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A California Landscape Conservation Cooperative Project

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Table of Contents

California Landscape Conservation Cooperative Project on Estuarine Shoals and Vertebrate Predators. Modeling Workshop, 26-27 October 2010, Berkeley, California

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I. EXECUTIVE SUMMARY

- **California Landscape Conservation Cooperative Project on estuarine shoals and vertebrate predators:** In this report, we describe the integrated research program supported by the California LCC addressing sea level rise effects on estuarine shoals and the vertebrate predators dependent on these habitats. We present results from the first year objectives to determine the feasibility of the project and to: 1) host a modeling workshop with partners to identify what parameters are needed to model effects of sea level rise on the ecology of shoals and migratory birds; 2) use existing shoals modeling grids (Ganju and Schoellhamer 2010) to develop methodology for quantifying key metrics for habitat change; 3) conduct a comprehensive review on foraging of migratory birds on shoal habitats, and 4) report on the findings of the workshop and proposed habitat change metrics from the grid approach.

- **Modeling Workshop Results:** On 26-27 October 2010, we hosted a workshop in Berkeley, California entitled "Modeling Effects of Sea Level Rise on the Ecology of Shoals and Migratory Birds." The two-day workshop invited 20 participants including invited speakers, research scientists, and resource managers. Expert modelers invited to participate included Dr. Dano Roelvink (Deltares, Netherlands), Dr. Neil Ganju (USGS Woods Hole Science Center), and Dr. Noah Knowles (USGS Menlo Park Science Center). The overall goal was to discuss modeling approaches and identify linkages between physical and biological models about this critical topic. Results from the discussions indicated that modeling sea level rise (SLR) effects on shoals was both feasible and timely with several complementary efforts (see below). A brief summary of key modeling topics are presented in following paragraphs.

- *Avian ecology on shoals:* Prey quality, abundance, distribution, and accessibility influence bird carrying capacity and population health. Prey and physical characteristics interact to determine the area available for foraging. Although invertebrates are primary food on shoals, biofilm may be a key food source for some smaller shorebirds. Physical factors influence prey abundance and availability, while habitat use is affected by proximity of suitable roosting or nesting areas. Some of these datasets are available from existing USGS shoals research studies.

- *Biophysical interface:* Physical drivers on biota include tidal inundation and exposure, salinity, temperature, water depth, and sediment type. Phytoplankton dynamics are an important interface between physical processes and invertebrate response. Predation pressure is determined by water depth, slope, movement of the tide line, and sediment permeability. Maintenance of biofilm requires sufficient light and low turbidity, and biofilm may determine cohesiveness of sediments. USGS Western Ecological Research Center currently is working on biofilm foraging by shorebirds in cooperation with world expert Dr. Tomohiro Kuwae.

- *Geomorphic modeling:* Downscaled global climate change models provide temperature and precipitation predictions to determine potential effects on hydrology. Delta inflows, winds, and SLR are used to model changes in hydrodynamics, sediment transport, and geomorphology. Hourly Golden Gate tides are modeled with global SLR scenarios, El Niño, storm surges, barometric pressure, and tides, and outputs include water levels, floodplain expansion, and sediment availability that are inputs to estuarine geomorphic models of tidal flat change. Delft-UNSTRUC model with 3-D grids may be used to simulate hydrodynamics, sediment, geomorphology, salinity, and temperature along a continuum of ocean to river under one model framework. We will coordinate this model with ongoing development of the USGS-led models under CASCaDE (Computational Assessments of Scenarios of Change for the Delta Ecosystem).

- *Habitat connectivity:* There is an integral link between destruction and formation of tidal flats and marshes. Marsh erosion and storm action are integral to the modeling. Work will be coordinated with USGS hydrodynamic studies at Corte Madera marsh, conducted in cooperation with the Army Corp of Engineers and the Bay Conservation and Development Commission.

- *Extreme events:* Frequency or severity of extreme events should be assessed with sea level rise. Historical datasets are critical to identify effects on birds and mud flats. Parameters include: rate and degree of sea level rise, frequency and severity of storms, extreme high tide events, marine influences (upwelling, North Pacific Gyre Oscillation, and El Niño), and acidification.

- *Key modeling parameters:* Habitat metrics include physical influences on avian foraging and prey accessibility (water depth, slope, movement of tide line, and sediment permeability), as well as factors determining the suitability of food sources. Density, distribution, biomass, and size classes of invertebrates are dependent on tidal inundation-exposure regime, predation pressure, water quality, benthic conditions, phytoplankton, and seasonally-variable external forcing factors.

- **Modeling grids:** Modeling grids from the ROMS model developed for Suisun Bay as part of CASCaDE were provided by Dr. Neil Ganju, our invited speaker and collaborator (Ganju and Schoellhamer 2010). We evaluated existing modeling grids and methods for quantifying key metrics of habitat change in the South Bay. A series of metrics for habitat change may be created by analyzing geomorphic change from these scenarios, and it is expected that model grid cell size will determine the spatial scale of the metrics. Limitations in use of output from hydrodynamic-sediment, transport geomorphic models on habitat metrics would be part of such an analysis.

- **Comprehensive literature review on migratory bird foraging on shoals:** We conducted a comprehensive overview of research on shoal habitats and foraging birds to help guide future directions for modeling. An extensive review of over 300 scientific journal articles was completed and incorporated into a scientific review paper. The literature review summarizes biotic and abiotic influences on foraging suitability for avian species on tidal flats and shoals, explores foraging strategies, species requirements, and community dynamics, discusses various influences on bird carrying capacity, outlines the threats to mud flat and shoal ecosystems, discusses the role of restoration and alternative or artificial habitats, and prioritizes research and management activities. The comprehensive bibliography is provided in this report.

- **Next steps:** Our workshop and results from this initial work have shown that modeling of SLR effects on shoals and vertebrate predators is feasible by adapting current models and would be very valuable in understanding future SLR scenarios in San Francisco Bay. Based on the findings from the California LCC workshop and comprehensive literature review, we will be submitting a California LCC proposal to continue the modeling effort. It will address 2011 California LCC priorities including ecosystem and species response to SLR. Initial work will develop modify existing models with Deltares to focus on SLR effects on shoals, as well as compiling the relevant information from the extensive USGS empirical datasets on key parameters and effects on vertebrates.

II. MODELING WORKSHOP

A. Workshop Presentation Summaries:

1. **CASCaDE: Integrated Modeling of the SF Bay-Delta System and the Effects of Sea Level Rise** ***— Noah Knowles (USGS Menlo Park Center)***
   http://cascade.wr.usgs.gov

- **CASCaDE***(Computational Assessments of Scenarios of Change for the Delta Ecosystem):* CASCaDE involves a series of linked numerical and statistical models that span climate, hydrology, and biology, with each model representing a different component of the system. Output from several different Global Climate Models were pulled from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (IPCC 2007) to represent the range of temperature and precipitation changes. These models were downscaled to regional models of the Sacramento-San Joaquin Delta watershed, in order to translate meteorological climate predictions into the hydrology of the watershed. Modeling involved stream flows, stream temperature, and man-made structures, and this ultimately led to the development of downstream models of sediment transport, geomorphology, water temperature, phytoplankton, benthos, contaminants, and fish. With the climate scenario that had the most warming (3.5°C increase) and strongest drying trend (-18% change in precipitation) by 2100 (Figure 1), models showed a decrease in run-off, water supply (-28% change in runoff to reservoirs), and freshwater floodplain habitat. All temperature and precipitation scenarios showed these same trends but with different magnitudes.

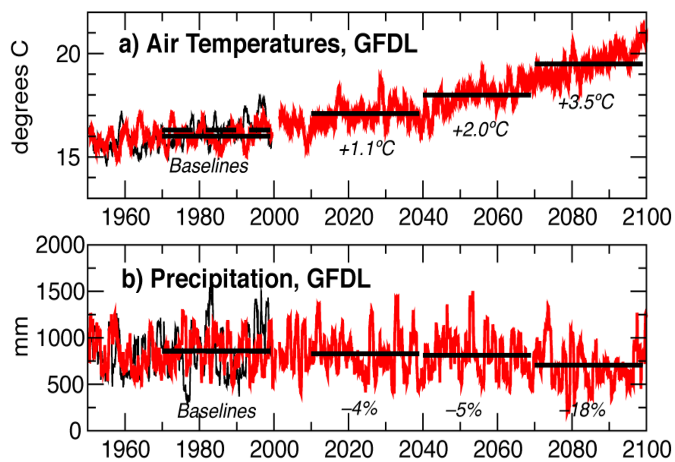

Figure 1. Climate scenario showing the largest increase in: a) air temperature and b) precipitation by 2100

- **CASCaDE II:** Next steps expand the scope of integrative hydrodynamic models to the larger San Francisco Bay. 3-D models of phytoplankton, hydrodynamics, and water temperature in a Delta flooded island (Mildred Island) have been developed from measured grazing, turbidity, meteorology, and tides. The goal is to take this modeling framework and expand it to the larger Delta and the San Francisco Bay. Models of contaminant dynamics at the food base can be integrated with physical models. It is necessary to understand how hydrology influences the movement of phytoplankton and sediment carrying contaminants relative to invertebrates (i.e. clams) involved in contaminant uptake into the food web. CASCaDE II (Figure 2) will involve the new Delft-UNSTRUC model to simulate hydrodynamics, sediment, geomorphology, salinity, and temperature along a continuum of ocean (Point Reyes) to river. Instead of just sharing inputs and outputs of different models, these factors are incorporated under one model framework. The fate of wetlands will also be included in CASCaDE II modeling.

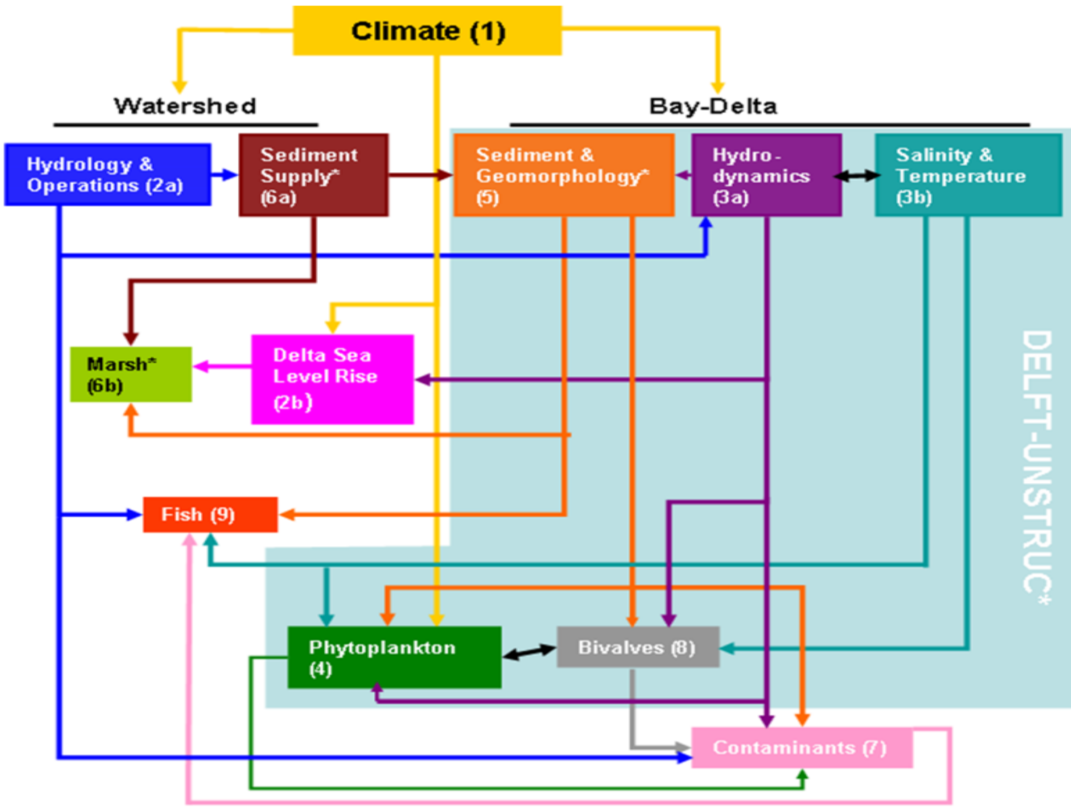

Figure 2. Components of the CASCaDE Project. Additions for CASCaDE II represented with *

*Roles for CASCaDE II (*new additions)*

- <u>Climate</u>: Dan Cayan, Mike Dettinger
- <u>Watershed/hydrology</u>: Noah Knowles, *student**
- <u>Hydrodynamics (salinity, temps)</u>: Mick van der Wegen, Dano Roelvink, *Bert Jagers*, Ap von Dongeren*, post-doc*, doctoral student**
- <u>Sediment Trends</u>: David Schoellhamer, Tara Morgan
- <u>Watershed sediment model</u>: *Scott Wright**
- <u>Geomorphology</u>: Bruce Jaffe
- <u>Wetlands</u>: *Judy Drexler**
- <u>Phytoplankton</u>: Lisa Lucas, Jim Cloern, *post-doc**
- <u>Benthos</u>: Jan Thompson, Francis Parchaso
- <u>Contaminants</u>: Robin Stewart, Sam Luoma
- <u>Fish</u>: Larry Brown

- **Sea Level Rise:** The effects of sea level rise in the San Francisco Bay were also assessed in CASCaDE I. The modeling boundary was at the confluence of the Delta and focused on marshes and dry lands at risk for inundation, but did not include shoals or shallow water. Hourly sea levels at the mouth of the estuary (Cayan et al. 2009) were based on Global Climate

Model outputs and were used to drive a hydrodynamic model of San Francisco Bay. Regression models included the various factors influencing hourly water level: El Nino, storm surges, barometric pressure changes, astronomical tides, and long-term sea level trends due to global warming. There is a commitment to assessing the effects of sea level rise beyond 2100.

- *Extreme water levels:* The water level modeling was incorporated with a TRIM2D Hydrodynamic Model and high resolution (2-meter) elevation data for the region, in order to assess extreme water levels and identify areas at risk. Cayan et al. (2009) showed an exponential increase in extreme water levels over the next century (Figure 3), which could have severe impacts in the estuary.

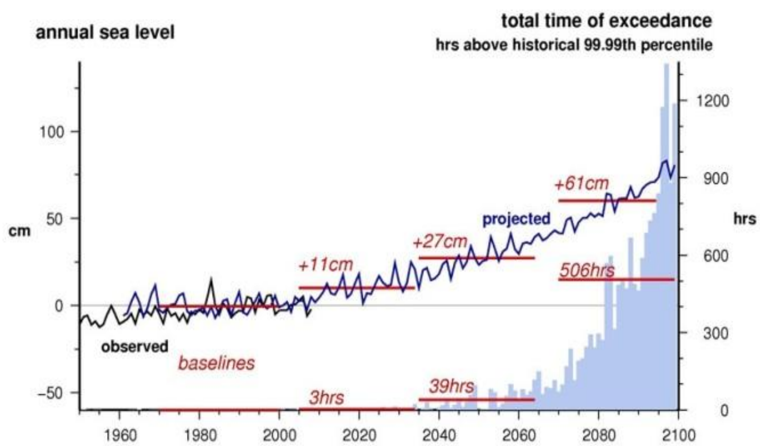

Figure 3. Total time water levels are expected to exceed the historical 99.99th percentile with predicted rises in annual sea level

- *Salinity:* Knowles, van der Wegen, and Roelvink incorporated the effects of both predicted sea level rise and upstream freshwater inflow changes to estimate salinity changes in the estuary. There is a predicted 37% increase in mean salinity in the North San Francisco Bay by 2100 (Figure 4), with one third of the increase due to salinity intrusion from sea level rise and two thirds due to changes in freshwater inflow.

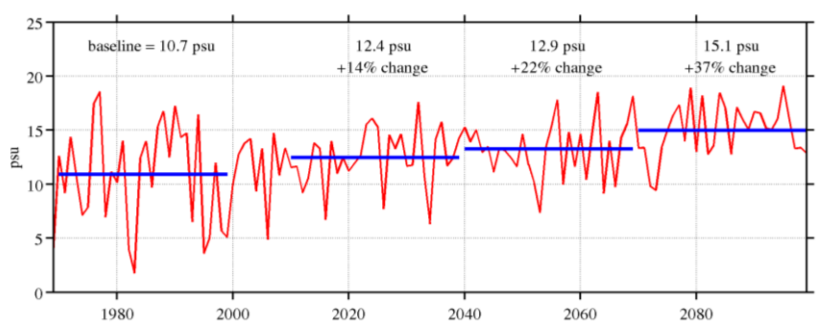

Figure 4. Mean salinity (blue) and salinity fluctuations (red) in the North San Francisco Bay from 1970 and projected to 2100

- *Floodplain Expansion:* Knowles also developed maps of floodplain expansion with different sea level rise scenarios (none, 50cm, 100cm, 150cm). The increased wetland areas below MLLW will lose gravity drainage, however maps have not accounted for estimated accretion.

- *Sediments:* An important consideration is that sea level rise accelerates with global temperatures, and the rates of sea level rise and required sediment accumulation increase linearly (Figures 5a & 5b). The volume of material required for wetlands and shoals to maintain their place in the tidal range will continually increase over time.

