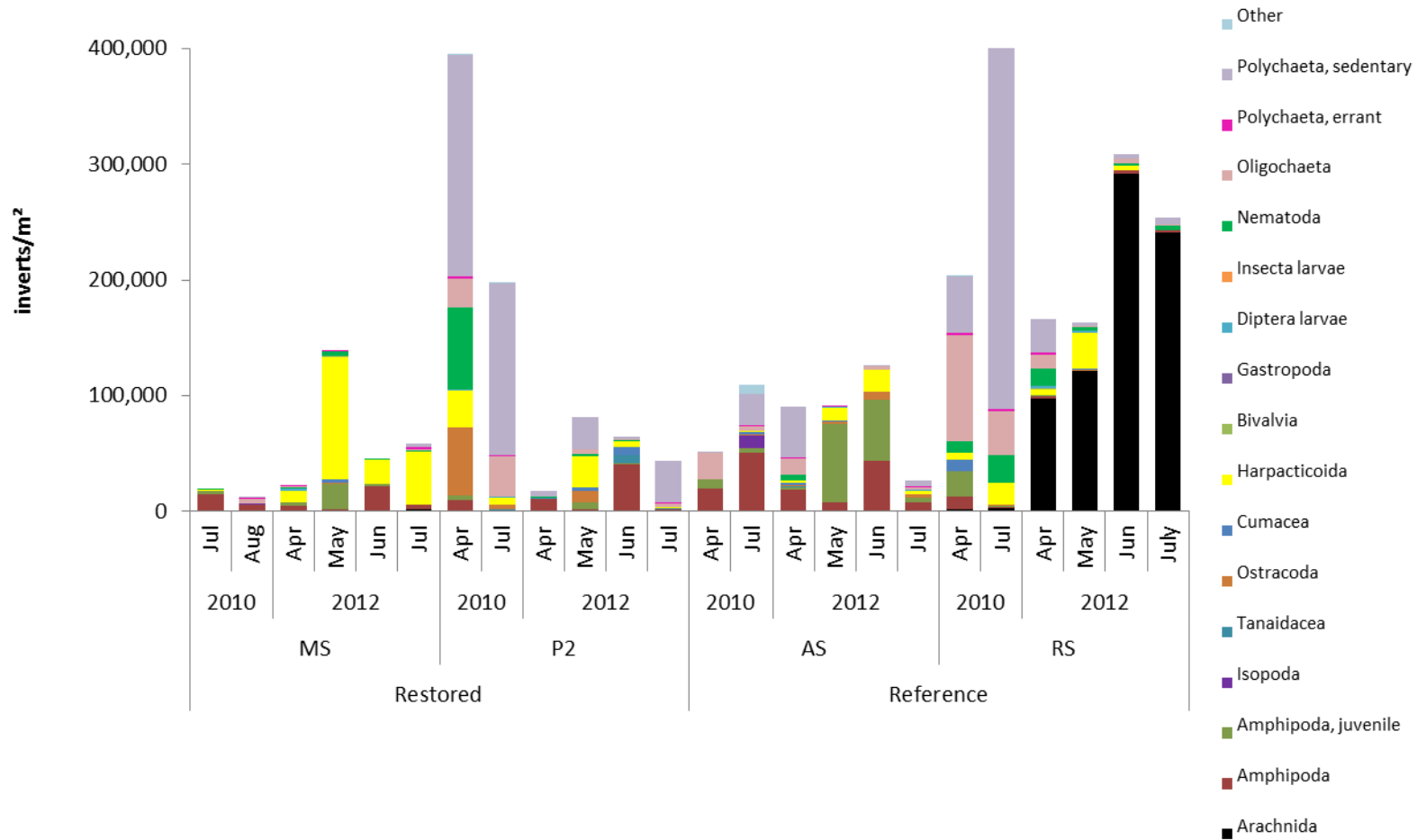
*Output E. Post-restoration invertebrate community composition and abundance with comparison between restoring and reference sites.*

Invertebrate prey composition and density was highly variable and dependent on sampling type and site. Benthic invertebrate cores contained the greatest density of all sampling types followed by Neuston net sweeps. Fallout traps yielded the lowest densities. In 2010, overall benthic invertebrate density was greatest at one of the reference sites (RS,  $\bar{x} = 569,000/\text{m}^2$ ), followed by the restored site from 2006 (P2,  $\bar{x} = 395,000/\text{m}^2$ ; Figure E1). The high densities in 2010 at these two sites were attributed to small sedentary polychaetes (*Manayunkia aestuarina* and other Sabellids). In 2010, the newest restored site had the lowest density (MS,  $\bar{x} = 14,000/\text{m}^2$ ) and was primarily comprised of amphipods and oligochaetes. The reference site adjacent to MS, had relatively low densities as well (AS,  $\bar{x} = 95,000/\text{m}^2$ ) and was primarily comprised of amphipods. In 2012, overall densities remained highest at Reference site RS ( $\bar{x} = 353,000/\text{m}^2$ ) and restored P2 ( $\bar{x} = 104,000/\text{m}^2$ ), however were reduced from 2010 observed densities. Sedentary polychaetes remained the most abundant taxa at P2, however there was a shift at RS from sedentary polychaetes to high concentrations of water mites, acari (Arachnida). Densities at MS and AS increased in 2012 (MS,  $\bar{x} = 144,000/\text{m}^2$ ; AS,  $\bar{x} = 142,000/\text{m}^2$ ). Harpacticoid copepods were the dominant taxa at the newly restored MS, comprising 70% of overall density, while the older restored slough P2 exhibited a more even community structure (Sedentary polychaetes, 34%; Amphipoda, 30%, Harpacticoida copepods, 20%).

Neuston samples were dominated by Harpacticoida copepods and other copepods (primarily Calanoida). Copepoda comprised 50% of all individuals counted in the neuston sweeps. Harpacticoids were most abundant at the newly restoring site, MS ( $\bar{x} = 2,000/\text{m}^3$  in 2010,  $\bar{x} = 5,600/\text{m}^3$  in 2012; Figure E2). Harpacticoids are commonly found in newly restoring environments due to the plentiful detrital organic material (Rieper 1982). Harpacticoid density was higher at all sites in 2010, except at RS ( $\bar{x} = 3,100/\text{m}^3$  in 2010,  $\bar{x} = 700/\text{m}^3$  in 2012). We also detected occasional blooms of Cirripedian naupli in 2012, appearing primarily at MS in April ( $x=3,900$ ), June ( $x=17,700$ ) and July ( $x=6,400$ ), but also at AS in May 2012 ( $x=13,300$ ).

Terrestrial invertebrate density from the fallout traps was highest at P2 ( $\bar{x} = 1,600/\text{m}^2$ ), followed by AS ( $\bar{x} = 1,200/\text{m}^2$ ), RS ( $\bar{x} = 1,100/\text{m}^2$ ), and MS ( $\bar{x} = 1,000/\text{m}^2$ ; Figure E3). The most dominant taxa were the shore fly, Dolichopodidae and the biting midge, Chironomidae.

Dolichopodids were the most abundant taxa at all sites, except P2, where Chironomids were the most prominent. Dolichopodidae abundance peaked across sites in July, whereas Chironomidae peak abundance occurred in May across all sampling years. Other common taxa detected in the fallout samples were Hemipterans (aphidae, cicadellidae, cercopidae, and saldidiae), Ephydriidae (Diptera), as well as acari and collembola.



**Figure E1. Benthic invertebrate density at Nisqually Delta in 2010 and 2012 across two restoring sites (Madrone Slough: MS; and Phase 2: P2) and two reference sites (Animal Slough: AS; and Reference Marsh: RS).**

