Adapting to Sea Level Rise Along the North Bay Shoreline

A report to the North Bay Watershed Association

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Contents

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Executive Summary

Due to global climate change, sea level is likely to rise between 0.42 and 1.66 m (16 in and 5.45 ft) within the San Francisco Bay within the next century (NRC, 2012). Rising waters present threats to coastal infrastructure and natural habitat. The San Francisco Bay area is especially vulnerable, as the sheer size of the Bay exposes a very large amount of area to the ocean. Sea levels at San Francisco (recorded at the Chrissy Field tidal gauge) have already risen 20 cm (8 in) over the last century; sea-level rise to the extent predicted will put hundreds of square kilometers at risk in San Francisco Bay.

The large range of possible future impacts, due to the uncertainty in sea-level rise and other physical processes as well as the potential costs of the worst-case scenario, argue for the use of adaptive management. An adaptive management strategy involves looking at the full range of potential outcomes in order to determine the best management actions, and then periodically reviewing the situation in light of new information and updating actions as necessary.

PRBO Conservation Science in coordination with the North Bay Watershed Association (NBWA) developed this report to demonstrate how the Future San Francisco Bay Tidal Marshes Climate Smart Planning Tool (www.prbo.org/sfbayslr) can be used by agencies responsible for coastal areas in North San Francisco Bay to develop adaptive management plans. We held two workshops that brought together 50 managers, scientists, and other stakeholders from groups in the North Bay to identify what information they needed, but currently lacked, to make decisions. As a result of feedback gathered in these workshops and a pre-workshop survey we decided on the following four goals for this study:

- Address the ecosystem value of tidal marshes by estimating the amount by which they attenuate incoming waves
- Analyze tidal marshes and other sites of interest in the North Bay region by calculating projected marsh composition, wave attenuation, and tidal marsh bird abundance
- Add summary reports containing these data for 344 tidal marshes across San Francisco Bay to PRBO's sea-level rise decision support tool (http://data.prbo.org/apps/sfbslr/index.php?page=marsh-reports)
- Produce more detailed vulnerability assessments (including estimates of adaptive capacity) for three case study areas selected as being of high interest to workshop participants: Inner Richardson Bay, Gallinas Creek, and Novato Creek

PRBO had previously produced models of sea-level rise in San Francisco Bay that looked at projected tidal elevations five times over the next 100 years (2030, 2050, 2070, 2090, and 2110). Uniquely, these models include not only the rate of sea-level rise but also the rate of marsh accretion due to the deposition of suspended sediment and organic material. Marsh accretion serves to offset the effects of sea-level rise, as it causes increases in marsh elevation that can potentially match losses due to sea-level rise.

For regions of the North Bay, we analyzed four scenarios at each time frame, for a total of 20 future projections. The four scenarios were formed by pairing either low or high rates of sea-level rise (0.52 m and 1.65 m over 100 years, baywide) with either low or high rates of sedimentation (dependent on watershed).

These elevation projections formed the basis for our subsequent analyses of wave attenuation and tidal marsh bird abundance. Due to a lack of specific data on wave attenuation in Bay Area marshes, we based our estimates of wave attenuation for each marsh class on values derived from the literature. We then applied these values to our projections of future marsh composition and estimated wave attenuation using a two-dimensional, exponential model of wave decay. We calculated wave attenuation/retention as a percentage of the initial wave energy, which assumes that the incident waves were approximately 1-4 ft in height and occurring at mean higher high water under normal conditions. Additional factors like king tides, extreme winds, and storm surges were not included; wave retention is likely to be much higher under such circumstances. We finally summarized wave retention for each site by looking at the average retention along adjacent levees or shorelines. We added the wave rentention projections to our San Francisco Bay Future Tidal Marshes website (www.prbo.org/sfbayslr).

We examined five species for bird abundance: Black Rail (*Laterallus jamaicensis*), Clapper Rail (*Rallus longirostris*), Common Yellowthroat (*Geothlypis trichas*), Marsh Wren (*Cistothorus palustris*), and Song Sparrow (*Melospiza melodia*). For each species, we created a model of their distribution based on their recent observations, including variables such as marsh elevation and salinity. We then used these models to project the future abundances of each of these five species for all future scenarios and times.