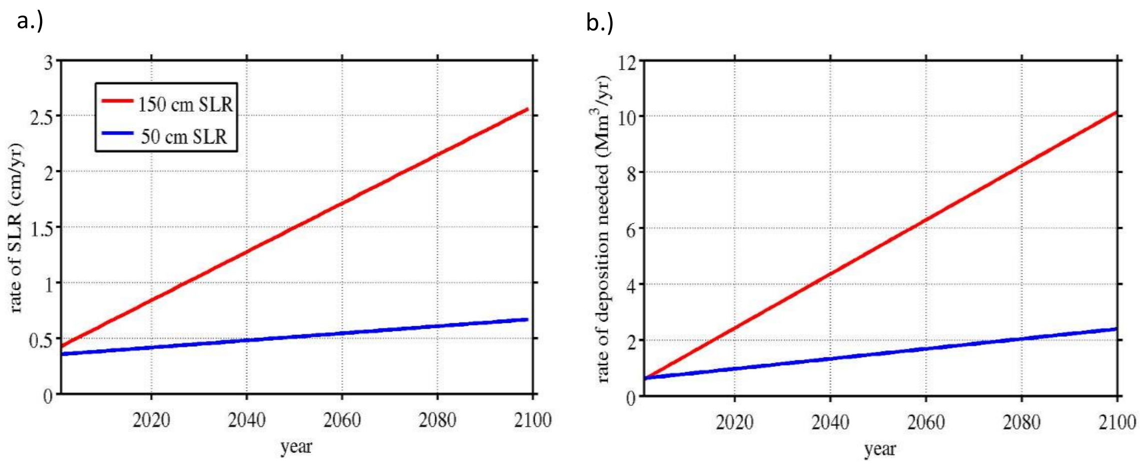

Figure 5. a) Rate of sea level with 50 cm vs. 150 cm of sea level rise by 2100, and b) Associated rate of deposition required to offset 50 cm vs. 150 cm of sea level rise by 2100

2. <u>Geomorphic modeling in estuaries: Linking sea-level rise, physical processes, and habitat development</u> — *Neil Ganju (USGS Woods Hole Center)*

- **Modeling Sedimentation and Geomorphology of Suisun Bay: (part of CASCaDE I)**
  - dGCM/BDWM Model Inputs: Delta inflows, winds, and sea level rise
  - ROMS/CSTM Modeling: Assess changes in hydrodynamics, sediment transport, and geomorphology
  - Outputs: Depth distribution, turbidity, and habitat distribution
- **Calibration with Historic Data:**
  - Bathymetric change in Suisun Bay (Capiella et al. 1999)
  - Transport of hydraulic mining debris (1850-1884)
  - Rapid deposition (1867-1887) followed by erosion (1887-1990)
  - Historical data is rare and needs to be simulated to test the model
  - Numerical model simulation from 1867-1887:
    - 3 different cross sections in Suisun Bay
    - Calibrated to idealized tides, waves, and seaward suspended sediment concentrations
    - Calculated subtle changes in sediment
    - Skill varied spatially, with best agreement in areas under 2 meters
    - First quantitative test of morphological evolution and acceleration in an estuary

- **Approach for Future Scenarios:**
  - <u>*Four scenarios*</u> (run over 20 years): (1) Base-case, (2) Warming and sea-level rise, (3) Decreased sediment loads and sea-level rise, and (4) Warming, decreased sediment loads & sea-level rise
  - <u>*Sources for signals*</u>:
    - *Warming*: Knowles and Cayan (2002)
    - *Sea-level rise*: 0.002 meters/year increase
    - *Sediment loads*: Wright and Schoellhamer (2004)- decrease extended to 2030
  - <u>*Different morphological hydrographs*</u> (moderate, wet, dry) were used to predict future fluctuations in freshwater inflow and sediment load:
    - Flow changes by 2030 are modest (Knowles and Cayan 2001)
    - Sediment load decrease ~30% by 2030 (from Wright and Schoellhamer 2005)
    - Dry years encourage landward transport in channel and no replenishment of shoals, while wet years encourage shoal deposition and scouring of channels (Ganju and Schoellhamer 2010)
  - <u>*Changes in bed level*</u> due to scenarios (Ganju and Schoellhamer 2010):
    - *Sea Level Rise*: Increased water depth reduces wave-induced shear stress (static wave field) and results in less erosion and less redistribution of sediments. However this assumes waves are the same regardless of water depth, which is a poor assumption.
    - *Warming*: Results show minor changes in redistribution.
    - *Sediment loads*: Decreased sediment supply results in widespread erosion except at the fringes.
  - <u>*Wave model*</u> to assess changes in turbidity due to wave propagation and sea level rise:
    - As water level rises, waves can penetrate deeper into the shoals
    - Flood-tide turbidity supplied to Delta increases as waves penetrate deeper into sub-bays.
    - Rapid sea level rise may outpace geomorphic change where supply is limited, and not allow marshes and mudflats with enough time to respond.
    - There are several scenarios of wave erosion and shoreline movement in response to sea level rise (Figure 6):
      - With a levee or seawall, there will be redistribution of wave energy resulting in a scouring of the mudflat.
      - A steep marsh edge will experience marsh slumping and particles of sediment and plant material may be redistributed to create new mudflats. A one-dimensional approach to modeling wave forces (Tonelli et al. 2010) on three types of marsh edges (vertical, sloping, and terraced) could be useful for different marsh edge types in San Francisco Bay, however this needs to be coupled with a model that includes geomorphology of flats.

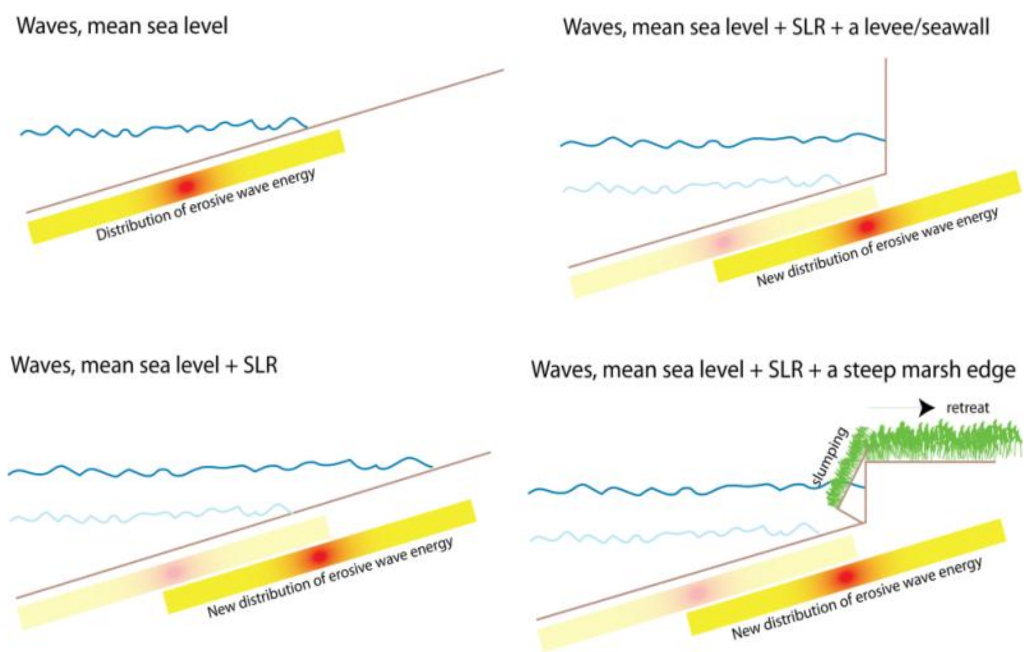

Figure 6. The distribution of erosive wave energy with waves and mean sea level, with the presence and absence of sea level rise and shoreline protection (levee/seawall or steep marsh edge)

- **The Estuarine Geomorphic Number:**
  The balance between depositional and erosional forces is represented with the estuarine geomorphic number (Figure 7), and it has been developed for the San Francisco Bay (Ganju and Schoellhamer 2010). The number will need to be modified to explain forces acting upon mud flats.

$$E_h = \frac{1}{\rho_d}\frac{Q_s}{Q}\frac{h^3}{Q_p}$$

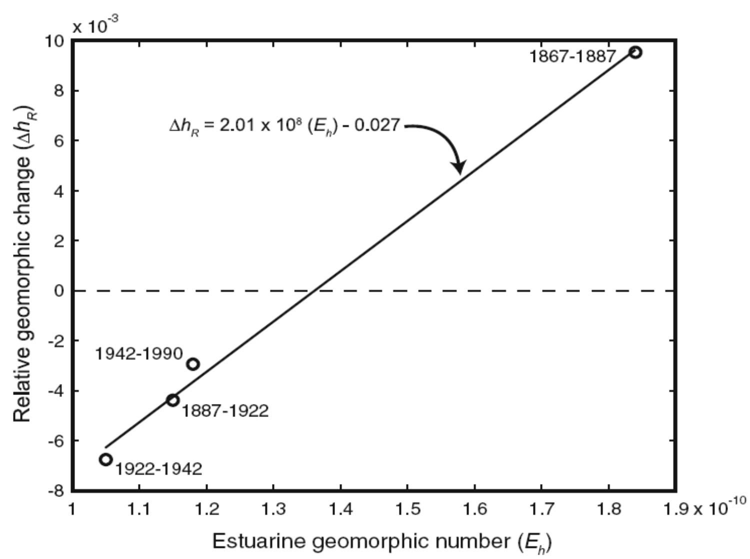

Figure 7. The estuarine geomorphic number, accounting for erosional and depositional influences on geomorphic change

- **Future Needs for Modeling Intertidal Habitat Change:**
  First steps should involve identifying profile types present in San Francisco Bay, and then applying a 1D or 2D vertical model for a set of different profiles with wave forcing, geomorphic change, and parameterization of marsh slumping. Sea level rise, morphological acceleration, and future wind-wave conditions could then be added to the model.

3. <u>Delft3D Modeling in San Francisco Bay</u> — *Dano Roelvink (UNESCO-IHE, Deltares)*

- ***<u>Hindcasting bathymetric change in San Pablo Bay: A step towards assessing likely geomorphic change in response to climate change</u>***

  - **Three characteristic periods of bathymetric change:**

  (1) Excess sediment supply from *hydraulic mining* from 1856 to 1887 resulted in average net deposition of 8 million m^3/year (Jaffe et al. 2007)
  (2) Dramatic decrease in sediment supply after stop in hydraulic mining and *dam construction* over the last century resulted in average net erosion of 0.25 m^3/year (Jaffe et al. 2007)
  (3) *Climate change* will further perturb morphodynamics as sea level rises and the river discharge regimes are altered by warming and precipitation changes, likely resulting in further erosion.

  - **Process-based, 3D, numerical model to reproduce historic sedimentation volumes and patterns (Figure 8):**
    - Shallow water equations
      - Hydrostatic pressure models
      - Salinity and density gradients
    - Multiple transport formulations
    - Multiple sediment fractions
    - Bed slope effects
    - Bed level update every time step
    - Waves, density currents

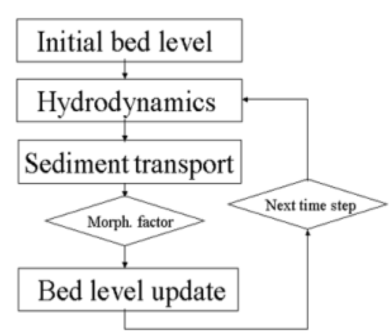

Figure 8. Flow chart of parameters in the Delft 3D sediment model

  - **Model schematization:**
    - Domain decomposition to vary different portions
    - Patch together domains *(ocean, SF Bay, Suisun Bay and Delta, rivers)*
    - Boundary conditions
      - River discharge *(very high for 1 month, low for 11 months)*
      - Sediment supply
    - Diurnal wind *(7 m/s at noon, with 6 months from west, 5 months from southeast)*

    - Sediment transport
    - 53 total parameters *(9 sand fractions, 20 mud fractions, 4 wind, 10 flow, 10 wave)*
  - **Sensitivity of model results to model parameter variation and flow schematization**
    - Model results compared to decadal measured bathymetric development.
    - Model can reproduce decadal sedimentation volumes and patterns fairly well.
    - Modeled deposition period is better than erosion period due to: (1) major sediment input signal (large volumes), (2) erosion requires more detailed but scarce information on bed composition.
    - Model results remain quite consistent by model parameter variation within reasonable limits
    - Suggests that the geometry and bathymetry play a major role in the morphodynamic development of San Pablo Bay.

- ***Sea level rise effects on wave attenuation and morphological development at the Corte Madera salt marsh***

  A modeling study on wave generation in San Francisco Bay is currently being developed with a detailed nested grid in the marsh. It successfully incorporates a wind model and data from Ralph Cheng (USGS). The study is a very preliminary assessment of morphology change and the sensitivity of wave attenuation to profile shape, levee, and vegetation. Preliminary results show that vegetation effects on wave height attenuation are important, however calibration and verification with field data is necessary. Detailed morphology needs to be accounted for through high resolution or sub-grid approaches.

- ***Working with D-flow in the San Francisco Estuary: Why would we need complexity in models?***

  D-flow is the conditional name for the unstructured version of Delft3D. A structured grid approach is not adequate or feasible in the San Francisco Bay-Delta. However, issues such as salt intrusion, fish migration, water quality, and wetland restoration projects can be addressed using the UNSTRUC model. The Delft-UNSTRUC Hydrodynamic Model is currently under development for the Delta and will soon be coupled with Delft3D water quality models. It involves a new hybrid grid (Figure 9), with fixed cells in some areas and curvilinear grids where resolution is needed. Unstructured mesh can arbitrarily zoom into areas for higher resolution. Although this can also be accomplished through domain decomposition, there would be boundary effects where the two domains meet. Parameters incorporated include hydrodynamics, salinity, temperature, sediment, phytoplankton, and bivalves. Although larger temporal scale for model simulations would increase computational time, this can be resolved through the use of additional processors (Table 1).

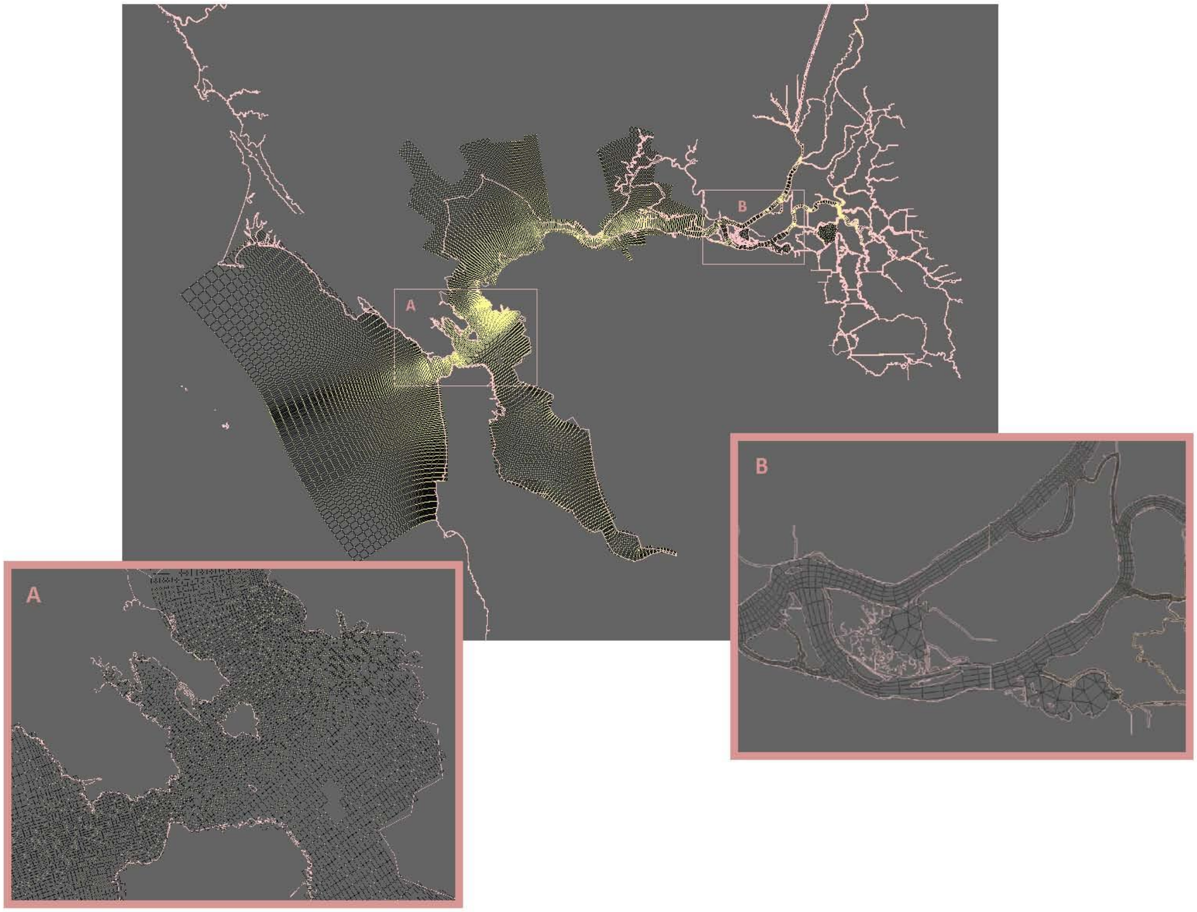

Figure 9. The SF Bay-Delta Delft-UNSTRUC Hydrodynamic Model incorporating a 3-dimensional hybrid grid from ocean to river.

Table 1. The D-flow model processing time based on temporal scale of model and number of processors

Days real time	Processors	Days runtime	Parallelization Factor
1	1	0.04	0.8
365	1	15.21	0.8
365	8	2.88	0.8
3650	8	28.81	0.8
3650	64	5.46	0.8

4. <u>Temporal and Spatial Patterns in Benthic Invertebrates in the San Francisco Bay</u>
— Isa Woo (USGS Western Ecological Research Center)

- **Salt Pond Restoration Uncertainties:**
  In 2003, federal and state agencies acquired 16,500 acres of commercial salt ponds in the South San Francisco Bay and 1,400 acres along the Napa River in the North Bay for the purposes of restoration within an adaptive management framework. This is the largest tidal wetland restoration on the west coast. However, there are uncertainties regarding how these restoration projects will affect adjacent estuarine shoals that support migratory birds and fishes, as well as how scenarios of climate change will influence wetland restoration processes and outcomes. Key uncertainties include sediment dynamics for restoration and accretion, avian habitat value and carrying capacity, effects on the ecology of fish and harbor seals, and effects of tidal prism on food dynamics.
- **Ecology of Shoals:**
  The largely unaltered shoals are a primary reason the San Francisco Bay is known for its rich estuarine communities. A conceptual model of the ecology of shoals (Figure 10) displays the interactive effects of physical forces with biota, showing links within the food web. There is high spatial and temporal variability in invertebrates due to both physical factors (hydrology, elevation, inundation time, water depth, sediment structure, water quality) and biological factors (predation, competition, recruitment, and available food resources). Secondary consumers are influenced by both top-down and bottom-up effects.