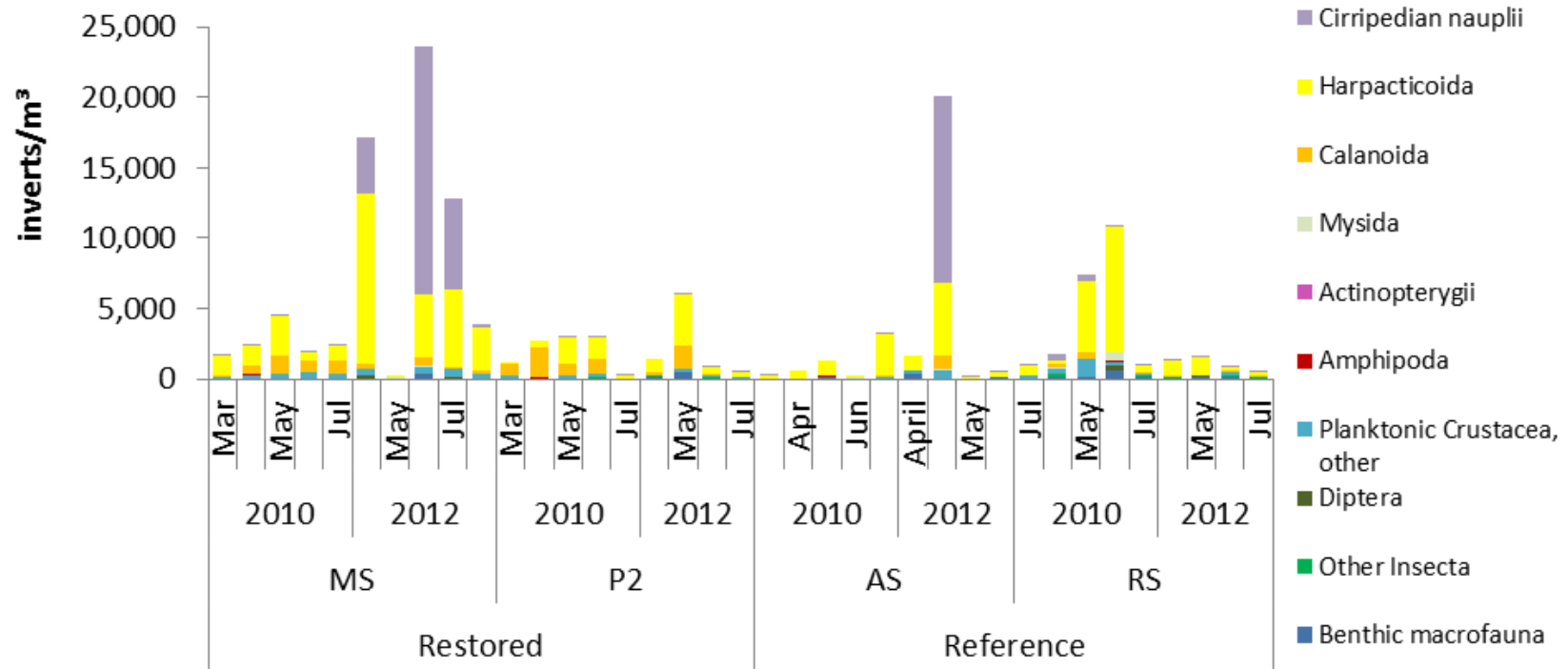
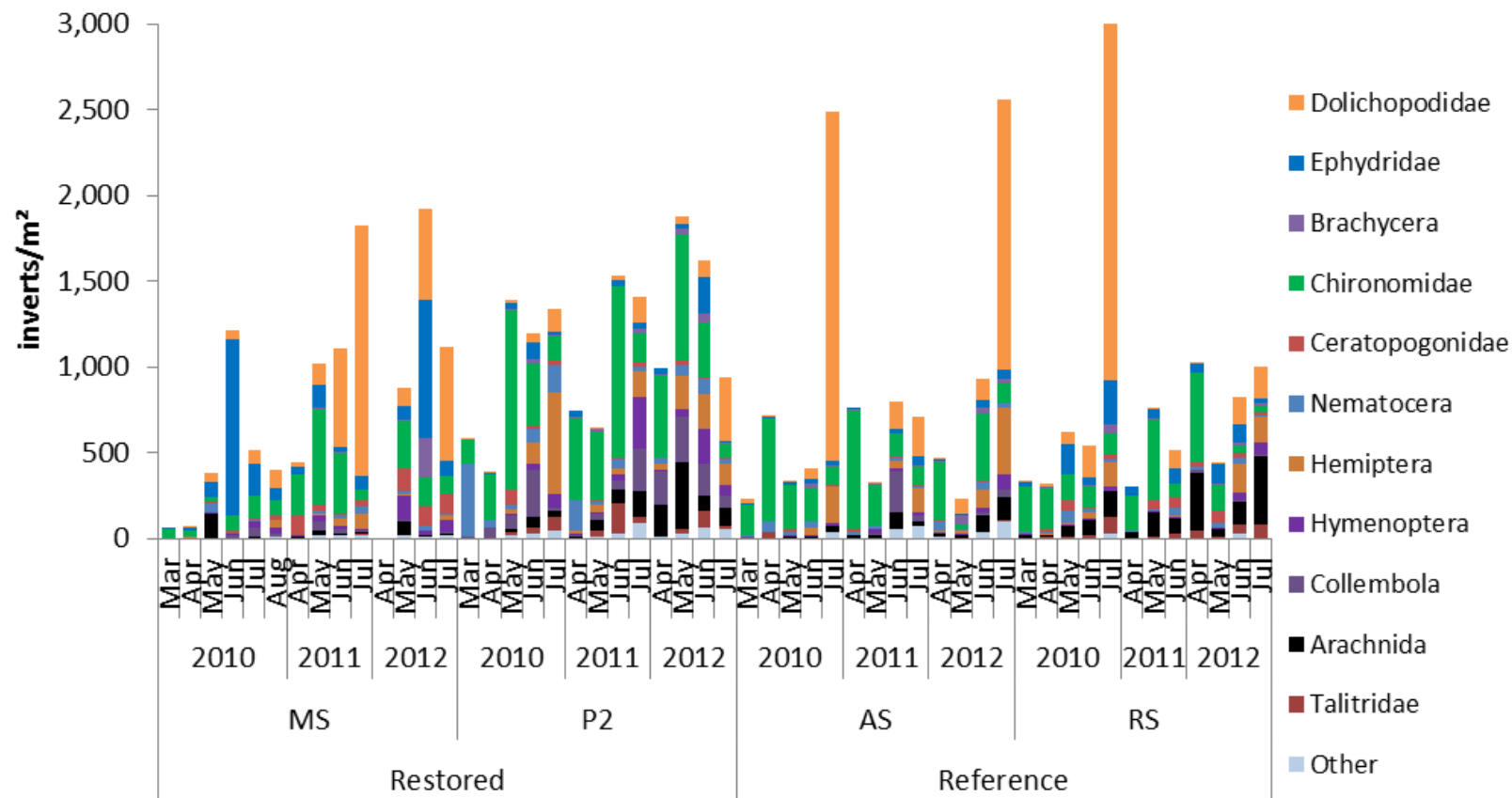


Figure E2. Invertebrate density in neuston surface tows at Nisqually Delta in 2010 and 2012 across two restoring sites (Madrone Slough: MS; and Phase 2: P2) and two reference sites (Animal Slough: AS; and Reference Marsh: RS).



**Figure E3. Terrestrial invertebrate density in Fallout traps at Nisqually Delta from 2010 - 2012 across two restoring sites (Madrone Slough: MS; and Phase 2: P2) and two reference sites (Animal Slough: AS; and Red Salmon Slough: RS).**

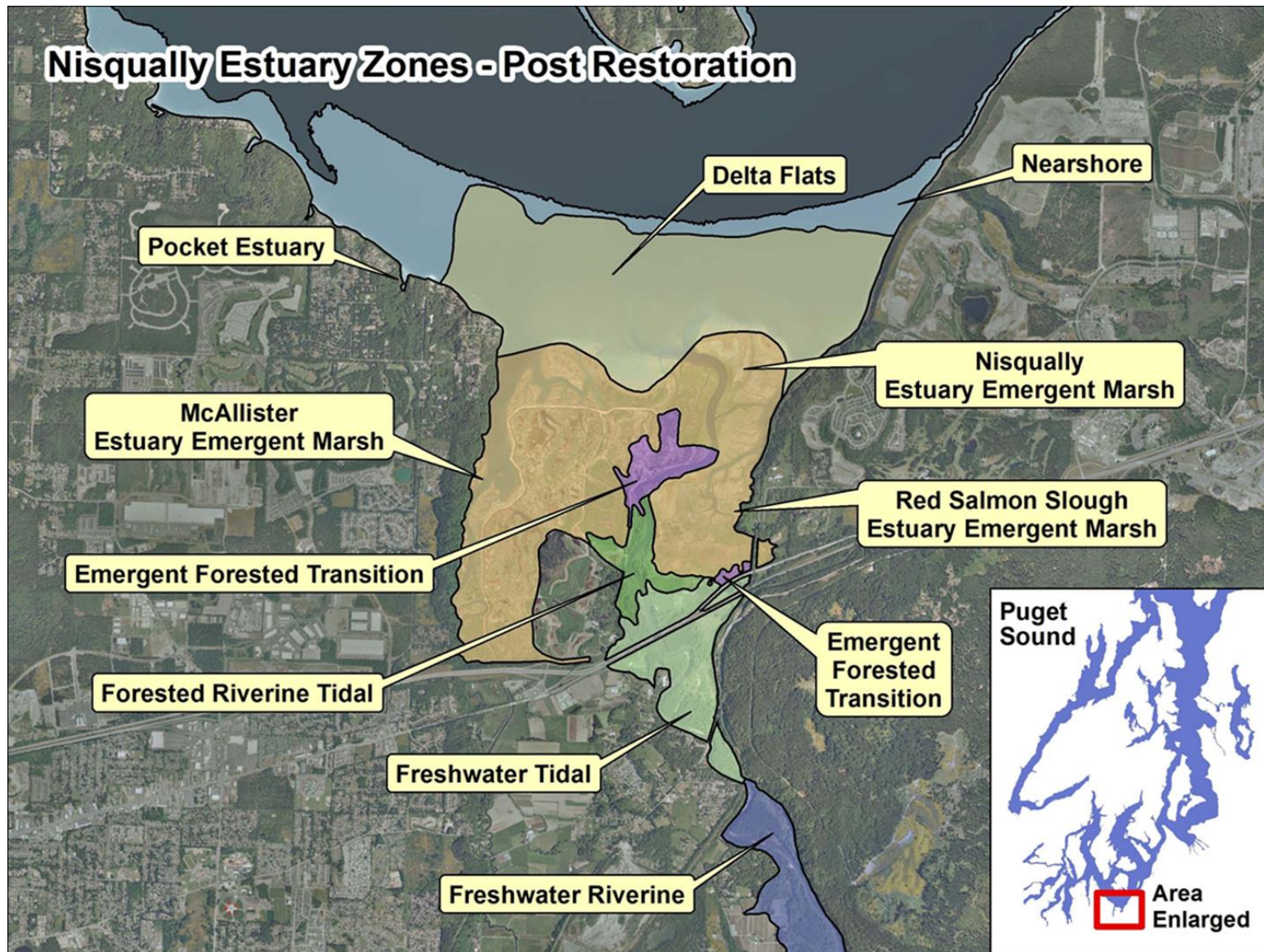


*Output F: A refined model of the distribution, abundance, and timing of Chinook and other fishes in freshwater, estuary, mud flats, and nearshore habitats.*

The Team utilized different sampling techniques to track Chinook rearing patterns from freshwater, through the estuary, and out into the Nisqually Reach Aquatic Reserve nearshore environment. The sampling area is divided into several distinct habitat zones (Map 3). Our sampling focused from the tidally influenced freshwater zone out into the nearshore. Beach seining was used extensively in all areas supplemented by lampara sampling in the Delta flats and nearshore, while fyke trapping was used to assess Chinook use of specific sloughs (Map 4). Beach seining captured fish utilizing shallow water habitats along the shoreline while lampara sampling captured fish using shallow water features off-shore like mud flats and eelgrass beds (Map 5).