In general, we project that the outlook for most tidal areas in the NBWA region is highly dependent on both the amount of sediment suspended in the water column and the amount of sea-level rise. However, the amount of sedimentation can matter more than the amount of sea-level rise. In our scenarios, we found that tidal marshes within watersheds with high amounts of sedimentation are likely to persist even under conditions of high sea-level rise. This is encouraging, as it points to the usefulness of sediment management strategies to reduce or even completely offset the losses of sea-level rise. On the other hand, this is also worrying, because the worst-case scenario of high sea-level rise and low sedimentation is detrimental to marshes in the NBWA area.

Some tidal marshes are more resistant to sea-level rise than others (because of their location, sediment availability, current elevation, and/or other factors), and will remain high quality habitat for wildlife across most climate change scenarios, and thus should be prioritized for conservation. In addition, some tidal marshes will continue to provide protection from wave erosion and flooding throughout this century. Appropriate adaptation planning will require an evaluation of where sites should be prioritized for maintaining and enhancing ecosystem services and where sites with existing tidal marsh systems are not sustainable given future scenarios. A summary of our key findings is presented on the next page.

Tidal marsh outlook:

- Over 90% of the sites examined in the North Bay are projected to maintain or increase the amount of vegetated marsh they contain under scenarios of high sedimentation, even when faced with high sea-level rise. Richardson Bay, with comparatively low levels of suspended sediment, is the major exception.
- Suspended sediment concentration is extremely important to tidal marsh sustainability and strategic sediment manipulation is a potentially powerful management option.

Wave retention:

- The ability of marshes to buffer incoming waves is highly dependent on the width of their vegetated area and the ability of marshes to keep pace with sea level rise.

Bird abundance:

- There are substantial differences among regions of the SF Bay Estuary in the population responses of tidal marsh birds to sea-level rise, so adaptation plans require strategies tailored for specific regions of the estuary.
- The most robust adaptation plans will consider all possible future scenarios and will prioritize actions which achieve the greatest benefits across scenarios.

Evaluating adaptive capacity

- We estimate the adaptive capacity of the Richardson Bay region to be relatively low because of the highly urbanized surrounding land use and the low levels of suspended sediment concentrations. The surrounding the land use makes levee realignment and marsh restoration politically and socially challenging while the low suspended sediment levels make using nature based flood protection strategies potentially infeasible.
- In contrast, we estimate that both Gallinas Creek and Novato Creek have higher adaptive capacity than inner Richardson Bay. Higher sediment levels in both watershed suggest that some sediment management could enhance the resilience of tidal marsh ecosystems to seal level rise.
- In the Novato Creek watershed, there are opportunities for tidal marsh restoration which could be resilient to high rates of sea level rise with adaptation actions. Initial elevations of restoration projects within the watershed should be raised to allow the marshes a better chance of keeping pace with sea level rise.

Introduction

Sea level is likely to rise between 0.42 and 1.66 m (16 in and 5.45 ft) by 2100 (NRC 2012). Determining which areas of natural habitat and human infrastructure are most vulnerable to these changes, as well as which areas are and will be of highest conservation concern and incorporating these assessments into policy and planning decisions is a high priority for coastal decision makers globally, as is reflected in the goals of the Marin County Watershed program. PRBO Conservation Science has developed an expertise in projecting the effects of sea-level rise and other climate change effects in the Bay Area (see: www.prbo.org/sfbayslr), and is committed to applying the most rigorous and up-to-date data and modeling approaches to help planners and managers increase habitat resilience to climate change.

Problem Statement

With the impending significant effects that climate change will have on San Francisco Bay's wetland ecosystems and human infrastructure, there is an urgent need to incorporate an assessment of these predicted impacts and to develop recommendations for associated adaptation. PRBO's recent modeling of tidal marsh ecosystem responses to sea-level rise in San Francisco Bay identified several impacts and potential adaptive conservation measures to offset these impacts. For example, our findings include:

- 93% of current mid and high tidal marsh in the SF Bay could be lost by 2100 under potential high sea level rise and low sedimentation scenarios.
- Suspended sediment concentration is extremely important to tidal marsh sustainability; strategic sediment manipulation is a potentially powerful management option.
- While there are only approximately 3,300 ha of upland habitat available that could accommodate future marshes, five times as much area could be reclaimed by removing levees and other barriers to tidal action.
- There are substantial differences among regions of the SF Bay Estuary in the population responses of tidal marsh birds to sea-level rise, so adaptation plans require strategies tailored for specific regions of the estuary.
- The most robust adaptation plans will consider all possible future scenarios and will prioritize actions which achieve the greatest benefits across scenarios.