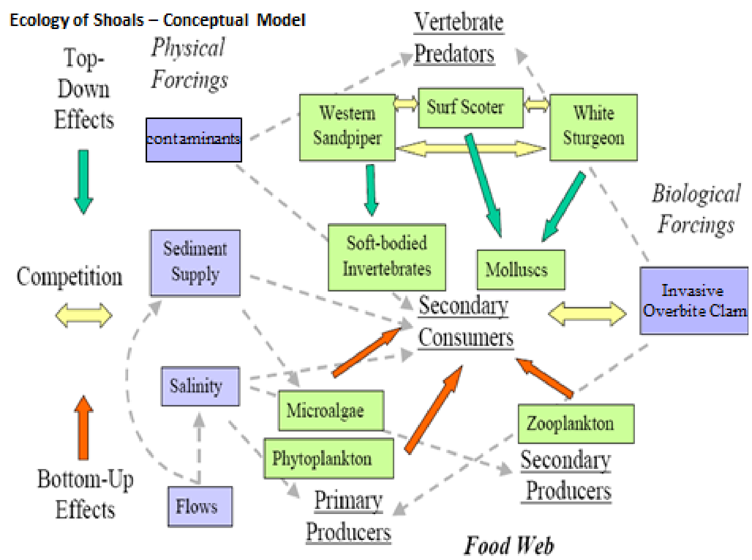

Figure 10. The interactive effects of physical forces and biota within the food web of shoal ecosystems

  - *<u>Bottom-up effects</u>*: Invertebrate depletion may reduce carrying capacity for avian predators. Kraan et al. (2009) tested the effects of declining food on mudflats (cockle harvest) for red knots based on yearly benthic mapping, color-ringing, and bird-counts from 1996-2005 in the western Dutch Wadden Sea. Through estimations of suitable foraging area, spatial predictability of food, and bird survival, it was demonstrated that the intertidal flats were being used to capacity by migrant shorebirds. Red knots lost 55 percent of their foraging area, resulting in a significant decline in both overall numbers and survival rate; however the numbers of birds per suitable area remained unchanged. Birds also responded by developing enlarged gizzards. 250-meter resolution benthic maps of invertebrates were used to estimate carrying capacity.

- *Top-down effects:* Shorebirds may exhibit top-down control on mud flat invertebrate communities, and thus phytoplankton. Thompson et al. (2008) and Lucas et al. (2009) found that grazing bivalves determined phytoplankton blooms, and above a grazing threshold blooms ceased. Bivalves, preyed upon by birds and fish in the fall and winter, disappear each year prior to the spring bloom. Growth of phytoplankton depends on shallow water processes, and change in benthic filter-feeders or their predators has great potential to change bloom dynamics.

- **Dumbarton Shoals Project:**
Project goals are to characterize spatial and temporal variability in benthic invertebrates, identify factors that drive invertebrate densities and biomass, and relate invertebrate distribution to physical conditions and avian predators. Invertebrate and sediment samples were collected monthly during high tide on three transects along an elevation gradient, with each core being 10-centimeters wide and 10-centimeters deep. Invertebrates are sorted to the lowest possible taxon, bivalves are sorted by size class, and ash-free dry weight is determined. Results include:
  - *Sediment grain size* decreases with increasing distance from shore (Jaffe et al.)
  - *Benthic invertebrate densities:*
    - *Temporal patterns*: Taxa densities varied over time, with bivalve numbers decreasing in mid-winter months (Figure 11).
    - *Spatial patterns:* Taxa densities varied by location and elevation, with high bivalve densities in shallow areas within 300 meters of the shoreline. Amphipods showed increased density in deeper water.

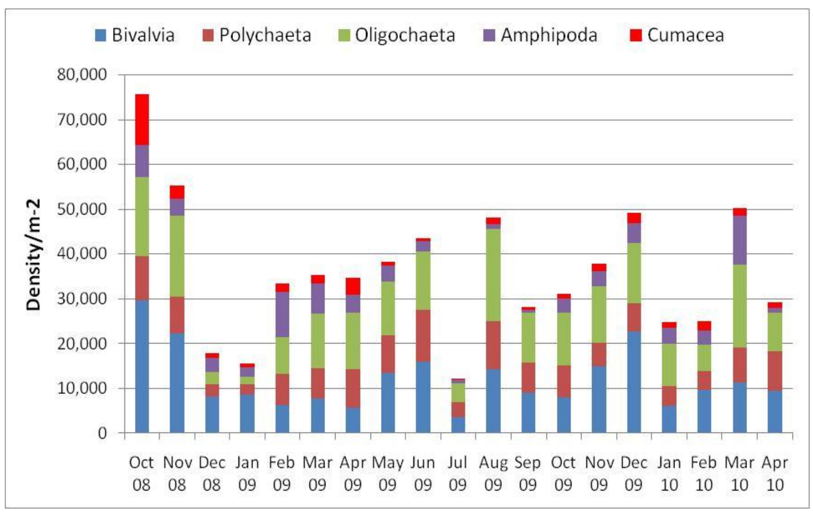

Figure 11. Relative density of benthic invertebrate taxa in the Dumbarton Shoals by month, from October 2008 to April 2010.

  - *Benthic invertebrate biomass:* Average ash-free dry weight (mg/m²) was interpolated for the entire area from sample points. Bivalves and polychaetes compromise the majority of the biomass. Patterns are patchy and change by season, but biomass is primarily higher in the shallow shoals, especially for bivalves.
  - *Predation effects on invertebrates:*
    - Size class matters for avian predators, so bivalve patterns were examined by size class. Bivalve temporal patterns may be explained by avian predation, particularly in the 2-6 millimeter size class that is depleted in the winter when birds are feeding (Figure 12).

However it is important to note that diving ducks will also eat bivalves up to 25 millimeters in diameter.

- Predator exclusion experiments are necessary to tease apart effects of predation (predator type) from seasonal and annual variability.

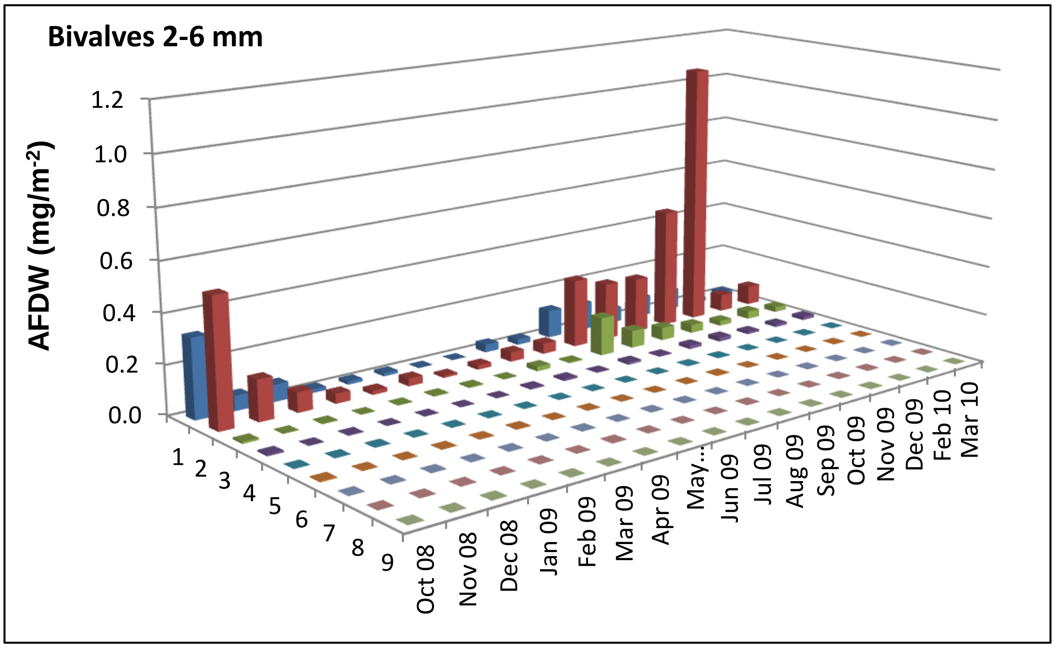

Figure 12. Monthly biomass (ash-free dry weight) of 2-6mm bivalves along an elevation gradient in the Dumbarton Shoals, going from October 2008 to March 2010

- *Bathymetry and water levels* are used to assess habitat availability for avian foragers, according to suitable foraging depths by species. The percent of time the mud flat is accessible is determined by calculating the percent of time the required foraging elevation is exposed.
  - Accessibility of the mud flat ranges from 40 percent near the shore to zero at the deepest areas, however this differs between shorebirds and ducks.
  - Relationship was identified between changes in elevation and inundation period. (10-centimeter change in elevation translates to about a 3 percent change in inundation)
  - With increased water levels and static mud flat elevations, available foraging habitat decreases for western sandpipers and lesser scaup (Figure 13a). With 150-centimeter increase in water level, WESA foraging time is down to approximately one percent (Figure 13b).

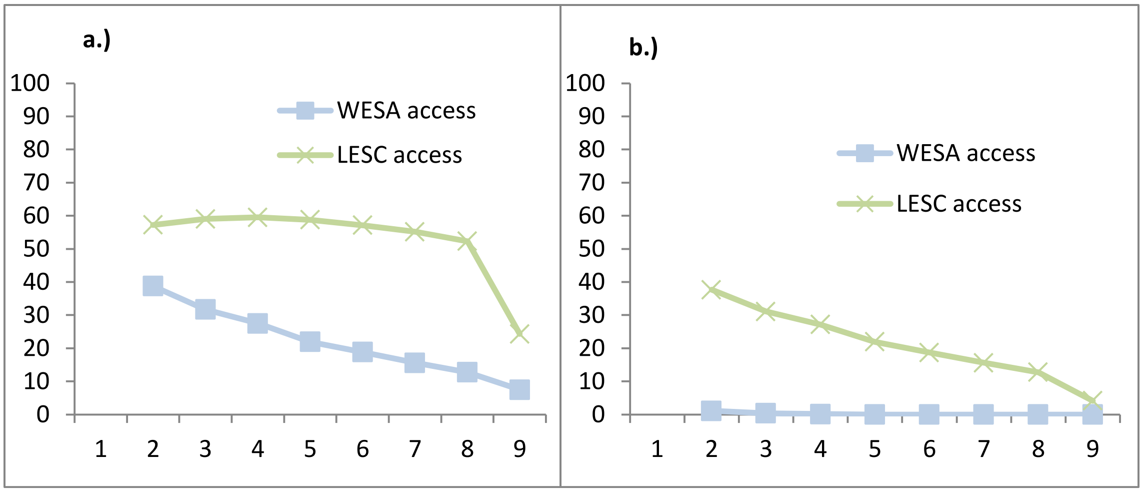

Figure 13. Percent of time the mudflat is accessible to western sandpipers and lesser scaup: a) along an elevation gradient with increasing water depth, and b) along the same elevation gradient combined with a 150 cm increase in water level

5. Carrying Capacity of Small Sandpipers on the Dumbarton Shoals (South Bay Salt Pond Restoration Program) — *Aariel Rowan (San Francisco State University)*

- **Importance of San Francisco Bay for Shorebirds:**
  The San Francisco Bay is designated an area of hemispheric importance for shorebirds, as over one million shorebirds come to the estuary annually and feed in the tidal flats. Shorebirds of North America have experienced population declines over several decades, therefore understanding the ecology of their key stopover sites is critical. Staging areas of the San Francisco Bay estuary are providing an important resource for shorebirds in their migratory path from Mexico to Alaska. During the 2008 Shorebird Census, Western Sandpipers were the most abundant shorebird in the San Francisco Bay with 30 percent of all birds, followed by Dunlin with 29 percent.
- **SF2 Dumbarton Shoals Project:**
  - Invertebrate and sediment samples collected monthly on transects along elevation gradient
  - Monthly bird surveys documented Western Sandpiper and Dunlin abundance, behavior, distance to water line, and time budgets
  - Sediment profile, terrestrial LiDAR, bathymetry, water quality, and tidal levels were all assessed.
- **Profitable prey for Western Sandpipers and Dunlin:** ***(from literature review)***
  - Weight of at least 0.06 mg (ash-free dry weight)
  - Include amphipods, bivalves, cumaceans, polychaetes, and oligochaetes
  - No bigger than 59mm (polychaetes) or 12mm (all others)

- **Determining distribution of macroinvertebrate prey accessible to Western Sandpipers and Dunlin given variable tidal exposure:**
  - Inverse distance weighting interpolation (IDW, ArcGIS Geostatistical Analyst, ESRI, Redlands CA) used to model prey densities from values at the nearest sampling station.
  - Assess temporal variability in biomass of prey
- **Carrying capacity of the site during different seasons**
  - Involves creation of a foraging model to determine shorebird use of mud flat prey based on energy content of accessible prey, assimilation efficiency, and daily energy expenditure (Figure 14).

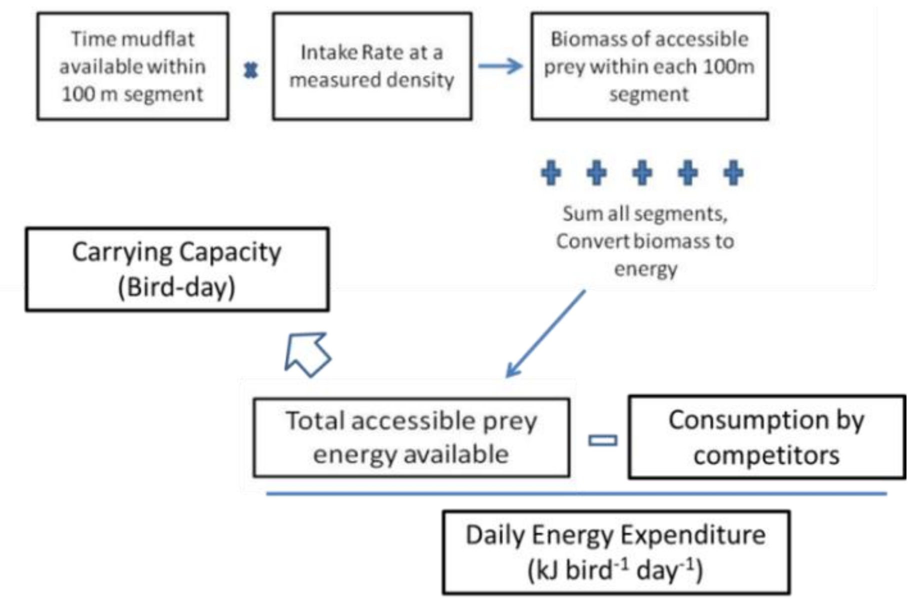

Figure 14. Foraging model used to determine bird carrying capacity, accounting for accessible energy from prey, consumption by competitors, and daily energy expenditure

  - If biofilm is a significant food source, it will also influence carrying capacity.
  - Bird functional response will determine how intake rate varies with prey density
  - The water level analysis involves elevation bands, the average rate of tidal water change, and the number of ebb tides that pass through each elevation band per month.
- **Potential impact to foraging small shorebirds given possible scenarios of mudflat change *(increased slope, overall loss of elevation).***
  - Any change to mud flat morphology or tidal prism will affect time available for foraging
  - Use sensitivity analysis to describe how each variable contributes to outcome
  - Latin Hypercube Method estimates the model with different values of each parameters to see which parameters carry the most weight on the outcome (DEE, intake rate, competition level from other predators, sediment elevation change, mud flat slope)

6. Carrying Capacity Modeling of Diving Benthivores on San Pablo Bay Shoals

— Susan De La Cruz (USGS Western Ecological Research Center)

- **Importance of San Francisco Bay for Waterfowl:** The San Francisco Bay is one of the most important wintering and staging areas for benthic-foraging, diving ducks in the Pacific Flyway. Approximately half of the flyway populations of Scaup (*Aythya marila* and *A. affinis*), Canvasback (*A. valisineria*), and Surf Scoter (*Melanitta perspicillata*) have been counted in the Bay during the U.S. Fish and Wildlife Service mid-winter survey (Figures 15a, 15b, and 15c). Many species using the San Francisco Bay are declining due to unknown causes, however wintering area factors may contribute, as food is a major limiting factor in sustaining birds through the winter season and their subsequent migration.
- **Measuring Carrying Capacity:** Models of carrying capacity, the maximum number of bird days that can be supported by the food supply within a defined site and time period, are currently being developed for diving ducks (Lesser Scaup, Greater Scaup, Canvasback, and Surf Scoter) utilizing San Pablo Bay Shoals. These models provide information for managing habitat and setting habitat acreage goals, and they will specifically assist the San Francisco Bay Joint Venture with establishing waterfowl population goals and habitat needs. Models can eventually be

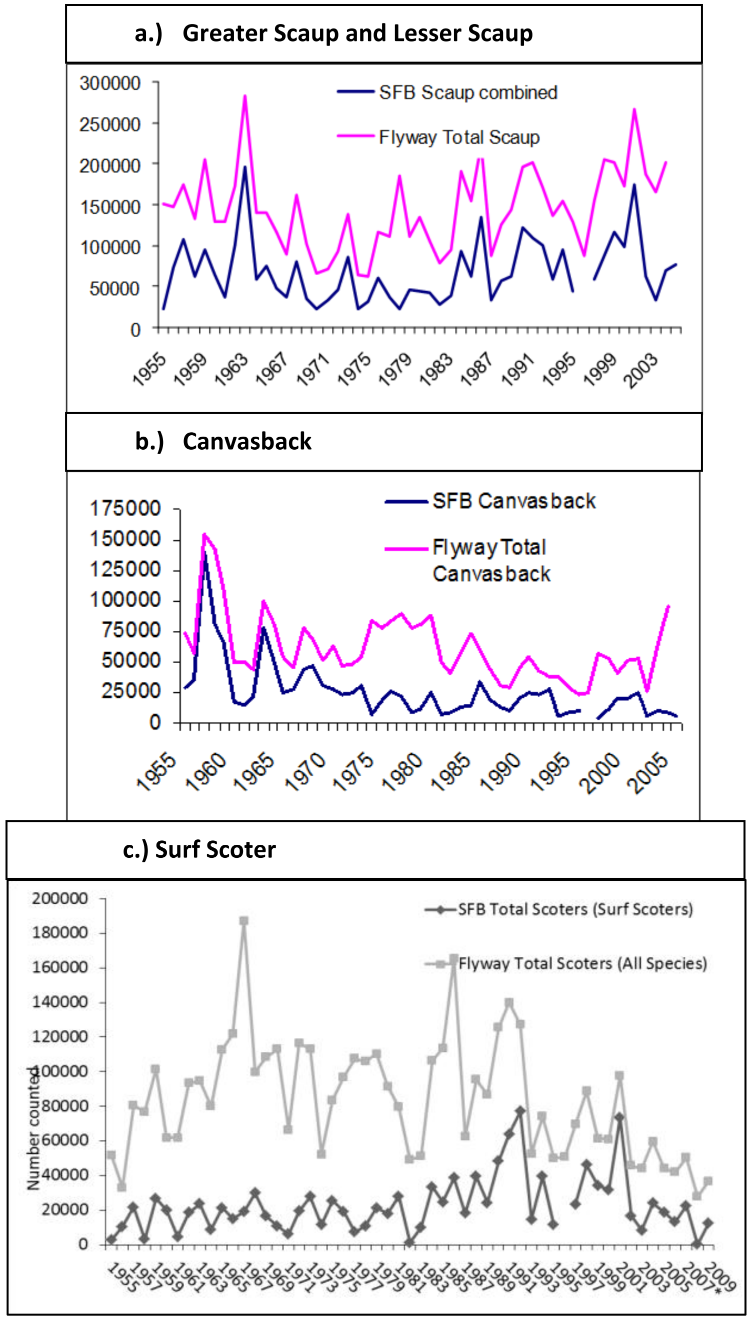

Figure 15. Pacific Flyway and San Francisco Bay diving duck population totals over the last half-century from the U.S. Fish and Wildlife Service mid-winter survey

modified according to information from sea level rise scenarios and geomorphic change models. Primary methods used to model carrying capacity include:

- o *Daily ration models:* based on the total biomass of accessible food, aggregated across all patches of differing food density, divided by an individual's daily energy requirement (Lovvorn and Baldwin 1996, Michot 1997).
- o *Individual behavior based models*: use a game theoretic approach to follow the patch-choice and body reserves of each individual animal on each day of a simulation (Goss-Custard et al. 2002, Lovvorn and Gillingham 1996).