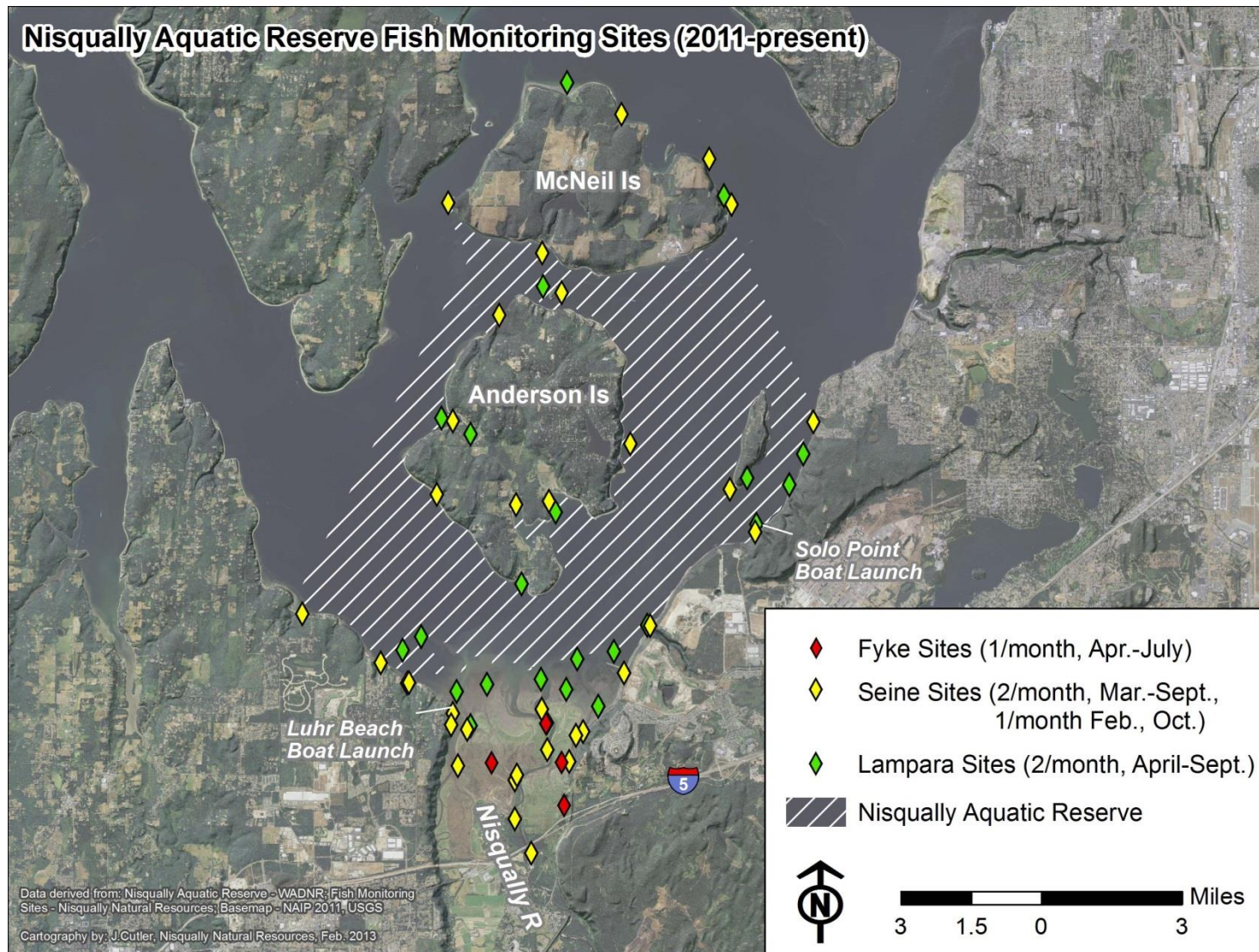
Beach seining was conducted in each of the habitat zones (Map 3) and we recorded hatchery and natural Chinook as well as chum salmon, the most estuary dependent salmonids, for both before (2004-2006) and after (2010-2013) the large scale restoration in 2009 (Figure F1). Patterns of distribution and relative abundance did not vary substantially before and after restoration. Unmarked (a.k.a. Natural) Chinook rear in high densities in the limited tidal freshwater zone around Interstate 5 before moving into the larger estuarine emergent marsh zone. Hatchery Chinook are widespread and abundant throughout the estuary after being released from the hatcheries in May. Chum salmon are widely distributed and especially dense along the nearshore shorelines adjacent to the Delta. A list of all species captured beach seining from 2010-2013 by habitat zone is presented in Table F1.

Lampara sampling allowed us to sample unique environments like eelgrass beds and mud flats (Map 5). Lampara catch rates at delta front eelgrass sites tended to be much lower than at nearshore sites in May but somewhat higher in July and August (Figure F2). Catch rates at other delta flat sites were usually lower than nearshore or delta front eelgrass sites.

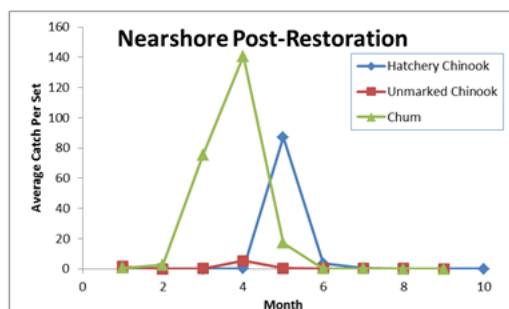
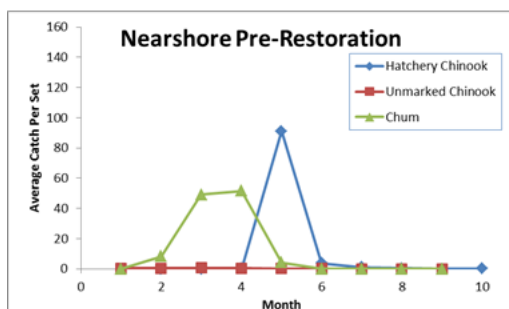
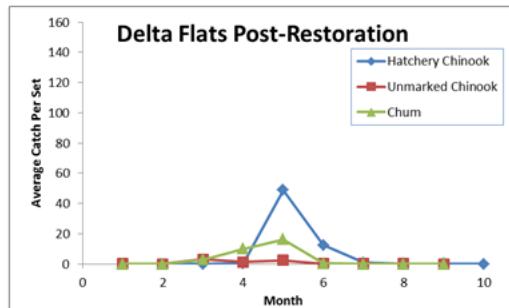
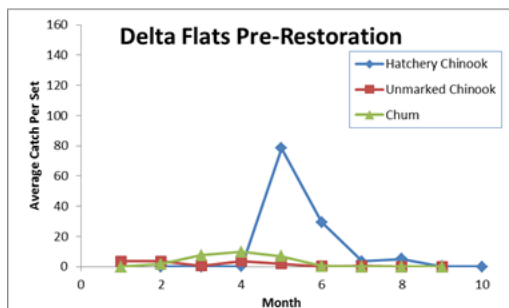
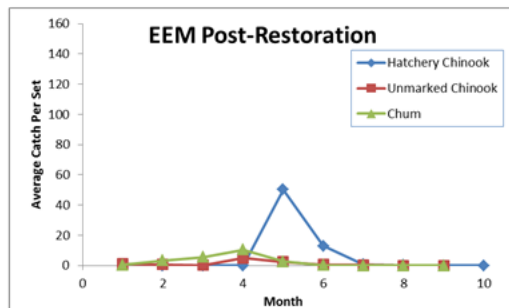
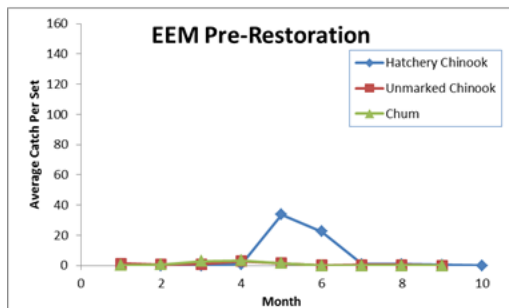
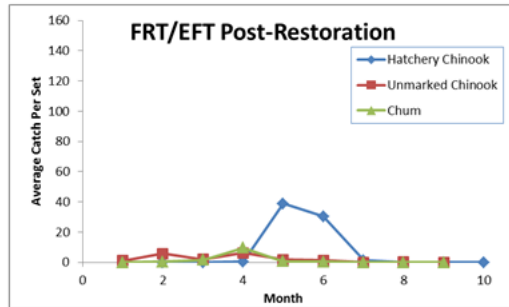
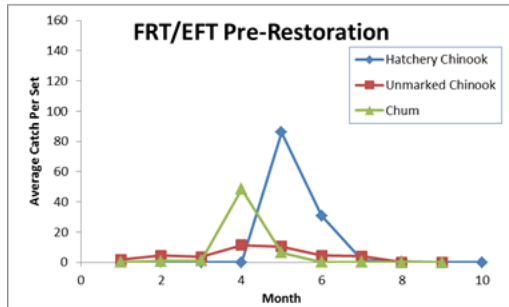
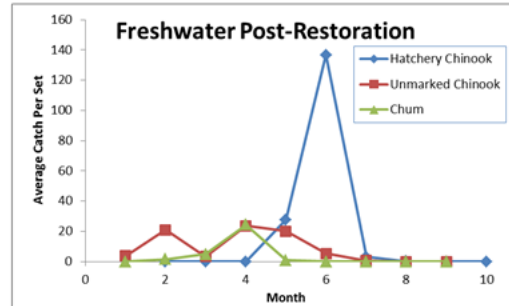
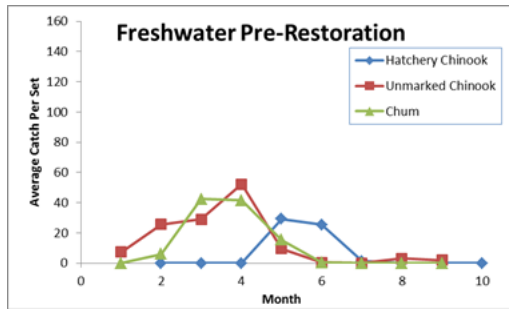