Some tidal marshes are more resistant to sea-level rise than others (because of their location, sediment availability, current elevation, and/or other factors), and will remain high quality habitat for wildlife across most climate change scenarios, and thus should be prioritized for conservation. In addition, some tidal marshes will continue to provide protection from wave erosion and flooding throughout this century. Appropriate adaptation planning will require an evaluation of where sites should be prioritized for maintaining and enhancing ecosystem services and where sites with existing tidal marsh systems are not sustainable given future scenarios.

Stakeholder Workshops

Introduction and informational presentations

In June 2012, PRBO and the North Bay Watershed Association invited stakeholders from the North Bay region to attend one of two workshops to solicit management information needs for planning for sea level rise within the planning area. The workshops were focused on the needs which could be addressed through the use of products from PRBO's Future San Francisco Bay Tidal Marshes decision support tool (www.prbo.org/sfbayslr).

During the workshops, PRBO staff presented the existing tool and explained how the tool and underlying models were developed. We demonstrated the tool's capabilities, showed examples of how the tool could be used to prioritize the conservation or restoration of tidal marsh sites, and exhibited how the tool could be used to identify vulnerabilities to sea level rise.

Pre-workshop Survey

Workshop participants were asked to fill out a pre-workshop survey so that the workshops could be structured to better identify management needs and to familiarize participants with the Future San Francisco Bay Tidal Marshes decision support tool. 55 participants responded to the survey.

Survey results

The first set of questions were designed to get a sense of the participants needs with regards to decision support for sea level rise planning.

Workshop participants were asked the question, "*What sea level rise planning resources do you currently use?*" The resource which was used most frequently by survey respondents was sea level rise projections (27%), followed by literature reviews (18%), expert consultation (12%), GIS analysis (11%) and vulnerability assessments (6%). Only 4% of respondents used decision support tools for planning for sea level rise.

Participants were asked, "*What is the technical capacity of the likely users of decision support tools in your organization?*" The majority of respondents felt that a decision support tool should be useable by people with basic computer skills (41%). For basic users, respondents felt that the tool should have a tutorial and tool tips. Additionally, the respondents felt that the tool should have solid visualizations and a map based interface. 35% of respondents felt that likely users would have GIS technical expertise and 25% felt that developers coders and engineers would use the tool.

To get a sense for the types of analyses that stakeholders would potentially be conducting, participants were asked, "*What are you concerned about being negatively impacted by sea level rise with respect to decisions you may have to make?* Ecosystem services were the highest ranking concern, followed by human infrastructure, wildlife habitat, private homes, agriculture, and finally recreational use of public lands.

In a follow up question, participants were asked, "*What aspects of sea level rise are you most concerned about?*" There was a fairly even spread of concerns (range of ranking = 3.19 - 3.9) but an increased chance of severe storms and large floods was the biggest concern. The second ranked concern was inundation of unprotected low-lying areas followed closely by erosion. Levee overtopping or failure and increased wave intensity through loss of buffers were ranked lowest.

Respondents were directed to PRBO's Future San Francisco Bay Tidal Marshes decision support tool to try out the tool and provide feedback on their experience. Participants were asked, "*How easy was it to use this tool?*" 84% of respondents felt that the tool is very easy to use and understand or somewhat easy to use and understand. 5% thought the tool was somewhat confusing and hard to use and 11% thought the tool was very confusing and hard to use.

In a follow up question, participants were asked, "*How useful was this tool?*" 58% of respondents thought the tool was somewhat useful while 26% of respondents thought it was very useful. 11% of respondents thought the tool was somewhat helpful and only 5% thought the tool was largely unhelpful.

Participants were then asked, "*What additional features or information would make this tool more useful?*" Examples of suggested features to add included:

- Create summaries and metrics to distill impacts.
- Add ability to query map and get a report for a selected area.
- Add a larger range of scenarios.
    - More sedimentation levels.
- Identify areas of greatest restoration and migration potential.
- Generate use-case scenarios to provide context.
- Table showing when (or what sea level increase) would cause a site to go under water.
- Change in wave intensity due to loss of marsh buffers.
- Include better help information.
- Recorded help videos.
- Tooltips.
- More control over the map, especially layer selection and layer opacity.
- Smoother zoom and pan.
- Geographic search (geocoding) to quickly navigate to area of interest.
- Integrated data download.