- **Spatial and Temporal Extent:**
This modeling effort excludes intertidal areas used by shorebirds and focuses on subtidal areas from 0-6m MLLW in San Pablo Bay during October to January, due to having the highest densities of all four diving duck species. Waterfowl diet and movement data is available for all species, and adequate benthic surveys are available from 1990, 1993, and 1999-2001. Declining numbers of all species by January suggest that the carrying capacity of the area is reached (Figure 16).

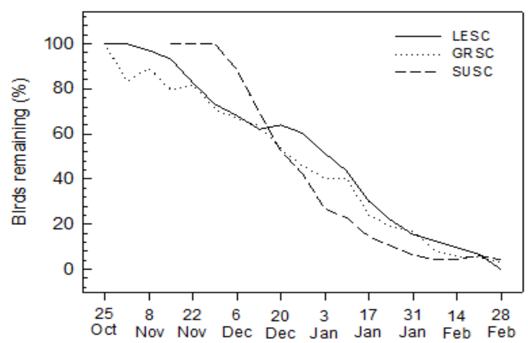

Figure 16. Departure chronology of lesser scaup, greater scaup, and surf scoters from San Pablo

- **The Two-Part Conceptual Approach to Modeling:**
Part I. Estimate threshold prey densities:
The threshold prey density is reached when energy gain equals the energy cost of foraging at a particular depth (Figure 17). When energy gain minus energy cost is greater than zero, foraging is profitable. Unlike for shorebirds, calculations of energy cost need to include dive costs for benthic-foraging waterfowl. A bird's functional response, its ability to increase its intake as prey density increases, must also be taken into account.

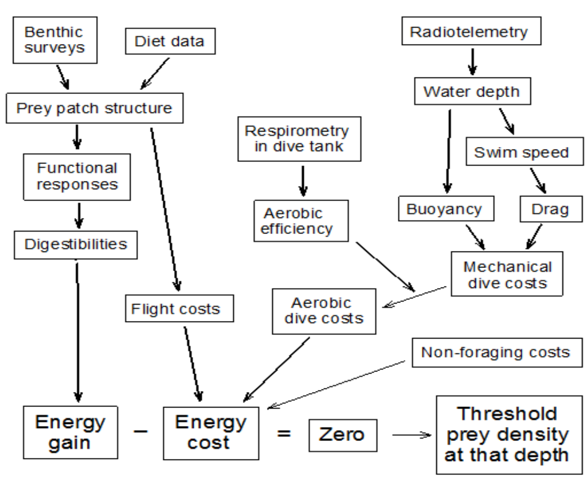

Figure 17. Simulation model for estimating the threshold density of prey above which diving ducks can achieve positive energy balance (Lovvorn et al, in prep.)

Part II. Estimate duck use-days for San Pablo Bay: Prey densities at a given location need to be adjusted for consumption by the four main non-avian competitors (Figure 18). In addition, the prey mass available to a particular duck species must also consider partitioning with all other duck species. Waterfowl may partition prey resources by prey size, prey species, foraging depth, and foraging location.

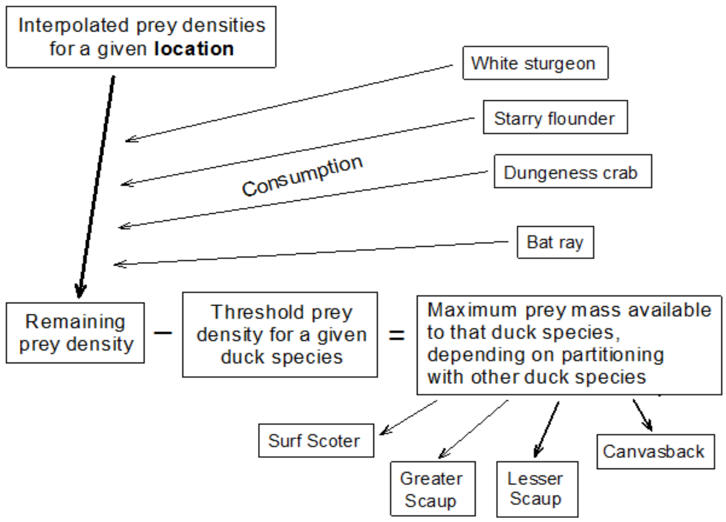

Figure 18. Algorithm for estimating number of duck-use-days that can be supported in San Pablo Bay over winter (Lovvorn et al., in prep.)

- **Data Informing the Model:**
  - *Diet data for diving ducks*:
    - *Corbula amurensis* is a dominant diet item for diving ducks in San Pablo Bay (Figure 20b), and there is some evidence of partitioning by size classes (Figure 19a).
    - *Macoma balthica* is important for canvasback (Figure 19b), particularly those foraging in intertidal and creek areas
    - Scoter diet differs among sub-bays

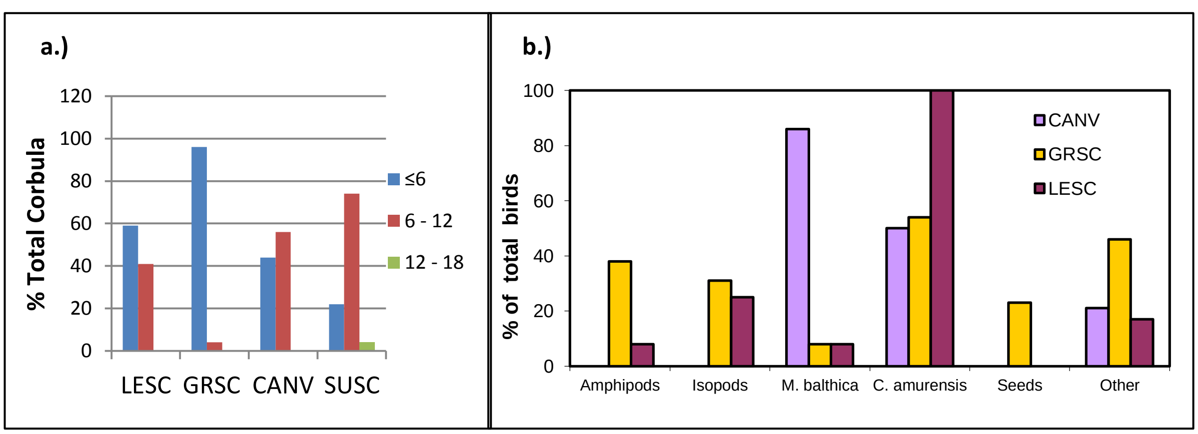

Figure 19. a) Proportion of different size classes of Corbula amurensis in the diets of lesser scaup, greater scaup, canvasback, and surf scoters. b) Percent of greater scaup, lesser scaup and canvasback with certain prey types in their diets

- *Duck foraging depths* are determined from telemetry and bathymetry (Figure 20b). Both scaup species predominantly overlap in preferred foraging depths, with lesser scaup tending toward shallower depths than greater scaup (Figure 20a).

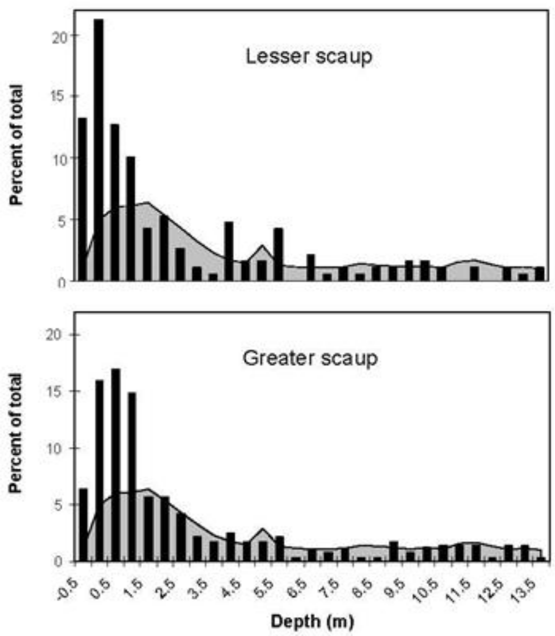

Figure 20a. Preference (bars) of two scaup species for shallow water foraging habitats compared with available habitats

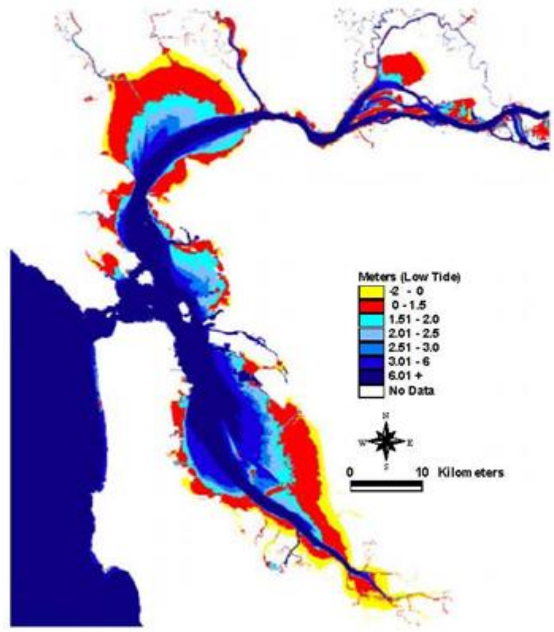

Figure 20b. Current availability of shoal habitats preferred by foraging scaup

- *The Benthic macroinvertebrate atlas* (Rowan et al., in prep.) is used to understand the spatial and temporal spread of prey resources around the bay.
  - Contributors include USGS, SFEI, CAS, DWR, NOAA, and CDFG.
  - Interpolation conducted to obtain prey densities for carrying capacity modeling.
- *Functional responses and different densities of prey*:
  - Tank experiments measure mechanical dive costs in different substrates (Perry et al. 2007, Richman and Lovvorn 2004)
  - Follow intake of bird to see if responding to increased prey density. Lesser Scaup were able to assimilate more energy with increasing density of *Corbula;* however energy gain was minimal with increasing density of *Macoma*, which is deeper in the sediment.
- *Consumption by non-avian competitors* is being estimated through an extensive literature review combined with allometric scaling.

- **Future Work:**
  - Expand model to include other sub-bays in the estuary
  - Determine how sea level rise and geomorphic change will influence available foraging habitat, energetics (i.e. dive costs with water depth), and prey densities.

7. **San Francisco Bay Subtidal Habitat Goals Project** — ***Marilyn Latta (California State Coastal Conservancy- Subtidal Habitat Goals)***

- **Project Goal:**
  - Develop priorities for subtidal habitats, with a focus on science, management, and restoration
  - Identify key research questions to answer the most pertinent management questions.
  - Link key areas of subtidal resources to future designs and planning.
- **Subtidal Habitat Categorization:**
  - Six habitat types: soft substrate(including mobile sediments such as mud, sand, and pebbles), rock (large islands and outcrops), artificial, shellfish, eelgrass, and seaweed beds
  - Includes intertidal mudflats because they were not included in the original Baylands Ecosystem Habitat Goals Report
  - Incorporates connectivity and linkages between habitat types
  - All habitat types have data gaps
- **Function and Knowledge of Stressors:**
  - Define all habitat stressors
  - Determine highest level of stressors to each habitat type
  - Conceptual model developed for stressor types (Science advisor, Wim Kimmerer, University of Maryland)
  - Scale, irreversibility, and scope lead to goals recommendations
  - Committee includes the National Oceanic and Atmospheric Administration, the San Francisco Bay Conservation and Development Commission, and the State Coastal Conservancy
- **Consultant Reports:**
  - 5 stressor narrative papers: contaminants, bottom sediments, suspended sediments, nutrients, and artificial structures (Andy Cohen)
  - Eelgrass opportunities and constraints (Kathy Boyer)
  - Shellfish (Grosholtz)
  - Survey of derelict pilings, their significance, and action plan for removal (San Francisco Estuary Institute)
- **Concept of Living Shorelines:**
  - Using natural materials as buffers on shorelines to stabilize sediment, reduce wave action, and provide habitat (i.e., oyster reef, eelgrass bed)
  - Goal to develop pilot projects at 3 sites (including Corte Madera and Eden Landing)
- **Final Subtidal Habitat Goals Report:**
  - Implementation directed toward resource managers, however the report is useful for anyone working in subtidal areas
  - Includes a 50-year set of goals
  - All consultant reports are included with the report
  - Final Report was released in January 2010 and is available at *http://www.sfbaysubtidal.org/report.html*

B. Workshop Discussion Topic Summaries:

1) AVIAN ECOLOGY OF SAN FRANCISCO BAY SHOALS

Shorebirds and waterfowl generally use different areas of shoals, intertidal and subtidal respectively, however habitat area overlaps somewhat in the intertidal zone. Suitability of avian habitat can be defined by both prey and physical characteristics (i.e. water depth, sediments, slope, salinity, inundation regime). All of these factors interact to determine the area available for foraging. Prey quality, abundance, distribution, and accessibility will influence bird carrying capacity and population health.

Invertebrates make up the primary food source for shorebirds and waterfowl in shoal environments. The presence of the introduced Overbite Clam, *Corbula amurensis*, since 1986 has drastically altered the food web, as it has become a main prey item for diving ducks and other species. Invertebrate populations are primarily influenced by phytoplankton, however top down effects on invertebrates are strong due to annual prey depletion by avian predators. The influence of additional predators (i.e. fish, crustaceans, rays, and sharks) also affects prey availability, and large upwelling events can exacerbate the issue due to predator invasion into the estuary.

Biofilm on intertidal mud flats may also be an important energy source for some shorebirds. Biofilm is a generic term for the top outer layer of sediment that contains primary producers (i.e. diatoms) within the interstitial spaces between sediment particles. When the mud flat is exposed, they migrate upward and are accessible to small foraging shorebirds, such as the Western Sandpiper.

Prey availability and accessibility are integrally linked to the cost-benefit balance of foraging behavior. Water depth and the movement of the tidal line determine the available foraging time and accessibility of prey. The timing of the tidal cycle, both daily and seasonally, also plays an important role in foraging response. While feeding shorebirds are strongly influenced by fine-scale tidal flat topography, waterfowl foraging habitat is more homogeneous and influenced by water depth. Both diving costs and depth thresholds must be considered as part of the energetic balance of foraging diving ducks, however these factors are variable by species.

Suitability of the adjacent landscape for roosting and/or nesting is also essential in evaluating overall habitat quality. The proximity of roost sites to daily feeding areas is important in maintaining the foraging profitability despite energy expenditure. Although most ducks are not present in the San Francisco Bay in the summer, there are some nesting shorebirds and waterbirds that forage in tidal flats. Shorebirds such as black-necked stilts, American avocets, and snowy plovers utilize adjacent salt ponds as breeding habitat. Nesting marsh birds (i.e. California clapper rails) will also forage in mud flats.

2) BIOPHYSICAL INTERFACE

- **Drivers of invertebrate density and distribution:**
  - *Tidal inundation and exposure regime* are the primary drivers of invertebrate distribution. Water inundation and exposure are driven by slope and elevation relative to the tidal cycle. Microtopography also plays a critical role along tidal edges.
  - *Salinity* is the other primary factor influencing invertebrate population response. Although the prominent invasive bivalve, *C. amurensis*, has a wide salinity tolerance from 2 ppt. to full ocean salinity at 35 ppt., it is more stressed in the 2-10 ppt range.
  - *Water temperature* must be maintained within a suitable range; however temperature tolerance varies by invertebrate species.
  - *Water depth*:
    - The ability of invertebrates to respond to deeper waters is species specific and dependent on sediment type.
    - An invertebrate gradient along elevation is apparent in the South San Francisco Bay; however it is unclear whether predation is creating gradient or invertebrates are directly responding to water depth.
    - Although clam density does not appear to be depth dependent, it is energy dependent and therefore indirectly influenced by depth.
  - *Sediment* requirements for invertebrates are generally all fine sediment.
  - *Phytoplankton*: Phytoplankton dynamics are a key aspect in predicting invertebrate abundance, distribution, and biomass. *P. amurensis* eat phytoplankton, bacteria, zooplankton larvae, microciliates. When phytoplankton is high in the South San Francisco Bay, bivalves can grow 5mm per month (J. Thompson, pers. comm.) Phytoplankton is dependent on residence time, grazing, and light availability. Suspended sediment concentrations and water depths will influence the light available to phytoplankton. Phytoplankton blooms are generally initiated in the shallow shoal environments, where cells have increased opportunity for light.
  - *Predation pressure:* Depletion of prey stocks is common, due to annual avian predation, the influence of non-avian predators, and potential predator invasion into the estuary due to upwelling. Predation pressure is dependent on foraging time and water depth. *P. amurensis* disappears in shallow water by every January in San Pablo Bay because of heavy predation by waterfowl. Although it is difficult to separate predation pressure from inundation and exposure effects on invertebrates, it can be accomplished using predator exclusion experiments.
  - *Marine Influences:* Seasonal and spatial variability in invertebrates can be difficult to discern due to upwelling, marine influences, and predator migration into the estuary. *P. amurensis* can be affected by extraordinary predation events, such as its disappearance in 2004 due to the arrival of offshore predators (i.e. shrimp).