Map 3. Nisqually Fish Sampling Habitat Zones.





**Map 4. Fish monitoring sites in Nisqually Delta and Nisqually Reach Aquatic Reserve.**

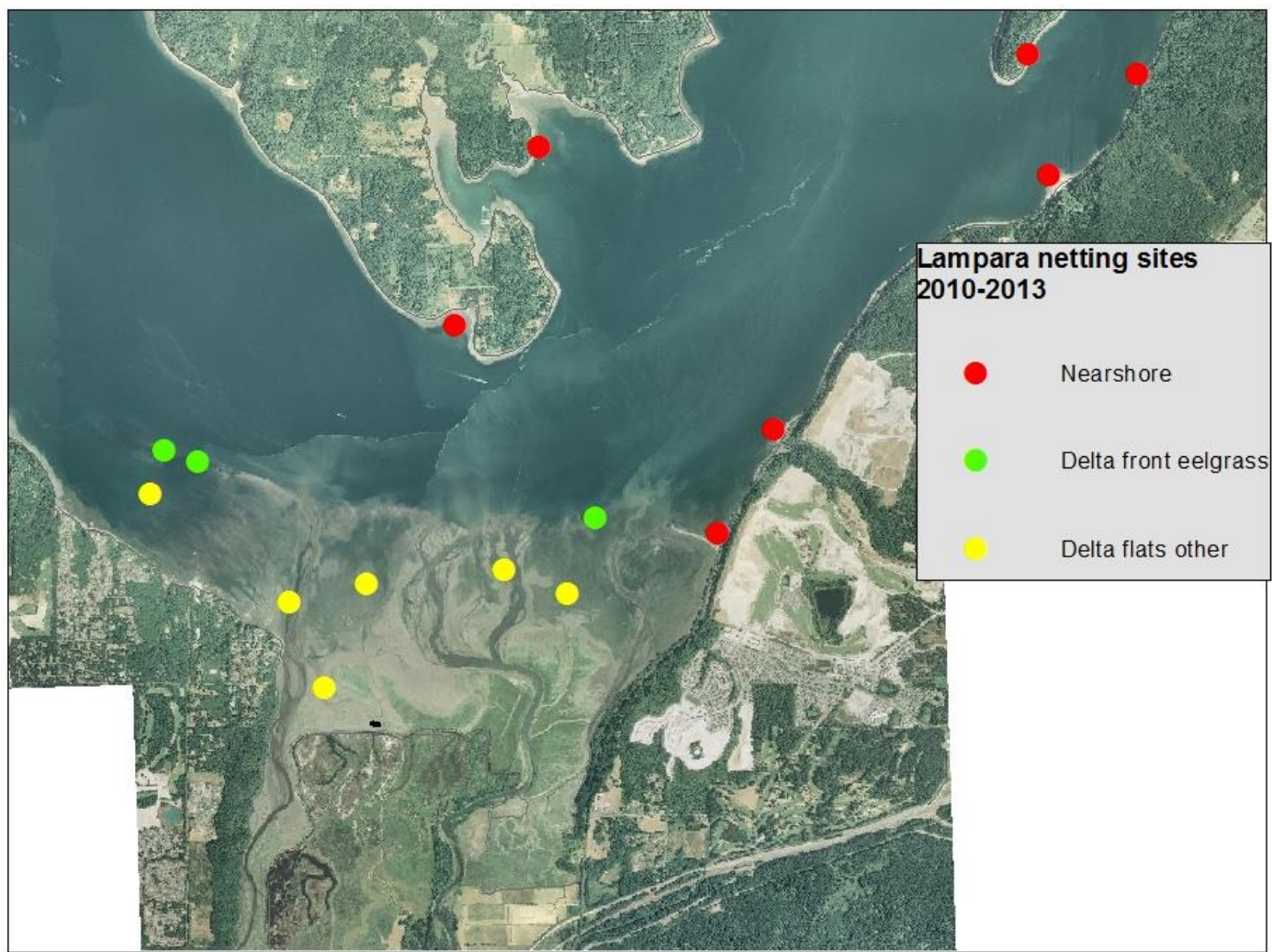


**Figure F1. Before (2004-2006) and after (2010-2013) restoration beach seine catch per set for Unmarked and Hatchery Chinook and chum salmon from Nisqually Delta habitat zones.**