- **Physical influences on prey accessibility for waterbird predators:**
  - Water depth thresholds
  - Timing of tidal cycle (i.e., daily, seasonally)
  - Sediment permeability
  - Slope
  - Microtopography
- **Biofilm dynamics:**
  - Develops over muddy intertidal estuarine flats with little sediment re-suspension
  - Requirements include sufficient light availability and low turbidity
  - Also important for the cohesiveness of sediments

3) THE SHOAL TO MARSH CONTINUUM

Shoals are flats that extend sub-tidally into the estuary from the intertidal zone. They encompass a majority of the non-channelized areas of the San Francisco Bay estuary. ***Intertidal flats*** are limited to areas of tidal inundation, and the term mud flat is commonly used due to their sediment composition. Mud flats transition into ***tidal marsh*** habitats as the deposition of sediments increases and erosion decreases. A continual cycle between sedimentation and erosion is important for healthy landscape dynamics, as it is necessary for wave energy to attack the marsh in order to build shoals and mud flats. There is equilibrium between when the mudflat begins to disappear, the marsh experiences increased erosion due to wave action, and the mudflat starts to regenerate. Although the erosion of shoals, mud flats, and marshes is generally thought of negatively, it is a natural component of a healthy system and long-term habitat maintenance.

The placement of hardened shorelines and the ability of the marsh to erode will determine the amount of ***sediment*** in the system. Therefore, the potential levels of marsh protection and the ability of storms to redistribute sediment to shoal habitats are important considerations. The balance between sedimentation and erosion occurs on an annual basis. Although the mud flats are continually influenced by wave action and tidal filling and emptying, marshes only experience erosion and deposition of sediments during storm events. Wave energy is necessary to distribute sediment, and if waves are dampened, there is no mechanism for sediment re-suspension and deposition on both flats and marsh. It is possible that waves will be a positive factor when associated with sea level rise. Although general protection of certain marshes may be necessary, allowing large storm events to occasionally redistribute sediments will be important to the health of both flats and marsh.

Despite the connectivity of the system, there is still somewhat of a trade-off between the ***protection*** of marsh and/or mudflat. In the San Francisco Bay management community, there is some tension about the preservation of different species in the respective habitats. Research and management has been primarily focused on tidal marshes instead of mud flats. There is competition between supporting habitat for migratory birds vs. the severely endangered tidal marsh species (i.e., Black

Rail, Clapper Rail, and Salt Marsh Harvest Mouse). There will continue to be political pressure regarding what areas are restored and protected, and further tension may result if the marsh protects inland developed areas from flooding. Although flats may come and go over short periods of time, marshes take a while to form. Natural areas that would allow for marsh succession are limited, and new marshes differ from older marshes in terms of their ecosystem function. Many habitats are also already disconnected and that will affect system dynamics. For instance, the location of the back side, or hard edge, of the marsh will affect the distribution of wave energy and the dynamics of erosion, deposition, and succession.

Salt ponds are another important component of the shoal to marsh habitat continuum. The sediment demands of salt pond restoration areas must be taken into account, as these areas are primary competitors for sediment. There is still great uncertainty regarding the amount of salt ponds in the South Bay that will be converted from pond to marsh, with numbers ranging from 50 to 90 percent, and therefore a huge range of sediments may be required. In addition, habitat provided by former salt ponds growing new marsh is providing valuable transitional habitat that may be lost if fully restored to marsh. Steps are currently being made to determine the energetic value of salt ponds to avian species. The availability of salt pond habitats is currently supplementing the carrying capacity of the flats for shorebirds; therefore future bird carrying capacity predictions will need to account for decreased habitat availability as these ponds transition into mature marshes.

It is logical for any discussion of shoals and ***climate change*** to also include tidal marshes. This habitat gradient is part of a continuum. As an extended system, the modeling aspect of the bay proper should be connected to the modeling in the marshes. Model predictions need to incorporate influences of landscape ecology in modeling scenarios. Sea level rise will add to an already dynamic system, and all factors must be accounted for when determining how birds will respond.

4) SEA LEVEL RISE IMPACTS

- **Initial loss of intertidal habitat**

With rising water, intertidal habitat could potentially transition spatially, however much of it would be lost as it moves landward and possibly into hard structures. In a sediment poor system with a hard shoreline and low wave energy, the effect of changing water depths on different avian species can initially be considered independent of geomorphic change. As flats stay submerged, many foraging areas in tidal flats would disappear for shorebirds.

- **Changing hydrodynamics**

As sea level increases, wave reflection from hard structures could increase erosion of mud flats. Although the sediment load from the Sacramento-San Joaquin Delta is decreasing, redistribution of sediments from the marsh edge will likely increase. Sediment redistribution would occur over several decades; however those sediments could disappear over the longer-term. The amount of sediment necessary to maintain mud flats and where there is sufficient sediment supply will need to be determined.

Rising seas will also drive salinity intrusion farther into the estuary. In addition, salinity stratification may result as water becomes deeper. Deeper areas have less vertical change, less freshwater, and farther intrusion of salt water.

- **Maintaining natural processes**

Wherever possible, it will be important to maintain transitional dynamics in the mud flat, through the right balance of erosional and depositional forces to offset the rising water. However, pushing tidal flats higher up the system may not be feasible due to levees and limited land. Identifying locations where a natural transitional zone can be maintained in the San Francisco Bay Area is essential. Modeling should involve determining the tipping points or thresholds for system change and when they might occur. Subsequently, sensitivities to different scenarios will need to be incorporated into avian models.

- **Influence of management activities**
  - *Shoreline protection:* Shoreline protection structures will have increased ramifications on adjacent wetlands and mud flats when combined with sea level rise. The location, height, construction material, and condition of levees are all factors to consider when assessing scenarios of changing hydrodynamics. It is especially important to know which levees will be retained and to incorporate this into future modeling of sea level rise effects on the availability of suitable water depths for foraging. Determining the political coverage of areas that will not be allowed to flood will be useful in evaluating probable scenarios of ecological change.
  - *Sediment supply:* A sufficient sediment supply for wetlands and mud flats is necessary to maintain suitable habitat in the face of sea level rise, and it will be important to identify locations with adequate sediment input. Unfortunately, the sediment supply is not enough to keep up with sea level rise in most areas. Supply from the watershed is currently limited due to the presence of numerous dams blocking sediment flow. There is a disconnected system of sediments with little back-side sediment supply to marshes from creeks or tidal sloughs. Additional sediment sources are stuck up channels, and there is no mechanism for moving this sediment. Boulder removal in the Delta could also result in an additional sediment sink.

- *Deepened channels:* Although future dredging activities are uncertain due to conflicts over disposal of dredge material, channels could also be deepened by an increased tidal prism. The impact of salinity intrusion would increase with deeper channels.

- **Alteration of food sources**

Changing physical conditions associated with sea level rise could alter the dynamics of avian food sources. Invertebrates would be primarily impacted by changes in salinity, temperature, phytoplankton, and tidal inundation regime, while biofilm would be influenced by changes in salinity, turbidity, and light availability. Models could assess how both invertebrates and biofilm may be altered through different climate scenarios. Changing hydrodynamics and energy could also encourage or discourage certain predators and influence top-down effects on food sources.

Phytoplankton is influenced by hydrological changes; therefore modeling phytoplankton dynamics will be integral to assessing sea level rise effects on prey populations. Shoals are important to blooms because cells have increased opportunity for light. It is possible that deeper shoals may cause blooms to be lost, as there is no positive net phytoplankton growth in channels. Because suspended sediment concentrations influence the light available to phytoplankton, decreased sediment concentrations could potentially offset the effects of increased water depth. Clam grazing also has less of an effect in deeper water because of low vertical turnover. However, the San Francisco Bay is already a nutrient-rich system and reaching the threshold for eutrophic conditions could be an issue.

- **Prey inaccessibility**

Foraging habitat loses suitability as water gets deeper, because prey either becomes physically inaccessible or the energetic costs of foraging become too high. The time available for foraging is influenced by tidal fluctuations and sea level rise. Shorebirds dependent on fine-scale movements of the tide line would lose available foraging habitat as intertidal mud flats disappear. Diving ducks may have difficulty finding enough foraging areas with suitable depth ranges for diving. Water depth thresholds are variable by species; therefore sea level rise may have differential impacts.

5) EXTREME EVENTS

The ecological response to the potential of an increase in frequency or severity of extreme events should also be assessed along with sea level rise. Capturing this scenario would involve comparing the model of mean conditions to models of extremes. Although this is possible for hydrological modeling, it could be more difficult for long-term geomorphology modeling that may require end-member conditions. However, the event scale should be based on what is of greatest concern to birds and what may leave a long-lasting signature on the ecosystem. It would involve discerning events that the system can recover from, versus “tipping-point” events that result in system change.

A key factor is whether extreme events would expedite already existing trends or result in drastic change.

Historical datasets are necessary to pinpoint the effects of extreme events on birds and the physical environment. A water level analysis can incorporate regression models of storms, El Nino, and tides to produce water level projections with climate change in the future. Conversely, capturing the effects of extreme events on biota may be difficult, because there is limited invertebrate data going back to the 1970s and historical bird data is a single point per year. However, strong year-to-year site fidelity may help to reveal trends, and localized effects may be observed, such as birds responding to an oil spill. Because most extreme events have implications beyond the San Francisco Bay estuary, analyzing regional and flyway data would be especially useful. Waterfowl data is more widespread, with transect surveys conducted across North America. Shorebirds have been infrequently counted at different sites, but a more unified Pacific Flyway effort is being developed.

- **Increased rate of sea level rise**

  In the context of climate change, the largest predicted change is in terms of sea level rise. Because sea level rise will accelerate as global temperatures warm, there is potential for the rate of sea level rise to be higher than expected. Sea level rise scenarios could be conservative estimates, since IPCC estimates do not include catastrophic glacial melt. An increased rate of change could impose deeper water levels on the flats without time for geomorphology to respond. These extremes should modeled, so appropriate contingency plans can be developed

- **Increased frequency and severity of storms**

  A higher frequency and severity of storms could drive increased deposition at certain sites, resulting in increased burying and loss of food availability. For example, a delta formed off of San Francisquito Creek due to flooding in 1995 and persisted many years. The formation of a delta can be recreated with models; however subsequent slow erosion may be more difficult. Models will need to include data on wave energy and slumping. In addition, location relative to sediment source is an important consideration, such as sediment inputs of local tributaries versus the Delta. The ability of biota to respond successfully to deposition events is dependent on both species and scale. The scale is very important for shorebirds focused on a narrow band of suitable foraging habitat. If shorebirds cannot access the flats, they must find other suitable habitat elsewhere within several days or mortality may result.

  There is no consensus on how storminess will change with climate change, however severe flow events are highly possible and would have community implications. The timing and degree of flow events may be altered, even though the total water input might stay the same. How land management responds to changing flood peaks in the Delta will influence the dynamics of freshwater flows reaching the Bay. Although snowpack variability is agreed upon, it will not affect tributaries in non-snowpack areas and it will likely affect salinity more than sediment.

Flow changes in the Bay would primarily affect invertebrates that are structured by salinity. For instance, large flow events between 1995 and 1998 changed invertebrates. Large rain events will also cause changes in the mud flat community. Species respond differently, with soft-bodied species being more susceptible and other species burrowing deeper. This could be assessed looking at shallow subtidal invertebrate data going back to the 1980s.

- **Extreme high tide events**

Combined with sea level rise, extreme high tides could have drastic effects on communities by further decreasing the accessibility of mudflat and shoal habitats for foraging. In areas like the North Bay, high river flows coinciding with extreme tides could especially be of concern. The possibility of nest inundation might also need to be considered for some breeding species. Although flooding has a major influence on nest failure in other areas, predation is a larger factor in the San Francisco Bay. Some birds (i.e. clapper rails) are adapted to water flows, because their nests and eggs can float and potentially survive inundation. However, if high water levels drastically decrease the amount of suitable habitat, birds and nests could become more exposed to predators.

- **Regular oceanic patterns**

The degree that the San Francisco Bay maintains equilibrium over larger timescales will determine the influence of global patterns and events. When considering the climate envelope of a species, population dynamics are regularly influenced by upwelling events, northern oscillations, southern oscillations, and El Nino. It will be essential to assess species responses to these events when combined with the effects of climate change.

  - *<u>Large upwelling events:</u>*
    Because productivity is driven by upwelling, the role of event scale and time period on the degree of biological effects will need to be determined. Coastal winds may also determine the upwelling value. Large events drive nutrient availability, thus creating more available food and encouraging additional predators. These effects could be modeled using an index number.
  - *<u>North Pacific Gyre Oscillation (NPGO):</u>*
    Timescale will be important when considering how populations are affected by northern and southern oscillations. The influence of the NPGO on populations over a 20-30 year period could be very large compared to climate change effects. Some studies in Europe have looked at the importance of northern and southern oscillations relative to migratory populations.
  - *<u>El Niño:</u>*
    El Niño events may be of concern if they make marginally suitable foraging habitat no longer acceptable, therefore the scope of El Niño effects will need to be determined. Over the short-term, water elevation could rise up to 20cm due to El Niño and this could

last a few months. Because these larger El Niño-type events are not only confined to the San Francisco Bay, their influence might be seen across many sites. With changing environmental conditions, birds must either move, adapt, or die. Temperature affects the chronology of bird migration relative to spawning, plant phenology, and snowpack. The effect of El Niño on species that "hop-scotch" up the flyway will need to be assessed. Looking at historic bird counts would be especially useful; however shorebird counts have not been conducted as regularly as waterfowl.

- **Toxic algal blooms**

The influence of algal blooms could increase due to higher temperatures. Toxic algal blooms are associated with water temperature and global ocean conditions, and this is being assessed through CASCaDE. A U.S. West Coast ROMS Model also has real-time data of temperature, salinity, currents, and upwelling that could be used to build a model of the temperature of the Bay. Birds may respond to toxic algae through reduced feeding activity, inability to lay eggs, and loss of motor coordination to death (Shumway et al. 2003). In Santa Cruz, mortality of birds has been associated with bloom events on the coast. Also, if red algae is deposited on shore, the mud flat can go anoxic and it could several years for the ecosystem to recover.

- **Acidification**

Although bays and estuaries tend to be more buffered than the open-coast, there is still a need to think about acidification effects on invertebrates and benthivores in the San Francisco Bay. Acidity has a different behavior in the bay; however it would still be influenced by any increase in ocean acidity. There are several studies of acidification currently being conducted at Bodega Bay, Tomales Bay, and there is also instrumentation collecting pH data in the South San Francisco Bay.

- **Contaminants**

Contaminants are of high concern to avian species in the San Francisco Bay, and have been shown to have a leading influence on nest failure in several species. Diving ducks are showing high Selenium concentrations, and those concentrations have recently increased. Few measurements have been taken of bird condition in response to contaminants; however effects have generally been seen on the immune system and subsequent survival.

Although it could be a secondary step in modeling efforts, contaminants should be incorporated with hydrodynamic models to see how trends are influenced by climate change. This will be a component of CASCaDE II, involving research that has been conducted on transport and contaminants. Selenium enters the food web through phytoplankton, and the effects of these inputs on concentrations down the line will need to be assessed. In addition, marsh erosion due to increased wave energy or storm severity could result in contaminant release (i.e. methylation).

6) KEY MODEL PARAMETERS:

Bird Requirements:

- Foraging time and accessibility of prey influenced by:
  - Water depth
  - Slope
  - Movement of tide line
  - Sediment permeability
- Suitability of prey populations determined by:
  - Density
  - Distribution
  - Biomass
  - Size classes
- Landscape factors include:
  - Proximity of suitable roosting or nesting habitat
  - Degree that adjacent salt ponds supplement carrying capacity

Influences on Invertebrate Populations:

- Inundation/exposure regime determined by:
  - Elevation
  - Slope
  - Tidal flow
- Predation pressure dependent on:
  - Foraging time
  - Prey accessibility
- Water quality parameters:
  - Salinity
  - Temperature
  - Dissolved oxygen
- Benthic conditions:
  - Sediment type
  - Organic matter
- Phytoplankton influenced by:
  - Light availability and suspended sediment concentrations (inverse relationship)
  - Clam grazing and water depth (inverse relationship)
  - Vertical mixing and salinity stratification (inverse relationship)
  - Upwelling
  - Threshold for eutrophic conditions
- Effects of extreme events:
  - Upwelling influences on predator invasion
  - High freshwater flow events
  - Burial events on invertebrate survival
  - Erosion events on invertebrate survival
  - Inundation events on marsh

Influences on Biofilm:

- Light availability
- Low turbidity
- Salinity

7) MODELING APPROACHES

a. GEOMORPHIC CHANGE MODELING:

- **Climate and hydrological changes**

The CASCaDE project has developed data on the cascading effects of changes under different climate scenarios as they propagate from the climate system to watersheds to river networks to the Delta and San Francisco Bay (Cayan et al. 2008a, 2008b, 2008c, Ganju et al. 2008, Ganju and Schoellhamer 2009). Global climate models are run under selected scenarios of future greenhouse gas emissions, and resulting precipitation and temperature projections are downscaled for use in hydrologic models, which provides input for geomorphic models. CASCaDE II additionally involves the Delft-UNSTRUC model, incorporates hydrodynamic effects from ocean to river, and includes the fate of wetlands. This LCC Project will build on upcoming work with CASCaDE II in order to evaluate climate change and sea level rise effects on birds (Figure 21).