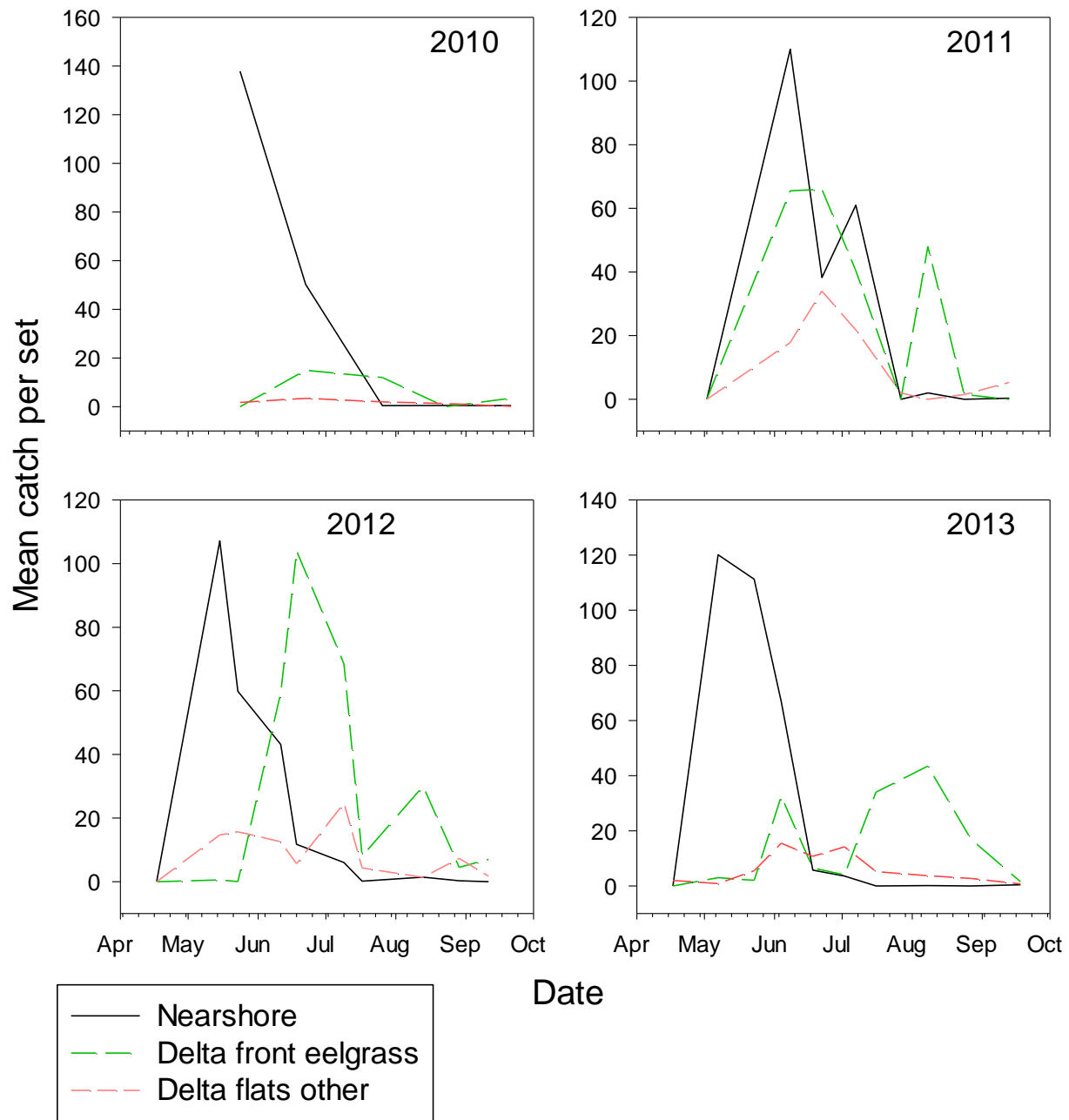


Species Present	Freshwater				EFT/FRT				EEM				Delta Flats				Nearshore			
	2010	2011	2012	2013	2010	2011	2012	2013	2010	2011	2012	2013	2010	2011	2012	2013	2010	2011	2012	2013
American Shad									X	X										
Bay Pipefish									X											X
Chinook Salmon	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Chum	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
C-O Sole																			X	
Coho Salmon	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Crescent Gunnel													X				X		X	X
Cutthroat Trout	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
English Sole											X				X	X			X	X
Lamprey	X					X		X												
Largescale Sucker	X	X																	X	X
Mountain Whitefish	X	X	X	X	X	X	X	X		X										
Pacific Herring									X	X	X	X	X		X	X			X	X
Pacific Lumpsucker																	X	X		
Pacific Sand Lance									X	X		X	X	X	X	X	X	X	X	X
Pacific Snake Prickleback													X		X			X	X	X
Penpoint Gunnel																	X	X	X	X
Pile Perch													X							
Pink Salmon	X		X		X		X		X		X	X	X		X		X		X	X
Poacher																			X	X
Red Gunnel																			X	
Saddleback Gunnel													X	X	X	X		X	X	X
Sand Sole									X											
Sculpin	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Shiner Perch									X	X	X	X	X	X	X	X	X	X	X	X
Snailfish																				X
Sockeye												X								
Speckled Dace			X	X			X													
Speckled Sanddab										X			X			X		X	X	X
Starry Flounder	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Steelhead Trout	X	X		X		X	X		X		X						X			
Striped Seaperch																			X	
Surf Smelt						X	X		X	X	X	X	X	X	X	X		X	X	X
Three Spine Stickleback	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Tube-snout														X	X				X	X
Juvenile Rockfish																	X			
White Spotted Greenling																				X

**Table F1. All species captured in beach seine sets from 2010-2013 at each habitat zone.**



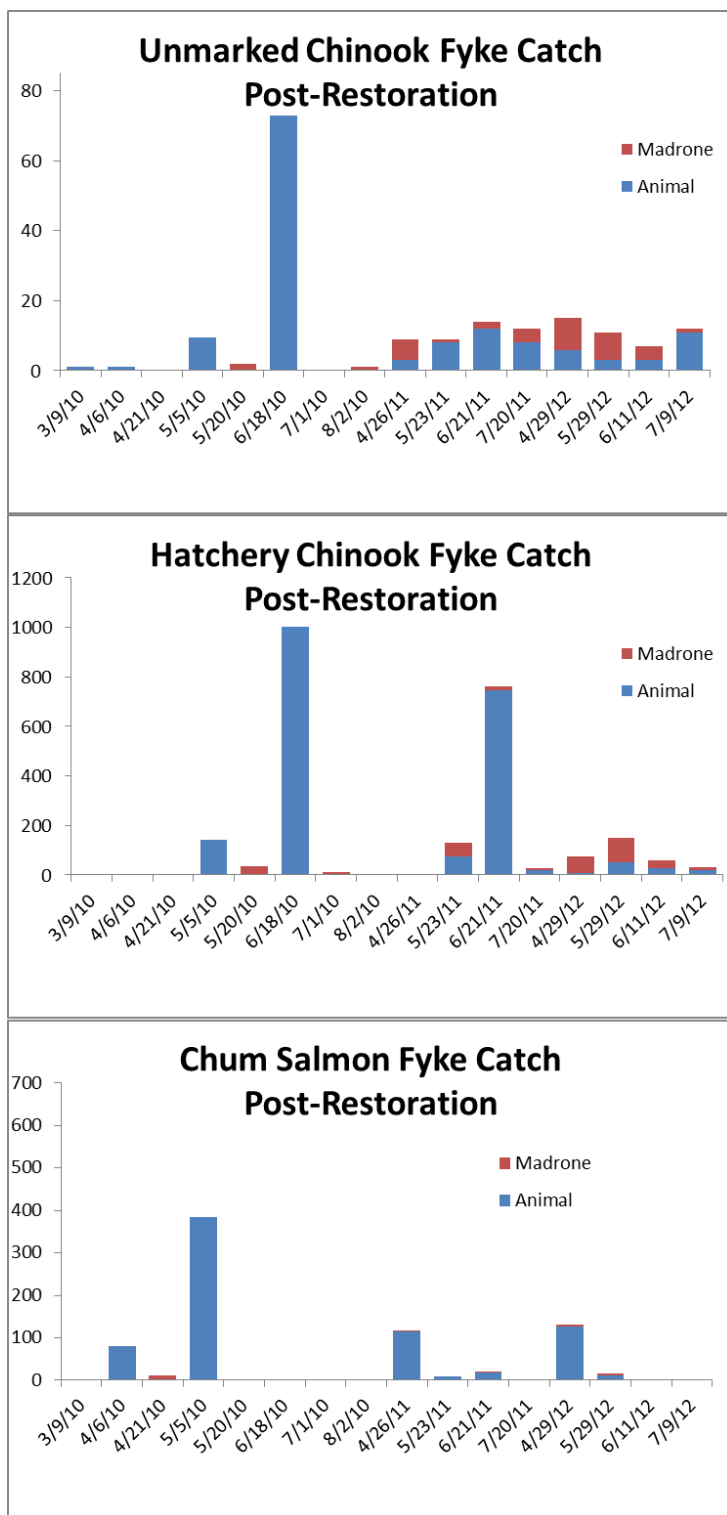
**Map 5. Location of lampara netting sites in each habitat type. Preliminary cluster-type analyses suggested that timing and abundance of Chinook catches were similar within each habitat type.**



**Figure F2. Chinook (marked + unmarked) catch rates by date and habitat type. Catch rates at nearshore sites tended to be high in May and early June and low from mid-July on. Catch rates at delta front eelgrass sites tended to be much lower than at nearshore sites in May but somewhat higher in July and August. Catch rates at other delta flat sites were usually lower than at nearshore or delta front eelgrass sites.**

*Output G: Chinook and other fish presence in restored and reference sloughs.*

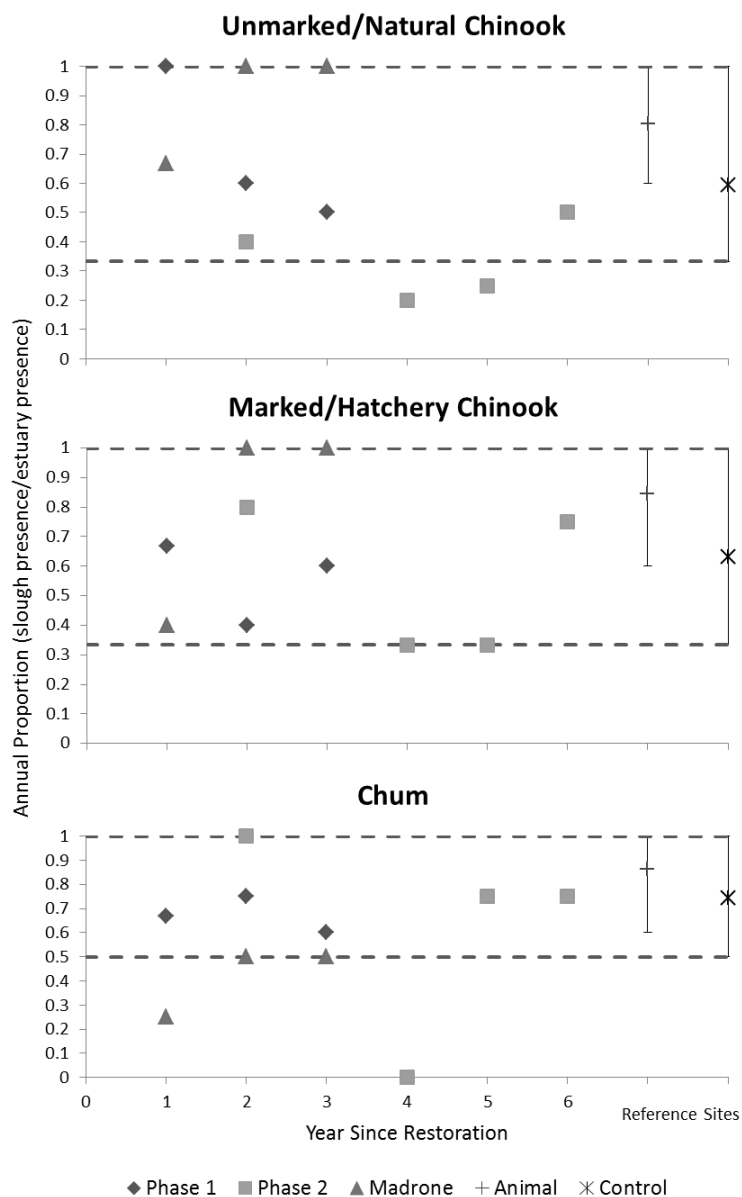
Fyke traps were used to sample Chinook and other fish in restored and reference tidal sloughs (Map 2 and 4). Fyke traps are placed across the channels at high tide and fished as the tide recedes. Unmarked (natural) Chinook utilized the restoration area (Madrone) the first spring (2010) after dike removal and had similar pattern of use by years 2 (2011) and 3 (2012) as the reference channel (Animal) (Figure G1). Hatchery Chinook use of the restored channel, Madrone, began to match the patterns observed in the reference site by year 3. Chum salmon did not utilize the restoration slough as heavily as the control slough during the three years of sampling.