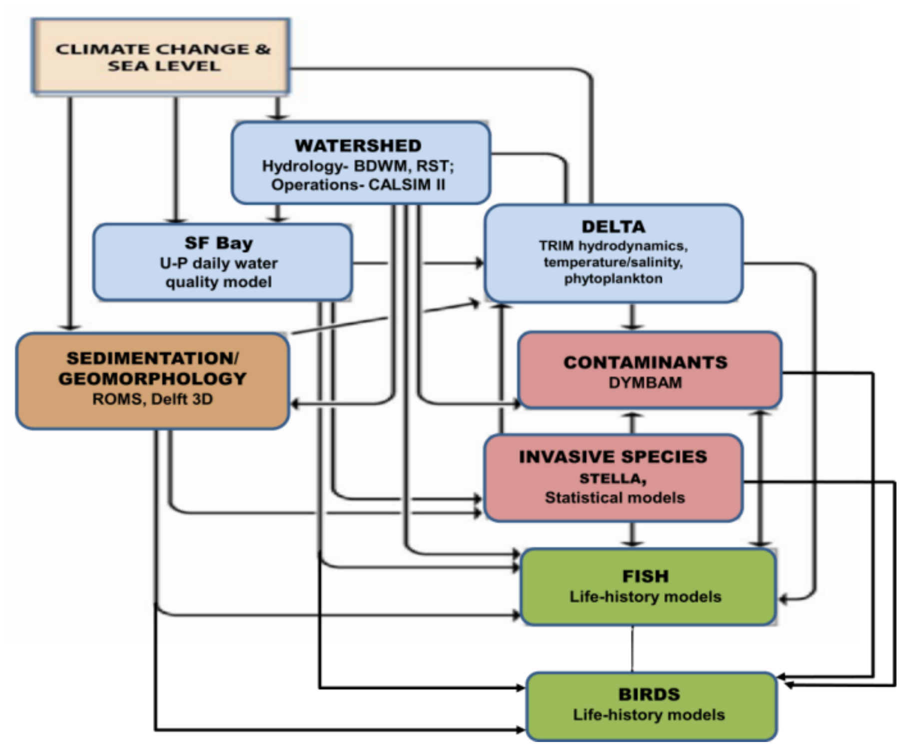

Figure 21. The CASCaDE conceptual model incorporating additional effects on birds

- **Geomorphology and sediment dynamics**

Initial steps of hydrological modeling can use current bathymetry and topography to explore the effects of sea level rise. The goal is to determine the overall availability of different depth ranges as sea level rises and intertidal habitat disappears. However, increasing wave reflection from hard structures would eventually increase erosion of the flats, and these potential bathymetric changes will also need to be modeled.

Methodologies for quantifying intertidal habitat change resulting from climate change and sea level rise can be developed based on modeled shoal changes for Suisun Bay (Ganju and Schoellhamer 2010). These simulations showed an increase in erosion of intertidal areas when a base-case scenario was compared with a scenario of warming, sea level rise, and decreased watershed sediment supply. Intertidal areas can be delineated from historic surveys, and change in tidal flats can then be quantified using recent light detection and ranging (LiDAR) surveys. Parameters that affect tidal flat change can be identified in order to determine the spatial distribution of wave energy, tidal currents, and sediment availability in the current system. Estuarine geomorphic numbers can be established for San Pablo Bay and the South Bay based on mud flat change over time. Hydrodynamic and sediment transport models can further refine these models.

- **Role of 1D, 2D, and 3D models**

Stratification of modeling scales and complexity are essential because the time to run the large scale, fully 3D models prohibits a large number of long-term simulations. The influence of sediment size, tidal range, and wave exposure should first be assessed at locations with characteristic profile shapes from around San Francisco Bay. Distilling to 1-D profiles of wave attenuation is very informative for determining how sea level rise affects the wave and the marsh. Looking at simplified models of profile behavior will be helpful in determining the key driving processes. The profile shape of accretional vs. erosional mud flats will influence sediment dynamics and sea level rise effects. When there is large tidal range and wave energy, the convex up shape is favored, indicating erosion. It will be important to capture different topologies, shoreline types, and the full transition from tidal flat to vegetated marsh, in order to assess how they will be affected by hydrological changes. Developing this tool to look at cross-shore behavior and marsh response will be useful in parameterizing the larger model. Sensitivity analyses should involve waves, sediment types, tides, upwelling, and vegetation response.

Ultimately, the Delft3D modeling system can be used to investigate sediment transport, hydrodynamics, and morphological change. A combination of the Delft 2DH (Roelvink et al. 2001) and 3D (Lesser et al. 2004, Winterwerp 2001) coupled hydrodynamic, sand and mud transport models and morphology models within the Delft3D system (http://delftsoftware.wldelft.nl/index.php?option=com_content&task=view&id=109 and http://www.wldelft.nl.soft/d3d/intro/) can assess likely changes to the intertidal, and because of its influence on the intertidal, the subtidal. Changes in depth, due to sediment redistribution, and sea level rise, alter the distribution of available habitat. Freshwater inflows and sediment supply are simulated from down-scaled GCCM output and combined with sea level rise and estuarine hydrodynamics to estimate likely future geomorphic change (Ganju et al. 2009; van der Wegen et al., accepted). These models are informed by research on historical intertidal changes in the northern San Francisco Estuary (Jaffe et al. 2007, Jaffe et al. 1998, Capiella et al. 1999). The same data also allow calibration and validation of the geomorphic models. GIS tools will be developed that integrate with the avian foraging model.

- **Addressing limitations of geomorphic models**

There can be variability in the accuracy of geomorphic models, because models are often conducted at a course resolution and some factors are not accounted for. For instance, critical sheer stress for mud can vary 20 percent over a year and from place to place (D. Roelvink, pers. comm.). The shape of the mudflat must be considered, however there is high variability and seasonality between locations at a fine scale. In addition, how sediment spreads out and is transported into salt pond restoration and tidal marsh areas can be difficult to accurately characterize. The calibration of the past is also not a guarantee for predicting the future, however focusing on scenario modeling can help to deal with uncertainty.

Detailed shoreline and levee data is needed to improve map accuracy and resolution. Refining shoreline extrapolation and calculating levee geometry (i.e. height, width, and shape) could be accomplished with the new LiDAR survey being flown with 1-meter resolution. In addition, the San Francisco Bay Conservation and Development Commission is considering a transportation vulnerability assessment focused on specific sub-regions of the Bay, which could also help in obtaining more accurate shoreline information.

- **Involving management approaches with sea level rise scenarios**

In addition to sea level rise scenarios, any modeling of habitat change must also incorporate management scenarios. Determining habitat suitability will need to account for realistic possibilities of how management will proceed. Developing color-coded maps for degree of sea level rise effects could be a first step. Although there may be some disagreement on accuracy, it could help in initiating a discussion regarding current and future management activities. Map have been created for other hazards (i.e. coastal erosion, tsunamis, hurricane surges) and the coloration of hazards can be used to show the degree of potential influence. The scenario approach is useful in determining the effect of human inhabitation, such the incorporation of water conveyance systems in CASCaDE I. Future hydrodynamic models will need to incorporate the future location, height, and condition of levees, as well as potential impacts of deepened shipping channels that could result in increased tidal prism and salinity intrusion.

b. AVIAN ECOLOGY MODELING:

- **Invertebrate response to changing physical conditions**

Spatially-explicit geographic information system-based analyses (ArcGIS, ESRI Systems, Redlands, CA) can be used to map expected macroinvertebrate densities in response to changing physical conditions. Model simulations determine how sediment and morphological changes may affect community composition and availability of food resources. CANOCO 4 (ter Braak and Smilauer 1998) can be used to perform canonical correspondence analyses (CCA; ter Braak 1986, ter Braak 1988) in order to reveal gradients in species composition and relate log-transformed macroinvertebrate abundance values to environmental variables (i.e., salinity, bed elevation, sediment grain size). The Benthic Atlas (Rowan et al., in prep.) can be used to assess spatial variability in invertebrates and elevation effects.

There are some difficulties in discerning interannual and seasonal variability in invertebrates due to the presence of external forcing factors and the complexity of phytoplankton dynamics. Although the magnitude between years fluctuates, similar patterns of rapid population declines are seen each year. Invertebrate biomass is driven by phytoplankton; however predation influences the crash of benthic populations. Oceanic upwelling events drive nutrient availability, and increased food availability encourages migration of additional predators (i.e. fish, shrimp, crabs) into the bay. Hindcasting long-term climate fluctuations with phytoplankton and invertebrate trends would require adequate historic data; however the prey data to analyze flyway-wide connections between different systems is limited. Because the current benthic system has changed many times, it is difficult to identify what invertebrate population is the norm. Seasonal patterns in San Pablo Bay are predictable due to bird predation, and there is data of invertebrate trends going back to 1986. However, patterns in the South San Francisco Bay are more difficult to determine.

Larger landscape factors have an influential role on invertebrate distribution and abundance in shoal habitats, therefore large spatial scales will be necessary to model annual changes in benthic communities relative to hydrology and phytoplankton. Models of ocean systems and data on upwelling can be used to assess changes on productivity should also account for larger scale fluctuations (i.e. El Nino and NPGO). The Delft-UNSTRUC model will include bivalves and phytoplankton dynamics as part of CASCaDE II. Pulling scenarios out of global climate models would be useful to resolve critical forcing factors affecting food source variability across the flyway. Furthermore, because shoals and wetlands are connected as part of a habitat continuum, modeling of invertebrates should also involve wetland dynamics. Wetlands influence the population dynamics of shoals by acting as nurseries for biota, such as amphipods, isopods, and fish.

Experiments on predator exclusion will be necessary for separating the effects of water depth and tidal inundation regime from predation effects. Because predator foraging activity is also influenced by water depth, it is unclear whether predation is creating this gradient or the invertebrates themselves are responding to water depth. Predator exclusion pens can be designed to remove particular predators or the predation component altogether. Analyzing patterns of prey size can also help to tease out the effects of different predators on invertebrate populations.

- **Avian response to geomorphic and invertebrate change**

Suitability of avian habitat needs to be defined by both prey and physical characteristics (i.e. water depth, sediments, slope, salinity, inundation regime). Water depth and the movement of the tidal line influence the available foraging time and accessibility of prey, while inundation/exposure and salinity are the biggest factors in determining invertebrate and prey distribution. The linkage between the physical environment (i.e. tides, water depth) on invertebrates will drive responses of avian predators. Prey quality, abundance, distribution, and accessibility will all influence bird carrying capacity.

Although foraging ecology modeling approaches are well developed, there is great variability in the types of models that are utilized. The life history of the species must be considered, and therefore models are variable by system. There is not one equation or principle universally used to progress to the next step, and model verifications are an essential part of the process. Looking at pathways of causation and using a correlation based approach are important in determining the key factors influencing bird abundance. The modeling process should also identify colinearities and confounding factors. Because invertebrate distribution can be difficult to predict, it is important that models account for all physical factors that may influence prey abundance, distribution, and accessibility to avian predators.

- *Modeling of Physical Habitat:*

Predictions of sea level rise relative to geomorphic change can be used to model the change in fine-scale tidal flat habitat for foraging shorebirds and the amount of shoal habitats at suitable water depths for foraging waterfowl. For diving ducks, both the energy cost of diving and the thresholds for diving depth are variable by species and will need to be considered.

Geographic information system-based analyses (ArcGIS, ESRI Systems, Redlands, CA) can compare the current and projected extent of shoal habitats through the next half century with knowledge of foraging ecology of migratory birds to estimate likely functional and numerical responses to alteration of their foraging resources. Spatially-explicit habitat suitability models or indices (HSI) involve factors influencing different groups of birds in order to determine degrees of suitability of specific areas. Because invertebrates are difficult to predict from year to year, models should focus on the spatial distribution of habitat. The percentage of shoals that are available and accessible for specific periods of time can be modeled according to species and/or guild. The number of acres at certain elevations and how moving water lines will change according to profile shape, slope, and tide will need to be determined. Landscape influences on the suitability of foraging sites, such as proximity to suitable roosting and nesting habitat, will also need to be assessed using spatial analyses.

Incorporating prey distributions as part of a habitat-based approach may be difficult with poor spatial prediction of invertebrates. A full 2-D spatial description would be necessary; however invertebrates are subject to regular fluctuations. The Benthic Atlas is the first step in locating benthic invertebrate concentrations, determining density and abundance of prey species, and can help in identifying important prey items by what is depleted first.

Initially using 1-D vertically integrated models can be very informative, and, where alongshore variability is small, can sometimes be used to mimic a 2-D or 3-D model. Slope and water depths along transects of shoreline types will be critical in 1-D models in order to predict bird response. 1-D models can be useful in determining a threshold of mudflat loss where bird use can no longer be supported, because the time the mudflat is accessible becomes too short to maintain daily energetic requirements. The first step is to develop relationships in 1-D models, and once modeling of geomorphic responses to sea level rise has been completed, those relationships can be applied to larger 2-D and 3-D models.

Probabilistic depth-distribution by cell can help in representing more complex small-scale topography. Variation in microtopography within a cell influences the movement of the tide line, water depths, and fine-scale prey and predator distributions. Because shorebirds are more refined in the habitat that they use, subgrid modeling should focus on near-shore areas.

- *Hindcasting causes of bird decline:*

Although a better understanding of historic conditions (benthic change, invertebrates, and disturbance) is necessary, it can be possible to hindcast causes of bird decline and changing habitat use patterns by analyzing more recent bird, invertebrate, and hydrological data over the last decade. Beyond that, historic bird numbers are also questionable, because transects in mid-winter aerial surveys were only developed more recently. Reproducing the past can help to determine what is driving trends and will assist in modeling future scenarios. Bird habitat utilization can be predicted based on benthic conditions in recent years, by modeling the influences on spatial variability of food sources from the Benthic Atlas (Rowan et al., in prep.). Habitat conditions that cause changes in invertebrates are driving factors of bird response. When a sufficient energy source is not available, birds will leave the area.

The USGS Western Ecological Research Center has conducted studies on the foraging ecology of migratory birds in San Francisco Bay for over 20 years, and there is data on bird declines along with benthic conditions in recent years. Extensive datasets exist on foraging behavior, detailed shorebird and invertebrate prey surveys have been conducted through the USGS Shoals Project, and there is knowledge of the current and past baywide distribution of migratory waterbirds (Takekawa et al. 2001, Takekawa et al. 2002, Warnock et al. 2002, Takekawa et al. 2006, Hickey et al. 2007, Takekawa et al. 2009). Presence-absence and density of surf scoters have also been modeled relative to habitat distribution. Next steps are to add details to models, such as the factors of disturbance and management, and then incorporate them into larger-scale models.

- *Carrying capacity modeling*:

Models of carrying capacity assist in determining the current baseline resource value in the estuary, which helps to estimate how bird populations will be affected by changing conditions. Carrying capacity models are parameterized with information from both prey-based and habitat-based models. They eventually determine the maximum number of bird days that can be supported by the supply available at a particular site. Threshold prey densities for species or guilds are determined through carrying capacity models, and modeling should account for all competitors (i.e. fish, crustaceans, rays, sharks) influencing their shared prey base. Next steps will need to involve fish biologists in order to assess how climate will affect fish communities and predator-competitor interactions. Models of carrying capacity have recently been developed for diving ducks of San Pablo Bay Shoals (Figures 17 and 18, Lovvorn et al. in prep., Lovvorn 2010), as well as small sandpipers on the Dumbarton Shoals (Figure 22, Rowan et al. in prep., Rowan 2010). A structured equation model can also be created based on invertebrate and bird data currently available for the Dumbarton Shoals.

Another important consideration is that habitat provided by former salt ponds growing new marsh is providing valuable transitional habitat that may be lost if fully restored to marsh. Steps are currently being made to determine the energetic value of salt ponds. The availability of salt pond habitats is currently supplementing the carrying capacity of the flats for shorebirds, therefore future carrying capacity predictions will need to account for decreased habitat availability as these ponds transition into mature marshes.

The carrying capacity of San Francisco Bay is independent of the flyway, but it has become a limiting factor for many migratory populations. The system is food limited and the resource value goes to zero very fast in some areas. Models provide the capacity of the bay (number of bird use days in a year), however they do not provide information on population and reproductive response. Body condition influences flyway decisions and breeding success, and bird presence alone may not be indicative of actual suitability and health. These lag effects across years are not included in carrying capacity modeling.

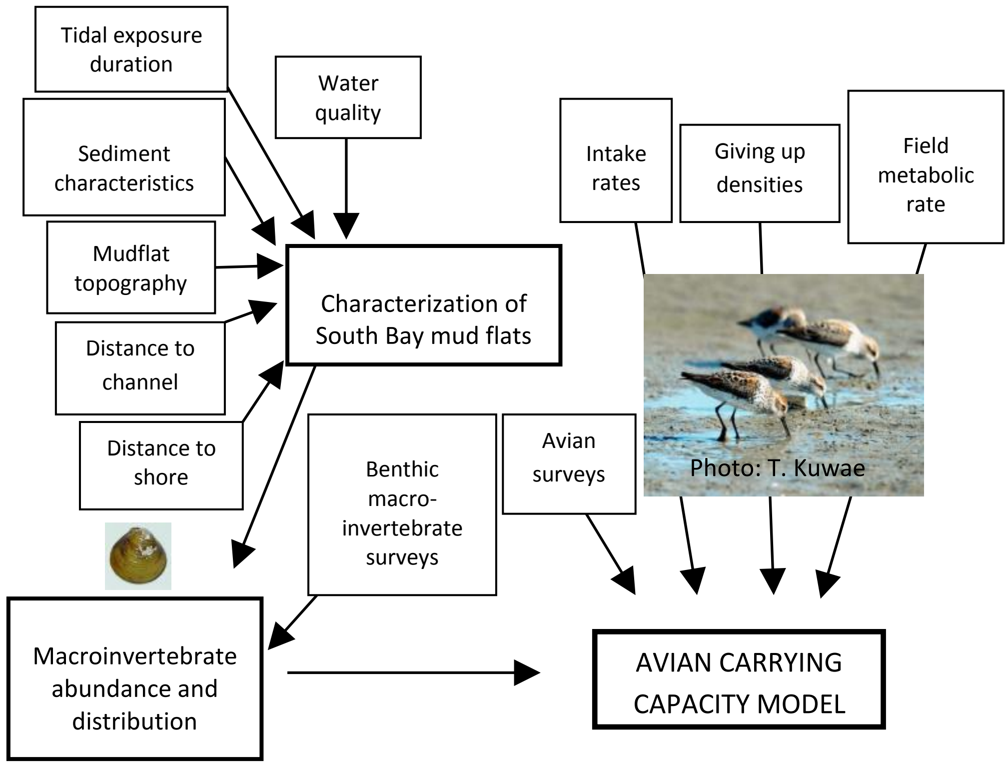

Figure 22. Parameters used to estimate carrying capacity for small sandpipers in the Dumbarton Shoals (Rowan et al., in prep.)

o *Final metrics to guide management*

Ultimately, there are several key metrics that can help direct management. It will be important to map the area and distribution of suitable habitats, both current and predicted into the future. Once the baseline resource value of this estuary is determined through carrying capacity modeling, the ability of management to hold that resource in light of predicted habitat changes can be assessed. However, unlike the agricultural systems in California's Central Valley, the ability of man to manipulate food and prey in the San Francisco Bay is somewhat limited.