**Figure G1. Unmarked Chinook, Hatchery Chinook, and chum salmon utilization of the 2009 restored slough, Madrone, and a reference slough, Animal, from 2010-2013.**



The Team built an index for tracking restoration progress over time by determining the annual proportion of months when juvenile Chinook and Chum salmon were detected in both a tidal slough (fyke trap) and the Nisqually estuary (beach seine) in each year since restoration for restored sloughs. The team utilized this index for each slough sampled during various phases of restoration since 2004 (Figure G2). Phase 1 was restored in 2004, Phase 2 in 2006, and Madrone in 2009.



**Figure G2. Annual proportion of months when juvenile Chinook and Chum salmon were detected in both a tidal slough (fyke trap) and the Nisqually estuary (beach seine) in each year since restoration for restored sloughs. Mean and standard deviation of all sampling years are shown for reference sites (Animal: 2004-2006 & 2010-2012; Control: 2003-2005 & 2010-2012).**

*Output H: Chinook diet composition comparisons between restored and reference sloughs*

Juvenile Chinook diet samples from 2010-2012 were diverse and variable across restoration and reference sloughs. Invertebrate taxa from all three strata were found in the gut contents, including several terrestrial flies (Dolichopodidae, Ceratopogonidae and Chironomidae), as well as aquatic taxa including Amphipods (*Eogammarus* sp. and Corophiidae), Copepods (harpacticoida), and Mysids (*Neomysis mercedis*). Across the 3 year sampling period, samples collected from MS had the greatest mean abundance of gut contents ( $\bar{x} = 26$ ) and were primarily comprised of ceratopogonidae, dolichopodidae, ephydriidae, harpacticoida, and eogammarus. RS had the second greatest mean gut abundance ( $\bar{x} = 17$ ), followed by P2 ( $\bar{x} = 11$ ) and AS ( $\bar{x} = 8$ ). *Eogammarus confervicolus* was the most common taxa found in juvenile Chinook gut samples, followed by ceratopogonidae, which was a surprising result given their relatively low densities in the prey availability sampling.

A bioenergetics analysis of Chinook growth potential at both restored and reference sites determined that no clear difference exists between the two habitats. Although restored sites were more variable due to larger temperature fluctuations (Figure H2 and H3 from David et al. *In Press*).

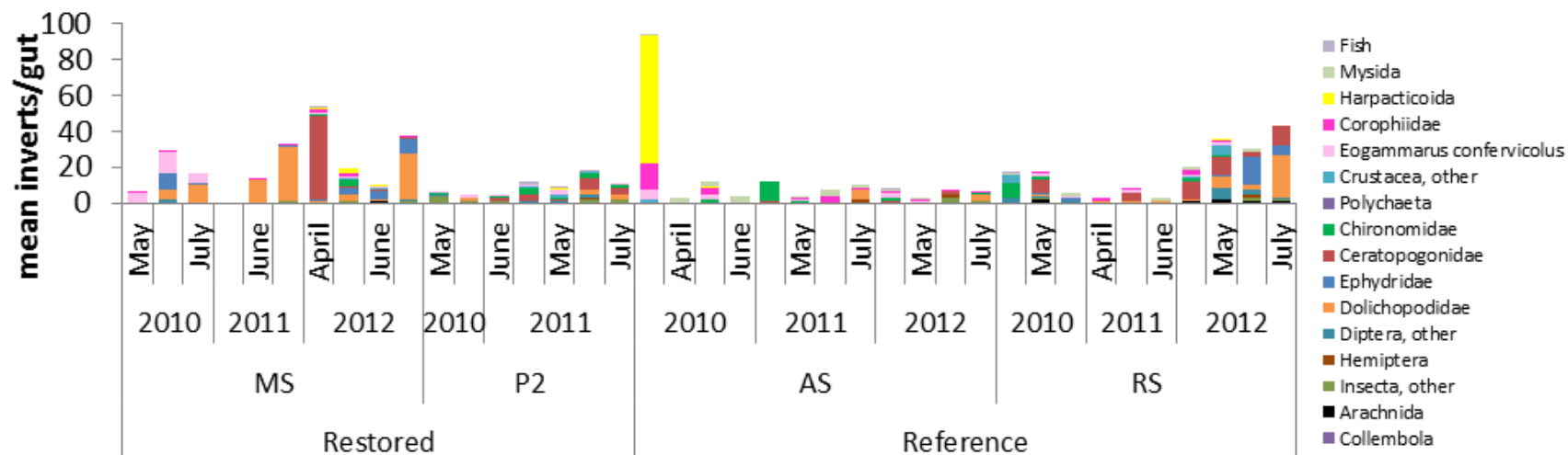
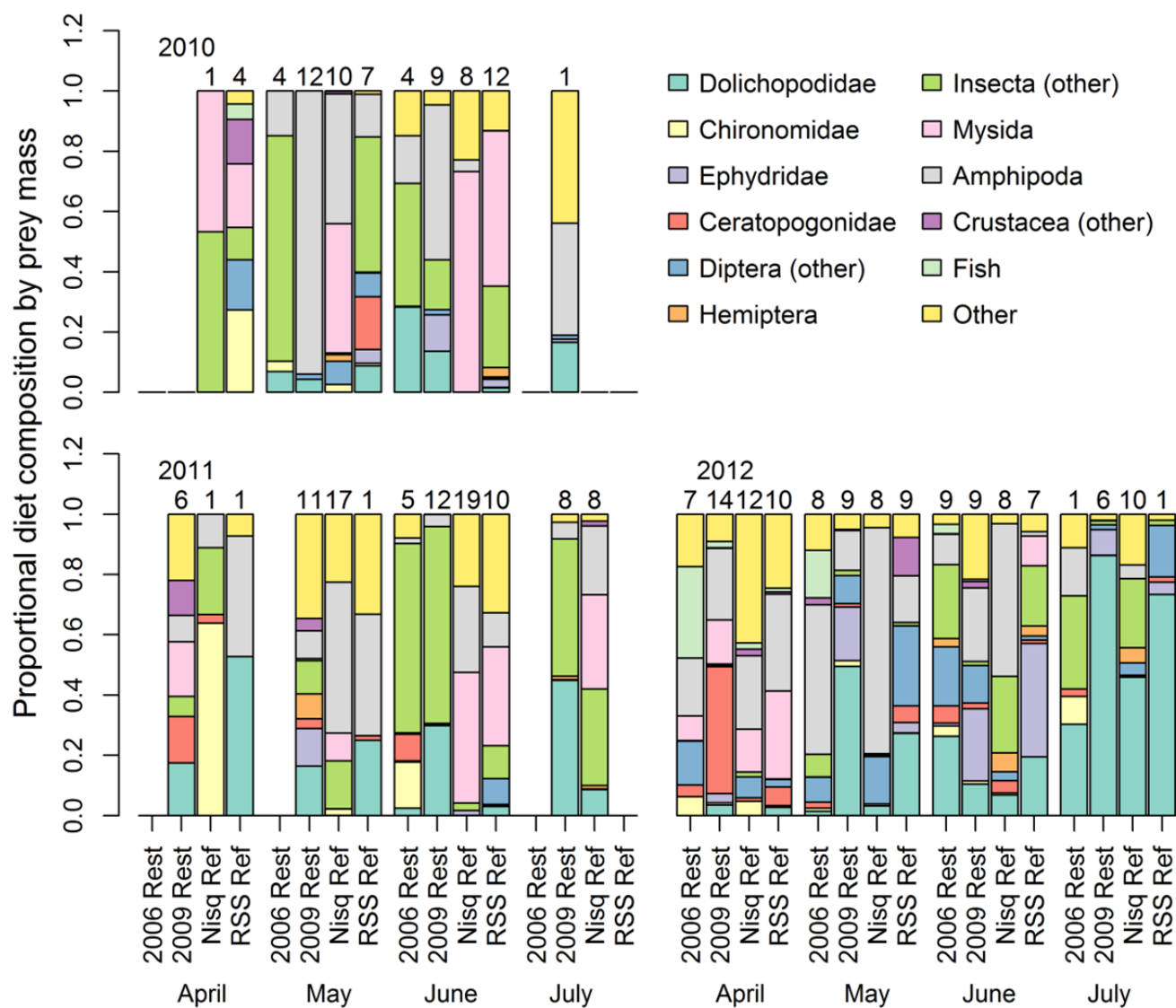


Figure H1. Diet contents of juvenile Chinook salmon at Nisqually Delta from 2010 - 2012 across two restoring sites (Madrone Slough: MS; and Phase 2: P2) and two reference sites (Animal Slough: AS; and Red Salmon Slough: RS).



**Figure H2. Chinook diet composition proportions by weight for fish sampled from the 2006 and 2009 Nisqually Estuary restoration phases and two reference sites (from David et al. *in press*).**

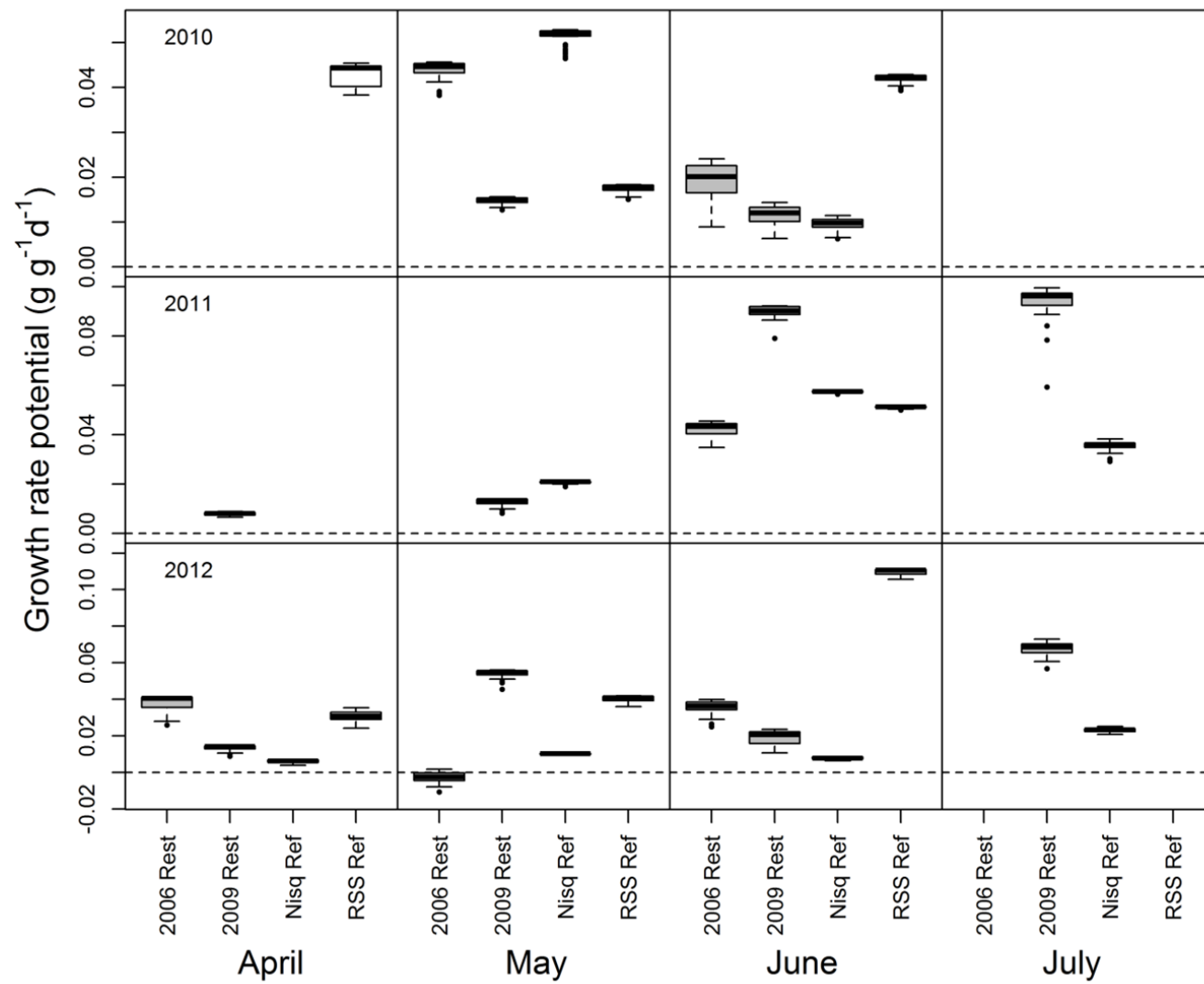


Figure H3. Chinook simulated growth rate potential in grams per grams of Chinook per day based on bioenergetic analysis (from David et al. *in press*).



*Output I: Chinook otoliths analyzed to quantify Chinook residency, growth, and life history diversity across multiple habitats.*

Otolith microstructure analysis was used in the Nisqually to characterize the importance of the estuary to Chinook salmon in the Nisqually River before and after large-scale estuary restoration. Otoliths are calcium carbonate structures in the inner ear that grow in proportion to the overall growth of the fish. Otoliths generally display incremental patterns and daily growth increments so that date and fish size at various habitat transitions can be determined. Careful analysis of otolith microstructure yields the number of days that a fish resided in the estuary as a juvenile, size at entrance to the estuary, size at egress, and the amount that the fish grew while in the estuary. All otolith analyses were conducted by the USGS Western Fisheries Research Center.

To date, two life history types were identified for juveniles and adults in pre-restoration years and one life history type identified for juveniles in post-restoration years. On average, during pre-restoration years, natural Chinook grew 23% faster in the tidal delta than in freshwater and hatchery Chinook grew 41% faster (Figure I1). During post-restoration years, on average natural Chinook grew 20% faster in the tidal delta habitat than in freshwater and hatchery Chinook grew 14% faster. Both natural and hatchery residence in the tidal delta were longer during post-restoration years (Figure I2). The average residence time in tidal delta habitat for natural juvenile Chinook salmon during pre-restoration years was 17 days (range 8-35 days) and hatchery Chinook resided on average for 9 days (range 2-30 days). During post-restoration years, natural Chinook resided in the tidal delta habitat for an average of 26 days (range 13-42 days) and hatchery Chinook for 15 days (range 5-39 days).

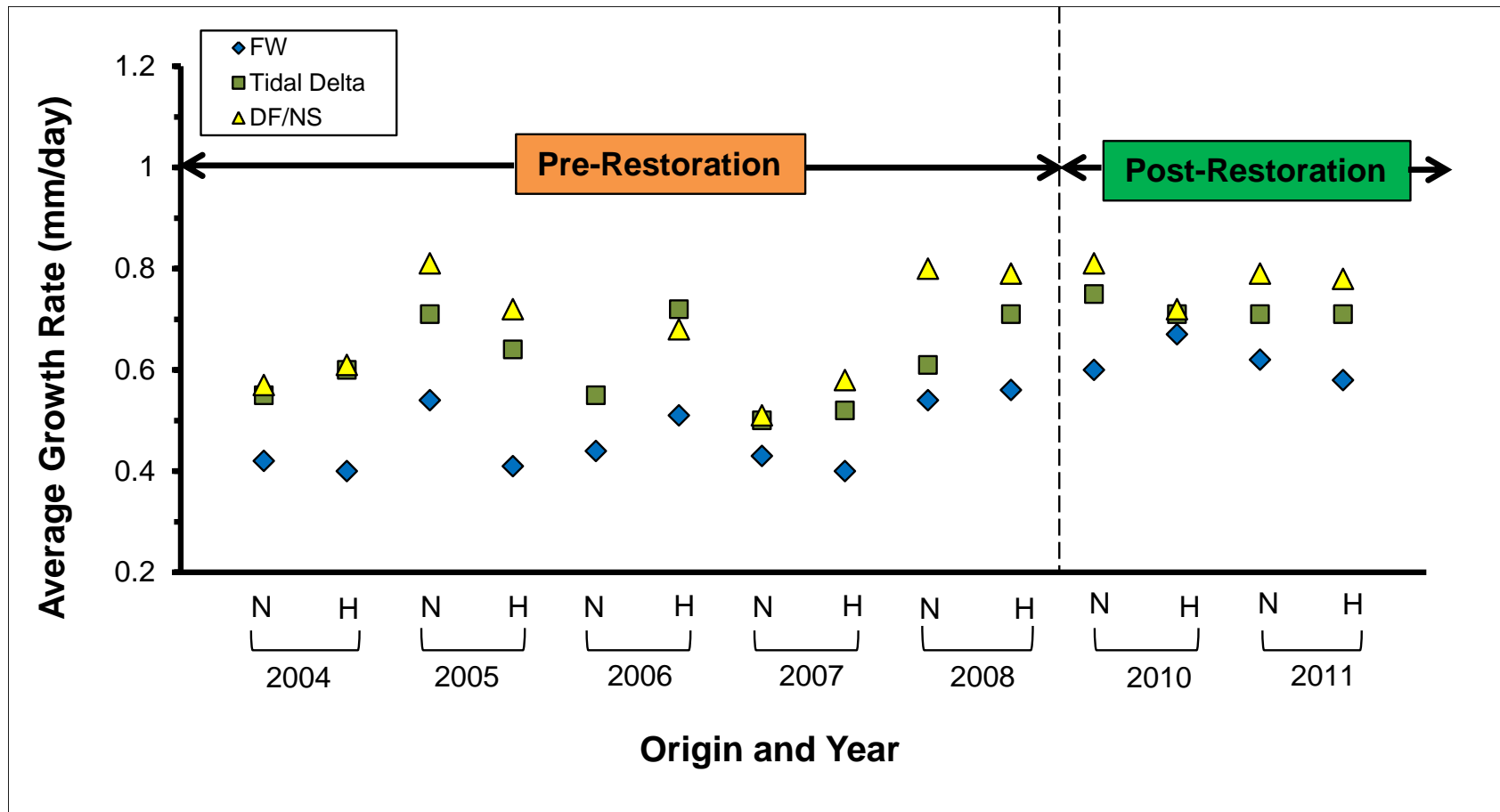


Figure I1: Pre- and post-restoration growth rates (mm/day), separated by year and origin (N=natural and H=hatchery), of juvenile Chinook salmon for freshwater (FW), tidal delta, and delta-flats/nearshore (DF/NS) portions of the otoliths.