It will be essential to identify the tipping points or thresholds for system change and when they might occur. Sensitivities to different scenarios from physical models will need to be incorporated into avian models, and this would also help to narrow down the important parameters. Bird counts can be a final metric in assessing whether minimum energy requirements are available for birds to stay in an area and under what conditions foraging costs become too high. This mechanistic approach can look how much a hectare could support and use total numbers of hectares to get bird numbers.

8) **SPATIAL SCALES:** Different spatial scales are necessary between biological and physical models. In general, larger spatial scales are necessary to model hydrology, geomorphology, phytoplankton, and changing benthic communities from year to year.

- **Resolution (*GRID SIZE*):**
  - *Geomorphic models:*
    - Suisun Bay Model (Ganju and Schoellhamer 2010): 200m square resolution, with smaller grids in certain areas
    - The Delft Model: 10m resolution for the finest unstructured grid size, with one model time-step limited by the most critical cell
    - Structured vs. Unstructured grids:
      - Structured grid modeling can involve step-wise nesting within grids to capture details in zones (i.e. near-shore), but does not always represent geometry accurately.
      - Unstructured grid modeling can be more flexible in how nesting is done in specific areas, but is more computationally intensive.
    - Limitations of large grids:
      - Variability in mudflat shape
      - Additional variability and seasonality between locations at fine-scale
      - Course scale models are less accurate for specific areas
  - *Invertebrate data:*
    - More limited by spatial scaling compared to geomorphology
    - Generally less dense than 100m grid spacing at Dumbarton
  - *Bird responses to water level changes:*
    - High resolution needed to assess shorebird response to water depth changes.
    - Shorebirds and invertebrates follow edge of tide line
    - Availability of food (invertebrates and biofilm) influenced by fine-scale movement of tidal line
    - At Dumbarton, a 10cm different over a year of water level data led to 5% change in inundation time
  - *SUBGRID MODELING:*
    - Possible by embayment
    - Cell-by-cell analysis is more accurate in areas where data was collected
    - Important when including marsh

      - Small creeks/channels that flood marshes must be parameterized in 2D model
      - Look at interaction of vegetation and mud
      - Small areas like Corte Madera could have this final resolution
    - Focus on near shore areas
      - Shorebirds are more refined in the habitat they use (compared to waterfowl)
      - Determine fine-scale distributions and variation in microtopography.
      - Variation in microtopography within a cell (influences movement of tide line, water depths, and fine-scale prey and predator distributions)
      - 1980s-90s bathymetry data goes up to 5 ft. above MLLW, and gap was interpolated to shore (100m horizontal)
      - Refine shoreline extrapolation with new LIDAR and re-determining mean high water line. Test data for NOAA LiDAR should be available by January 2011.
- **Modeling Scale:**
  - <u>*Bay-wide analysis:*</u>
    - Done from Point Reyes to Delta
    - Could specify boundary conditions
    - Important to use larger models/maps to see general trends
    - Larger scale is important for hydrology and geomorphology:
      - Freshwater signal is from Delta to San Mateo bridge
      - Delta sediments are still important for the entire South Bay
    - Phytoplankton modeling needs a larger scale, because of advection
    - SPB Delft model went from ocean to delta and was easier than boundary conditions of smaller model to San Pablo Bay
    - Could have a diffusion process between different types of models (channels, shoals)
    - Incorporate scenarios of salt ponds with sediments and hydrology
  - <u>*Sub-bay analyses:*</u>
    - Biological forcing factors are at the scale of embayment
    - Bird dynamics are specific to sub-bay. Different prey densities and species compositions influence bird response.
      - Sub-bay analyses could still be run simultaneously
      - *San Pablo Bay:*
        - Shoals/flats are wider
        - Hydrology models are more well developed
        - Good reach of grids
        - May be appropriate for sub-grid analysis
        - More ducks
      - *South Bay:*
        - Smaller shoal area
        - Shoals Project is currently underway
        - More shorebirds

        - Prey data north of the San Mateo Bridge is very sparse
        - 2-year baseline invertebrate data prior to changes in Alviso salt ponds
        - Shorebird data available off of Eden landing
        - Sea level rise effects could be more severe due to land management needs in the region
    - *Local site analyses:*
        - Assess locally for fine-scale modeling
        - Involve a refined nested grid
        - Appropriate scale for managers who are interested in effects to their distinct local area. However, if models are too specific, inaccuracies may be common.
        - Identify profile areas:
            - Characterize the different types of shoal environments according to distinct characteristics and similarities between profile shapes
            - Determine 5-6 keystone profiles of bay to marsh
            - Map size and location of different shoal types
            - Run over sea level and wave profiles
            - See how they change under a variety of scenarios (sediment, bathymetry, upwelling, etc.) over the next 100 years
            - Scale up to see how species would utilize habitat
        - Conduct location specific modeling to assess bird carrying capacity and response to habitat change:
            - Determine dynamics of prey density on wide shoal vs. narrow shoal
            - Collect bird and invertebrate data on mudflats of different sizes and slopes
            - Identify different predator/competitor dynamics between locations

9) TEMPORAL SCALES:

- **Predictions of morphological changes:**
    - Use short-term scenarios now
    - Project future with long-term morphology changes
        - Determine what is most reliable to predict long-term changes
        - Do future projections with acceleration factors
        - Box model types for decadal scales
        - Geomorphic scale should be over 100 years
- **Operational (day to day) modeling:**
    - Get daily feedback (i.e. PORTS or ROMS models)
    - Shorter time period, so computational time is realistic
    - Identify key parameters for long-term modeling
    - Comparable modeling for birds?
        - May be difficult because data collection is so time intensive

        - Could get signals with a week prediction time, and then check to see how birds respond
        - Adaptive modeling would inform management at a small scale
- **Seasonal variability in birds and invertebrates:**
    - Narrow the scope to be season specific:
        - Determine the most limiting periods (winter, migratory stopovers)
        - Possibly eliminate summer from the model, because birds are not there
    - Track one season over time:
        - Look at seasonal variation in hydrodynamics
        - Focus on simplified 1D tidal flat profile for specific season (tides and waves)
        - Interannual variability of sediments will set the profile (seasonal vs. long-term changes)
        - Sediment is cumulative, so whole year still needs to be included. Annual sediment is related to watershed inputs.
        - Ocean conditions would need to be nested (time series through the winter and inputs to the Bay)
- **Daily and Seasonal Timing of Tides and Effect on Communities:**
    - *Tides relative to sunlight and primary producers:*
        - Changes in the phasing of ebb tide and sunlight over this century could result in altered dynamics of phytoplankton and biofilm. The high tide cycle changes over the decadal scale relative to the day/night cycle.
        - The 50-100 year tidal cycle can be assessed according to phasing of daylight.
        - Increased high tide spillover at night could result in lowered water temperatures.
    - *Tides relative to wind and wave action:*
        - Different wind and wave patterns at high tides would influence geomorphic change through sediment redistribution.
    - *Diurnal and nocturnal foraging activity and habitat availability***:**
        - Evidence that birds feed at night (telemetry, videos documenting consumption rates by measuring bird output- Kuwae), however it is poorly understood.
        - Increased disturbance during the day can create unavailability
        - Unavailability can cause birds to feed at night
        - Different predators and levels of predation between day and night
        - What happens if best low tide foraging shifts to night?
- **Management timeframe:**
    - LCC time-scale has not been determined yet
    - 30-year time scales are feasible and help to inform management decisions

10) MODEL INTEGRATION

- Use linked computational models with a high level of communication across disciplines, similar to integrating models in CASCaDE.
- Synthesize different modeling efforts according to interfaces with specific ecosystem processes.
- Focus on systems with as much available data as possible
- Start with what needs to be predicted first. Model physical processes and then move up to invertebrates and birds.
- Determine appropriate model domains, resolutions, and approaches
- Finalize inputs/outputs for each of the physical and biological models
- Integrate models by using the same spatial and temporal scale
- When working with different scales and subgrids, the process needs interlinking so it behaves reasonably. Limited by understanding of process interactions and computer time.
- Identify models that allow for nested parameters.
- Develop profile models for both physical parameters and birds. Start with less complexity by creating early bird products using 1D vertically-integrated models.
- Blend the physical and biotic models and run sensitivity analyses to narrow down the important parameters.
- Parameterize energetic and carrying capacity models with additional habitat-based data
- Develop indicators at each of the modeling steps (hydrology to geomorphic to invertebrates and birds)
    - Critical to know threshold values at the beginning
    - Determine when indicator is reached
    - Do long-term monitoring of key parameters (e.g., days exceeding a temperature threshold for watershed models)
- Due to a wide-range of uncertainty, scenario-based runs of potential inputs creating a range of outputs would be more appropriate than direct predictions
- Conduct modeling often and put results out often, so a large group of people can regularly test model reliability
- Address the issue of tidal datums in determining periods of exposure
- Identify all model constraints before integration

11) NEXT STEPS

- Develop targets on types of models to try initially
- Determine which models are separate and which will need to be integrated
- Determine grid size, time steps, and specific parameters needed from each party
- Fine-tune predictions of water depth in order to move forward with specifics of bird and invertebrate response:
  - Determine relative changes in water depth, with the interaction of sea level rise and erosion vs. accretion in certain areas
  - Determine area of water depths, extent of inundation, etc.
- Categorize dominant type localities of shoal/mudflat around the bay (vertical marsh faces, sloping, terraced) and determine proximity to a certain type
- Feed profile models with time series of wave height, sediment concentration, water level, flows, wave stirring, and then involve invertebrates so that the bird models could be more accurate
- Model percentage of shoals that are available/accessible for specific periods of time
  - Number of acres at certain elevation
  - Movement of water line according to profile shape, slope, and tide
  - Look at how channel widens/deepens and influences the shape and slope of the flat
- Create product based on phasing of tides and daylight, and determine how this intersects with invertebrate activity and bird foraging behavior
- Conduct spatial analysis of proximity to roosting and nesting sites using GIS
  - Cost of distance to roost area can be included in energetic models
  - Incorporate into habitat-based model
- Evaluate how restoration projects are affecting the benthic invertebrate community
- Continue modeling work of determining salt pond value energetically, and evaluate the feasibility of combining flats and salt ponds in an energetic model
- Involve fish biologists:
  - How will fish communities be affected by climate change?
  - How will that influence predator and competitor interactions?
- Involve managers to determine the range of potential management options to include in models
- Identify data gaps that may be difficult to fill in
- Build on components of CASCaDE II
- Finalize modeling roles and responsibilities
- Hold a future modeling workshop:
  - Include a field trip to the mudflats
  - Iron out modeling specifics with a funded project
  - Involve managers in identifying trigger points

III, METHODOLOGY FOR QUANTIFYING KEY METRICS OF HABITAT CHANGE

An important step in assessing the likely response of shoals habitats to sea level rise and climate change is to develop a methodology for quantifying key metrics of habitat change from model results. Here we focus on the physical metrics which in turn, influence the ecology of the habitat. We used the existing shoals modeling grids of Ganju and Schoellhamer (2010), which were generously provided by Neil Ganju, as a basis for the first step in developing such a methodology. In addition, discussions on modeling approaches and metrics of habitat change at the October 26-27 workshop focused our approach.

Ganju and Schoellhamer (2010) estimated geomorphic changes in Suisun Bay, CA, by comparing a simulation of present-day conditions to three future scenarios using the Regional Ocean Modeling System (ROMS), a tidal-timescale hydrodynamic/sediment transport model. The three future scenarios were (1) sea-level rise and freshwater flow changes of 2030; (2) sea-level rise and decreased watershed sediment supply of 2030; and (3) sea-level rise, freshwater flow changes, and decreased watershed sediment supply of 2030. Although the results of the Ganju and Schoellhamer study are both insightful and relevant to potential shoals habitat change in the future (see Figure 23 for example), the specifics of the study are not pertinent here. What was however, of great benefit was using actual output from a study that modeled long time scales to develop realistic approaches for identifying metrics as well as potential challenges.

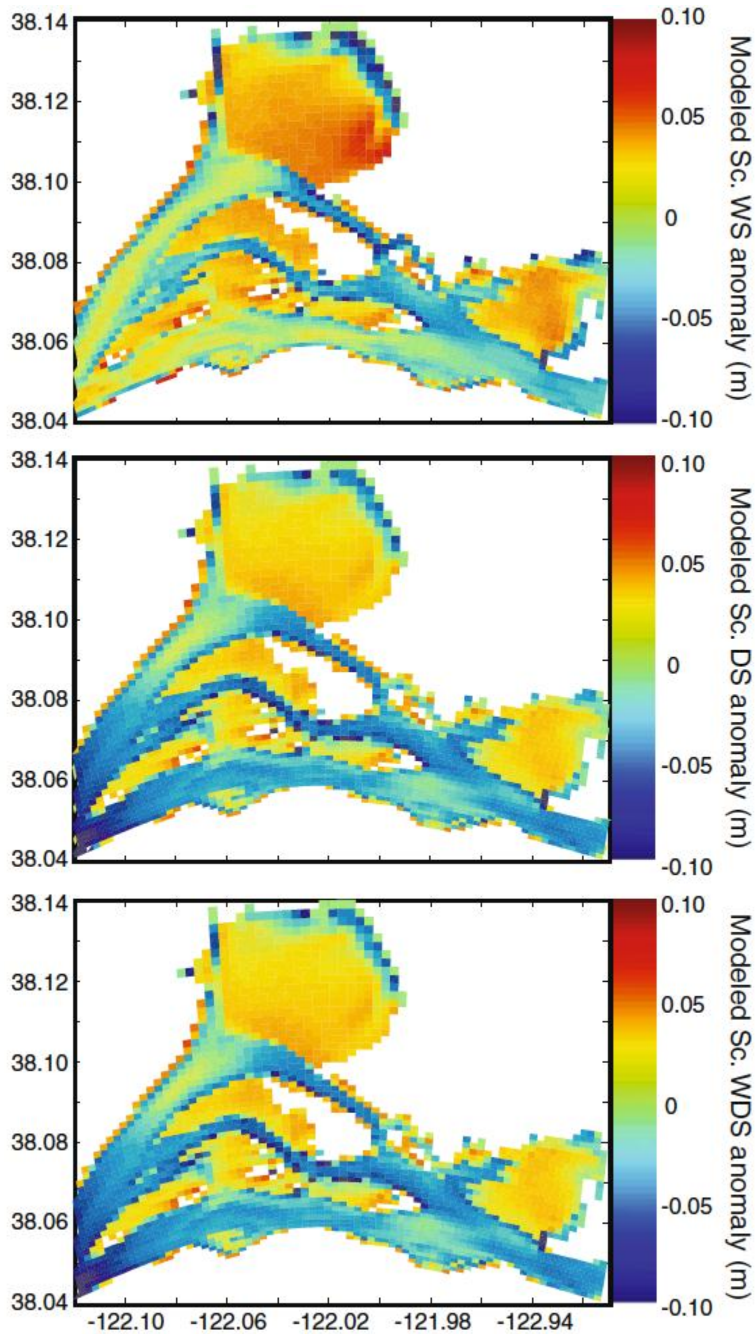

Figure 23. Anomalies of bathymetric change for three scenarios (top panel: warming and sea level rise; middle panel: decreased sediment supply and sea level rise; bottom panel: warming, decreased sediment supply, and sea level rise) relative to a base case (Fig. 5 from Ganju and Schoellhamer, 2010). Note that the coarse grid size was necessary for computational efficiency because of the long-term simulations.

We received the Ganju and Schoellhamer model output as MATLAB files. MATLAB is a common tool that modelers use to analyze and display their results. The first obstacle we encountered was transferring data from a curvilinear orthogonal grid (used by both the ROMS and DELFT3D models) to ArcGIS. ArcGIS requires either uniform rectangular grids or point data. Although this transformation is possible, care must be taken when choosing the ArcGIS grid size and conversion technique. The grid size must be small enough to capture the spatial variability of the curvilinear grid while minimizing potential interpolation error from restructuring curvilinear data (or grids) into rectangular coordinates (used by ArcGIS). This is not an insurmountable obstacle, but again, care must be taken when performing the transformation.

The second obstacle to characterizing metrics that either describe or influence habitat change is selecting an optimal model resolution or grid size for the task at hand. The Ganju and Schoellhamer grid cells are relatively coarse (Figure 24), ranging from 72 to 593 m on a side, because of limitations in computer speed that make runs with small grid cells take days or weeks for modeling the long (decadal) time scales that are of interest. There is trade-off between using an efficient coarser model that runs faster and a fine-scale model that gives more detail on a metric's spatial variation but runs slowly. This competition is inherent in all computationally intensive models, not only the ROMS model applied by Ganju and Schoellhamer (2010). It is possible, however, to make many runs at lower resolution or using a 2D (either 2DH that depth averages or 2DV that contains depth variability along a profile) to learn the response of the system being modeled and, once the model is well constrained, perform the computationally intensive, longer 3D runs. Again, grid coarseness is an obstacle that can be overcome.

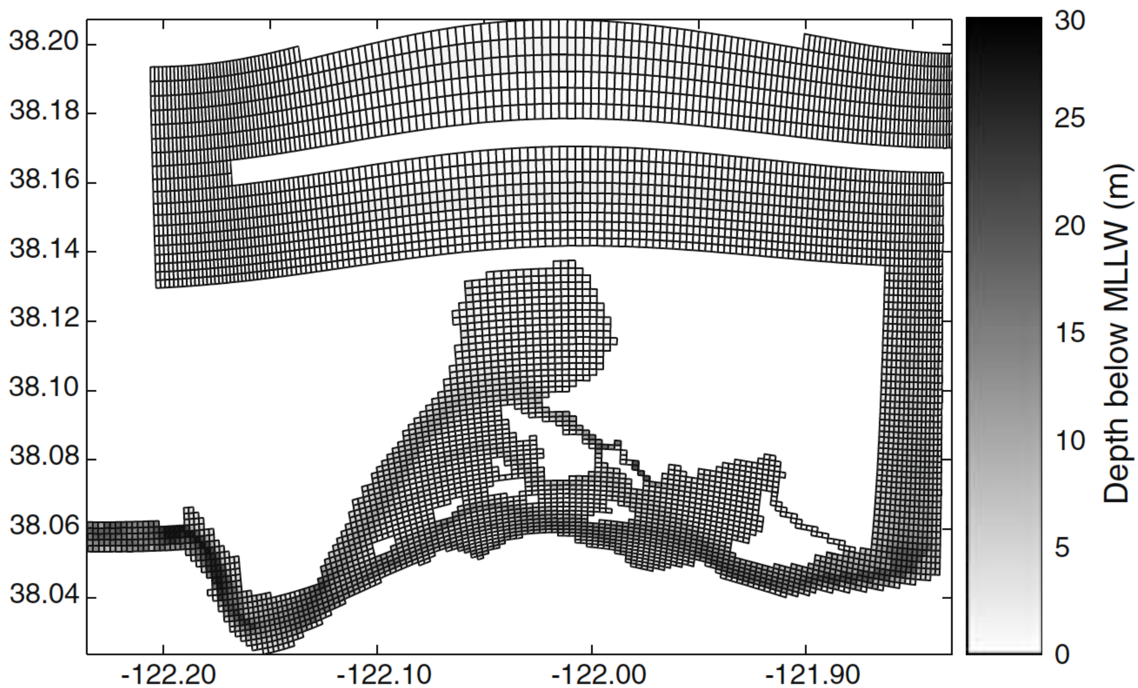

Figure 24. Ganju and Schoellhamer (2010) model grid (Fig. 2 from Ganju and Schoellhamer, 2010). Coarse grids derive from limitations in computer speed that make runs with small grid cells take days or weeks for modeling the long (decadal) time scales that are of interest. Coarse grids are typically used for modeling long time scales for large domains (e.g., Van der Wegen et al., accepted).

Models that use unstructured grids can decrease computation time and allow variable scale grid cells that can represent small scales where needed. Deltares and UNESCO-IHE, the Netherlands, are developing an unstructured numerical model (Unstruc or D-Flow) that includes both the Delta and the Bay and uses a finite volume approach. The unstructured grid is flexible allowing, for example, complex marsh channels to be easily included (Figures 25 and 26). The model is being applied to sea level and climate change scenarios in the USGS CaSCADE-II project (http://cascade.wr.usgs.gov/). Presently, the hydrodynamic component of the model is operational (http://cascade.wr.usgs.gov/reports/Mick_vanderWegen_101215.zip). An advantage of the model is that, when fully developed, it will be a coupled hydrodynamic/sediment transport/geomorphic model like its structured predecessor, DELFT3D (http://www.netcoast.nl/tools/rikz/delft3d.htm and http://www.wldelft.nl/soft/d3d/intro/). This coupling allows long-term simulations of shoals habitat change where morphology changes can affect hydrodynamics, turbidity, salinity, etc.

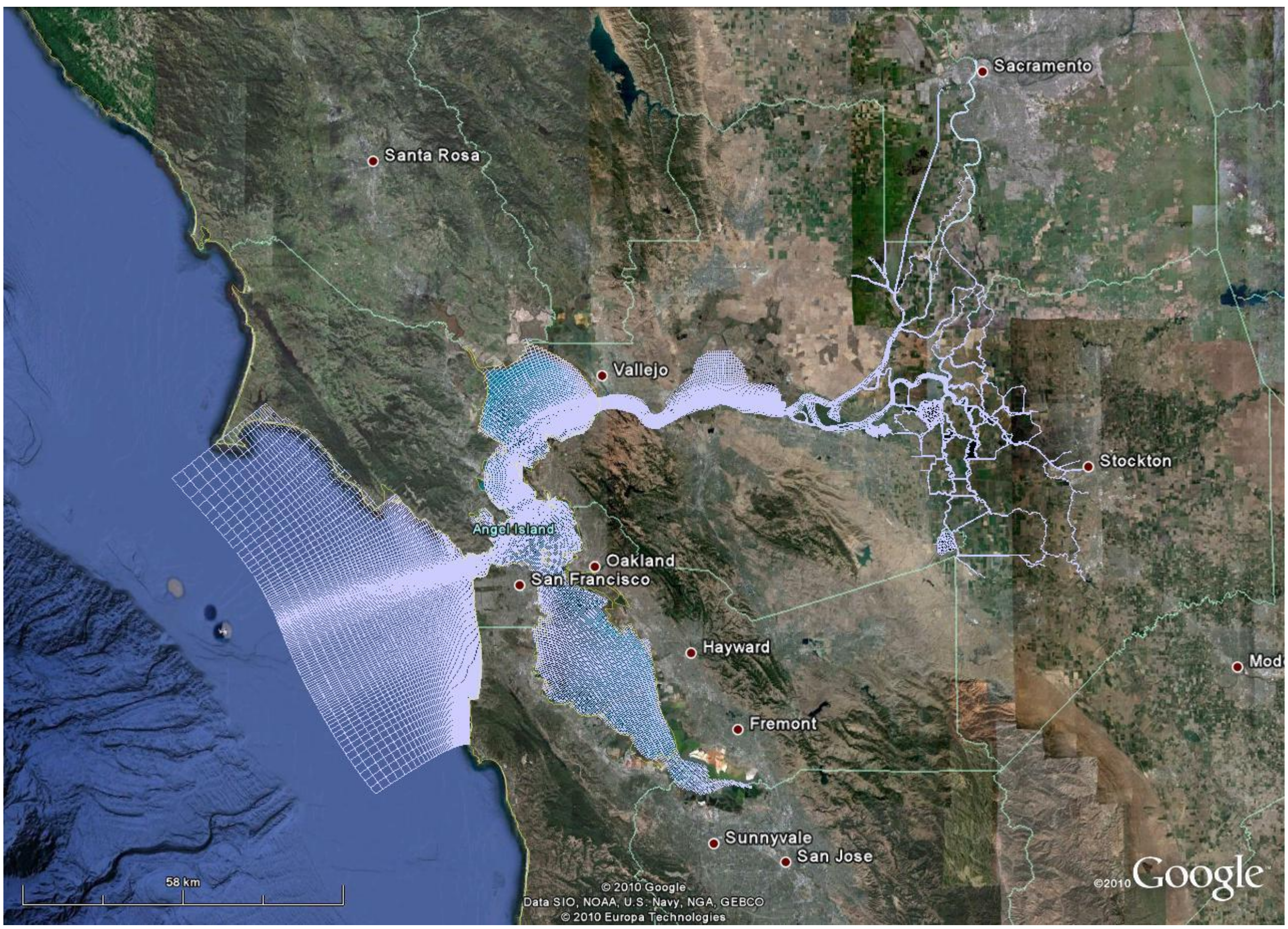

Figure 25. The Unstruc grid in the Pacific, Bay, and Delta. For more accurate modeling of habitat change in the Bay, refinement of the grid in shoals habitat is planned. A December 15, 2010 ppt presentation of the current state of development of the unstructured model is at http://cascade.wr.usgs.gov/reports/Mick_vanderWegen_101215.zip

Figure 26. Example of the Unstruc grid in the Delta. The irregular polygon shapes allow computationally efficient modeling of complex geometries.

Figures 27 and 28 summarize the steps in developing metrics from model output for scenarios runs. These flowcharts emphasize the value of a combined approach of using tools that are readily compatible with model output, such as MATLAB, and ones that are designed to exploit spatial information, such as ArcGIS. These flowcharts are a snapshot of our current thinking on how best to develop metrics of habitat change for scenarios such as sea level rise. Additional work is needed to fully develop optimal methodologies. The trajectory of this work is clear, however, and eminently doable.

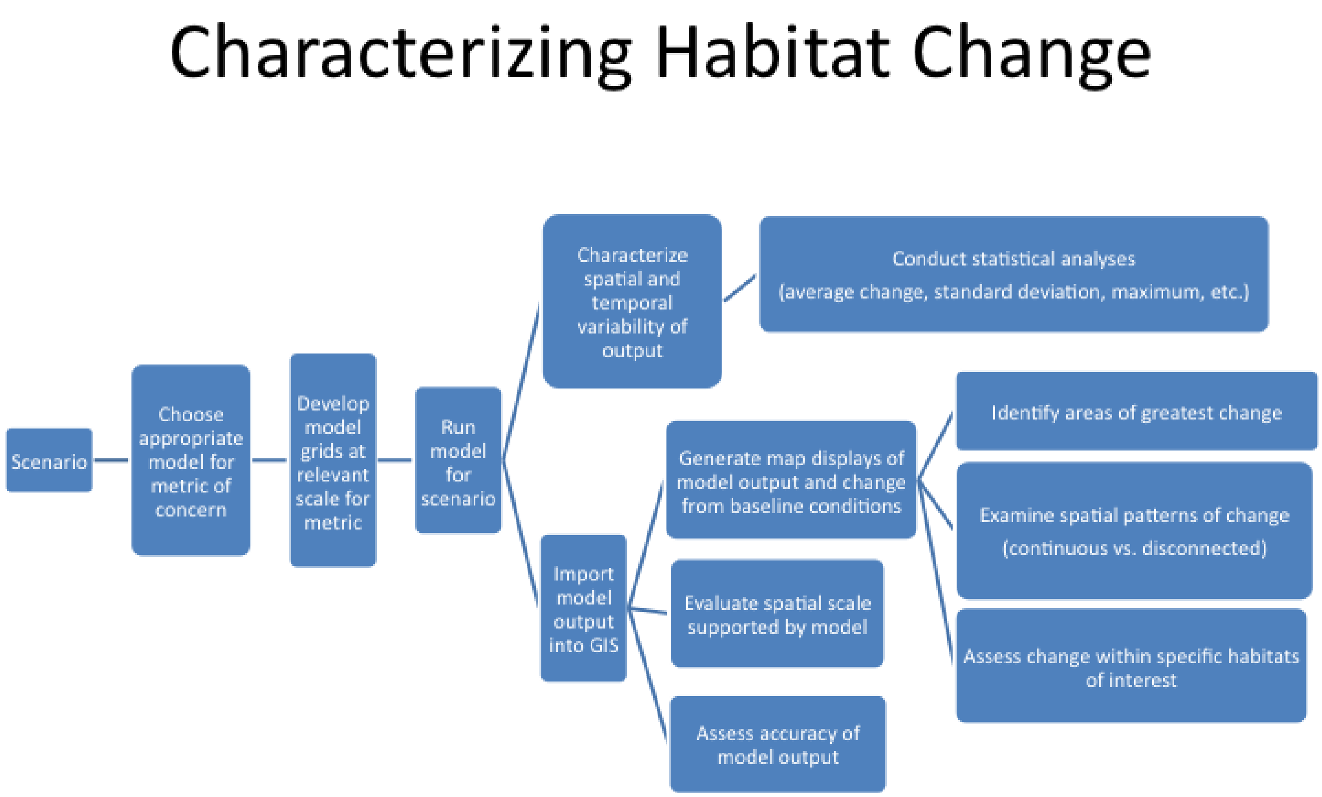

Figure 27. Flowchart for developing change metric from model output for a given scenario.

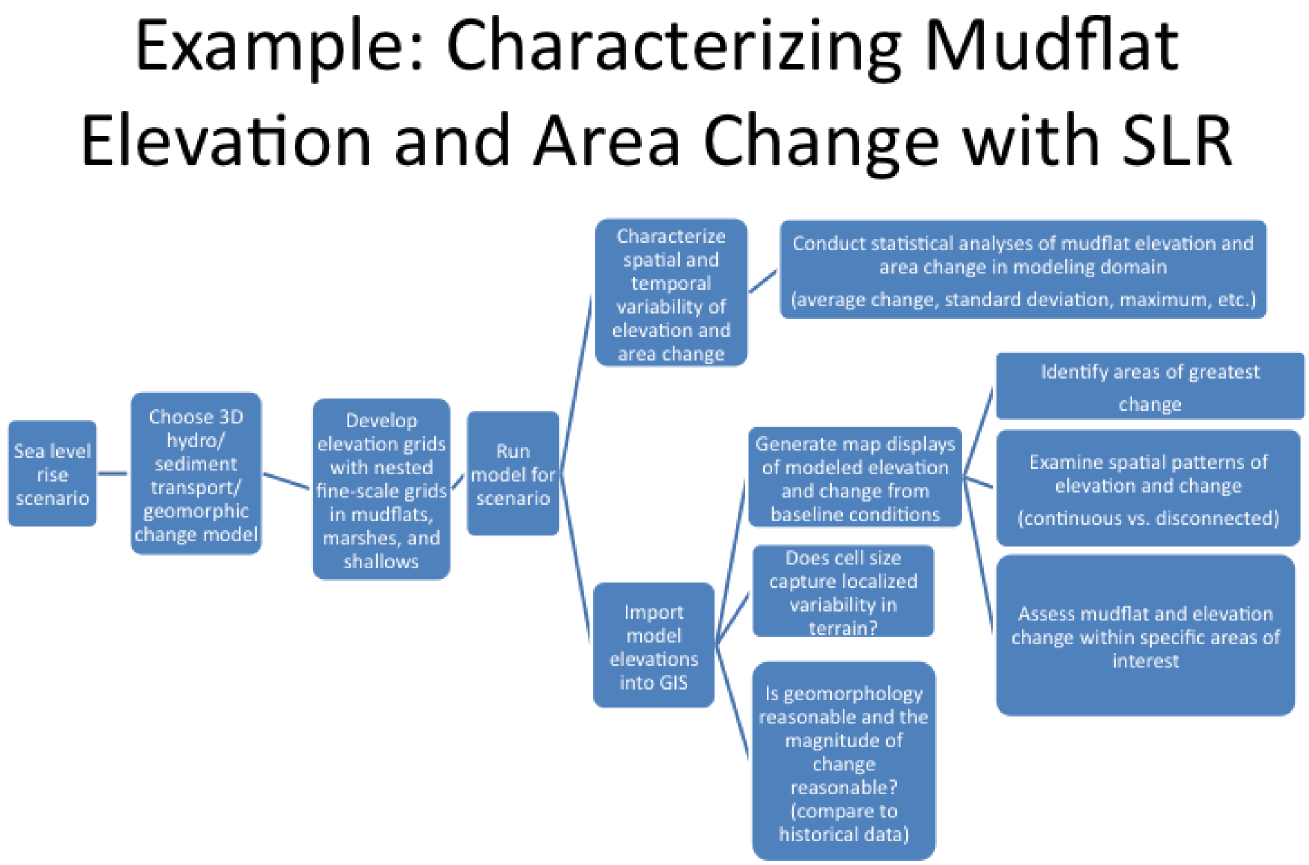

Figure 28. Flowchart for developing mud flat elevation and area change metric from model output from scenario of sea level rise

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IV. BIBLIOGRAPHY ON AVIAN FORAGING ECOLOGY OF MUD FLATS AND SHOALS

A comprehensive overview of research on shoal habitats and foraging birds was conducted to help guide future directions for modeling. Key information has been incorporated into a scientific review paper. The review discusses abiotic influences on avian food supply and prey accessibility, bird foraging responses to variability in prey resources, landscape influences on habitat suitability, effects of carrying capacity and ecological cascades, threats to mud flat and shoal ecosystems (i.e. climate change, contaminants, invasive species), the role of restoration and alternative habitats (i.e. salt ponds), and priorities for research and management. Relevant published research from around the world has been reviewed, however the general discussion relates to physical processes and habitat suitability parameters for avian species of San Francisco Bay shoals.

The following bibliography is broken up into primary topic areas: prey availability and avian response; shorebird foraging ecology; waterfowl ecology; general avian ecology; invertebrate dynamics; phytoplankton and algal blooms; dynamics of biofilm/microphytobenthos; submerged aquatic vegetation; top-down effects; nutrients and eutrophication; geomorphology and hydrology; landscape influences on habitat suitability; salt ponds and anthropogenically-altered wetlands; avian responses to habitat change, resource depletion, and carrying capacity; effects of global climate change; role of contaminants; effects of invasive *Spartina*; and disturbance factors.

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V. APPENDICES

A) WORKSHOP AGENDA

Tuesday, October 26, 2010 (Day 1)

9:00am – 9:30am: Welcome / Workshop Goals and Logistics:

Bruce Jaffe (USGS Pacific Coastal and Marine Science Center)
John Takekawa (USGS Western Ecological Research Center)

Introduction of Attendees

9:30am – 11:00am: **PRESENTATIONS**

- *Noah Knowles (USGS Menlo Park Center)*—CASCaDE and Modeling Sea Level Rise in San Francisco Bay
- *Neil Ganju (USGS Woods Hole Center)*-- Geomorphic Change in Suisun Bay Under Future Climate Change and Sea Level Rise Scenarios
- *Susan De La Cruz (USGS Western Ecological Research Center)*—Carrying Capacity Modeling of Diving Benthivores on San Pablo Bay Shoals

11:00am – 11:15am: *Break*

11:15am – 4:15pm: DISCUSSIONS

11:15am – 12:15pm: State of the Art of Geomorphic Change Modeling

12:15pm – 1:15pm: *Lunch*

1:15pm – 2:00pm: State of the Art of Avian Ecology Modeling

2:00pm – 2:30pm: Biophysical Interface between Physical and Ecological Models

2:30pm – 3:00pm: Key Model Parameters

3:00pm – 3:15pm: *Break*

3:15pm – 4:15pm: Spatial and Temporal Scales of Geomorphic and Ecologic Shoal Systems

4:15pm – 4:30pm: Impromptu Presentations by Attendees

4:30pm – 5:00pm: Summarize Accomplishments of Day 1 and Priorities for Day 2

Wednesday, October 27, 2010 (Day 2)

9:00am – 10:00am: Summary of Day 1 and Workshop Progress/Goals:

10:00am – 11:30am: PRESENTATIONS

- *Dano Roelvink (UNESCO-IHE, Deltares)*—Delft3D Modeling in San Francisco Bay
- *Isa Woo (USGS Western Ecological Research Center)*— Temporal and Spatial Patterns in Benthic Invertebrates in the San Francisco Bay
- *Aariel Rowan (San Francisco State University)*— South Bay Mudflats and Their Carrying Capacity for Shorebirds

11:30am – 5:00pm: DISCUSSIONS

11:30am – 12:30pm: Extreme Events

12:30pm – 1:30pm: *Lunch*

1:30pm – 2:00pm: The Shoal to Marsh Continuum

2:00pm – 3:00pm: Issues for Model Integration

3:00pm – 3:20pm: *Break*

3:20pm – 4:00pm: Next Steps

4:00pm – 5:00pm: Model Development and Proposal Directions

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