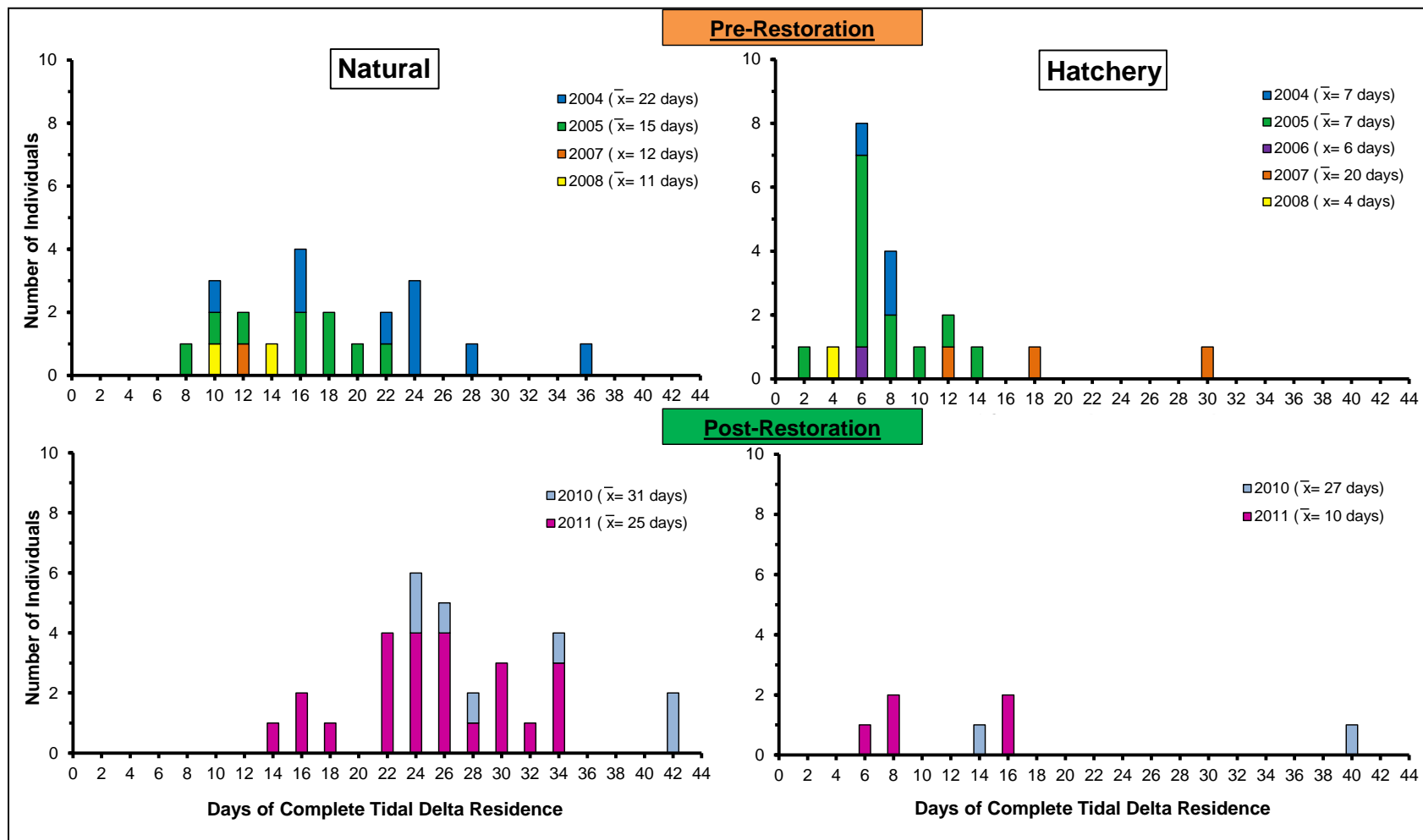


Figure 12: Pre- and post-restoration complete tidal delta residence time (days), separated by year and origin for juvenile Chinook salmon.

## Logic Model Outcomes, Reflections on the Project, and Broader Perspective

The logic model contained in the Team's original proposal to the EPA:

Inputs	Outputs		Outcomes		
	Activities	Participants	Short Term	Medium Term	Long Term
EPA Funds: \$600,000  In-kind resources from project partners	Conduct extensive restoration effectiveness monitoring and adaptive management research in the Nisqually Delta.  Examples of key outputs include: 1) A sediment rating curve for Nisqually River above the delta; 2) Numerical modeling of nearshore hydrodynamics; 3) Post-restoration vegetation development; 4) Post-restoration invertebrate community composition; 5) A refined model of the distribution, abundance, and timing of Chinook and other fishes in freshwater, estuary, mud flats, and nearshore; 6) Chinook and other fish presence in restored and reference sloughs; 7) Chinook diet composition at restored and reference sloughs; 8) Quantified metrics of Chinook residency, growth, and life history diversity across multiple habitats.	Nisqually Indian Tribe Salmon Recovery Program  Nisqually National Wildlife Refuge  USGS Western Fisheries Research Center  USGS Western Ecological Research Center	Quantitative and qualitative assessment of the short term habitat development trajectory and biological response (emphasis on Chinook salmon) resulting from the largest Puget Sound river delta restoration project to date.	Physical and biological indicators and modeling tools used to help predict the long term habitat mosaic of the Nisqually Delta in the face of climate change and other large scale impacts (e.g., hydropower). Lessons learned from Nisqually study applied to other Puget Sound delta restoration efforts.	Resilient and diverse mosaic of estuarine habitats throughout the Nisqually Delta which helps to ensure productive, diverse, abundant, and harvestable Chinook and other salmon populations in the Nisqually.
5 years of baseline fish ecology and habitat research by Nisqually Tribe, Nisqually NWR, and USGS.					
Nisqually Delta property owned and managed for conservation by Nisqually Tribe, Nisqually National Wildlife Refuge, and Washington Department of Fish and Wildlife.  Over 900 acres of estuary restoration projects implemented by Nisqually Tribe, Nisqually NWR, and Ducks Unlimited.  Puget Sound Partnership Action Agenda Priorities: B.1.2 and E.3.2		USGS Coastal Habitats in Puget Sound	Outcome Measures		
			Project report which describes: 1) Sediment accretion, erosion, and redistribution throughout the Delta.  2) Status of salt marsh, scrub shrub, and other vegetation colonization.  3) Distribution and abundance of estuarine insects, crustaceans, and other invertebrates.  4) Fish community composition, distribution, and abundance plus Chinook growth, residency, and feeding ecology throughout the Nisqually Delta.  5) Initial development of adaptive management indicators and modeling tools for immediate and long term management of the Nisqually Delta by the Nisqually Tribe and Nisqually NWR.	Implementation of adaptive management recommendations and indicator monitoring for long term management of the Nisqually Delta by both the Nisqually Tribe and Nisqually NWR.  Hydrodynamic model of Nisqually Delta used to run scenarios.  Delta morphology and vegetation communities' mapped.  Chinook salmon population show increased smolt to adult survival.	Salmon runs are productive, diverse, abundant, and harvestable. Chinook meet escapement goals of Nisqually Chinook Recovery Plan and PS Action Agenda.

The long-term outcome listed in our logic model reads:

*Resilient and diverse mosaic of estuarine habitats throughout the Nisqually Delta which helps to ensure productive, diverse, abundant, and harvestable Chinook and other salmon populations in the Nisqually.*

In order to reach this long term goal the Nisqually Delta resources managers, Nisqually Indian Tribe and USFWS Nisqually National Wildlife Refuge, must utilize the results of this project and follow up research to craft a long term management plan for the delta. This project generated the following key insights that must be considered:

1. Juvenile Chinook rely heavily on all habitat components of the Nisqually Delta and Nisqually Reach nearshore for rearing, including the tidally influenced freshwater area around I-5. An area truncated by the I-5 Bridge and flood control dikes.
2. Juvenile Chinook respond rapidly and positively to delta restoration, even when the restored site lacks mature estuarine habitat characteristics like salt marsh vegetation.
3. Upstream land use can significantly alter the habitat forming processes of a delta. In the Nisqually, hydropower operations have dramatically reduced sediment supply to the delta. The near term habitat development of the restoration area as well as the long term viability of the delta is threatened by this constriction. Climate change induced sea level rise will drastically reduce delta structure and function if habitat forming processes are not restored or enhanced.
4. Upstream flood control, flood plain development, and the I-5 causeway exacerbate the impact of reduced sediment supply caused by hydropower development. Sediment routing to the delta from the Nisqually River relies heavily on tidal forcing via tidal channels, so much of the riverine sediment is lost offshore. The lack of distributary channels upstream of I-5 impairs the efficient distribution of sediment. Additionally, the I-5 causeway may inhibit the upstream retreat of estuarine habitats as sea level rises.

More resources will be needed for additional studies in order for managers to develop plans for addressing substantial impacts to the habitat forming processes in the Delta. This project provides a solid base of information to build on. Future studies should expand existing hydrodynamic models to included areas upstream of I-5 and use the model to run sediment supply restoration scenarios. Habitat structure and fish utilization information generated during this project can be used to estimate the impact of various scenarios on vegetation, invertebrates, and ultimately Chinook salmon.

This multi-disciplinary study established key measures of restoration development, Chinook salmon response, and habitat processes for the largest delta restoration project in the Pacific Northwest that will have long term management ramifications locally and throughout the region. The Team is working on distributing this information through various forms of publication and through presentations to broad audiences. Our project is a clear example of a successful use of a multi-disciplinary team to conduct wide ranging investigations and provide key information for adaptive management at an ecosystem scale.



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