There were several suggestions for analyses which were beyond the scope of this project. For example, many of the suggestions included evaluating the risks associated with storm surges and storm flooding. The type of modeling will be done through the Our Coast Our Future project over the next two years but was beyond the scope for this project. Additionally, although participants requested an economic valuation of human and ecosystem services, we do not have the data to complete this type of analysis. However, our results can be used in an economic analysis in the future (see below).

Breakout Groups

After introductory presentations, workshop attendees participated in smaller breakout groups to discuss, *"How can the PRBO decision support tool be used or improved to support your organization in developing adaptation strategies for sea level rise?"* The decision support needs of the group were investigated by:

- Discussing questions that participants needed answered to make decisions.
- Identifying areas or projects that could serve as case studies to distill complex issues into a story that hits home.
- Identifying ways the existing tool could be improved.
- Identifying what management questions are not being addressed and what actions are not being pursued because of lack of information in the form of tools or data.

Synthesis of Management Questions

The need to address the following high priority management questions was presented by at least two of breakout groups:

- What are the ecosystem services provided by tidal marshes and how will these services change in the future?
    - What is the replacement cost of levees without tidal marsh protection?
    - How much flood protection is provided by tidal marshes and how will this change in the future?
    - Will marsh restoration lead to increased flood protection?
    - How will populations of wildlife change in the future?
- What adaptation actions could reduce vulnerability to sea level rise?
    - Where will we need to raise levees or place new levees?
    - Where should existing levees be removed?
    - Where should existing infrastructure be raised or moved?
    - Where could dredge spoils increase marsh resilience?
    - Where should we promote upslope marsh migration?
    - Identify areas that should not be developed.

Case study suggestions

The following areas or projects were suggested by at least two breakout groups to illustrate how the existing tool can be applied to support sea level rise adaptation planning:

- Las Gallinas Creek
- Novato Creek Watershed Program
- Tam Highway/Miller Ave. area in Richardson Bay

Workshop Summary

Through both the pre-workshop survey and discussions at the workshop, we were able to identify how PRBO Conservation Science's existing decision support tool could be used to support adaptation planning for sea level rise. We also determined where new analyses could make the products from our modeling useable beyond conservation applications. Many of the workshop participants appreciated the value of the existing tool for identifying vulnerabilities to wildlife but were not convinced that the tool is as useful for other audiences that need to make decisions about protecting human infrastructure. Participants felt that a valuable addition to the tool would be to make the tool useful to a broader audience and to ensure that the tool would be functional for these groups.

Quantifying ecosystem services of tidal marshes

Workshop participants repeatedly mentioned that for broader audiences to use the tool, we need to do a better job of demonstrating the value of marshes to groups other than conservation managers. At the same time, participants appreciated how the tool quantifies the impacts to wildlife from increasing sea level rise and climate change. The ability to quantify the level of natural flood protection which tidal marshes provide was consistently mentioned as a way to show the co-benefits of tidal marshes to people and wildlife.

The best way to use our existing models of changes in marsh elevation was to quantify the changes in wave attenuation expected under our eight different scenarios of suspended sediment concentrations, organic accumulation rates, and sea level rise. Although there are no existing models of waves for both current and future conditions, wave attenuation serves as an index of the protections marshes provide our levees from erosion and overtopping. Thus, by showing changes in wave attenuation due to changes in marsh elevation, we can assess the vulnerabilities of levees due to a loss of buffering effect of tidal marshes.

Decision support tool enhancement

Workshop participants suggested three main ways for modifying our existing decision support to enhance its application for sea level rise adaptation planning. First, the users felt that, on its own, the tool was too complicated for an average user to understand. Several participants suggested that expanded help features would enable less technical users to use the site. Second, the workshop participants stated that a demonstration of the tool's use through case studies would promote the use of the tool more broadly. Finally, workshop participants requested that new layers be added to the site which demonstrates other ecosystem services beyond the benefits to plants and wildlife.

Quantifying the added protection of tidal marshes to levees in the North Bay

Modeling changes in tidal marsh elevation (2010-2110)

Through previous work, PRBO Conservation Science has developed a set of projections of changes in tidal marsh elevations for eight different scenarios throughout the San Francisco Estuary. Marsh accretion (the vertical accumulation of mineral and organic material) was estimated using the Marsh98 model, which has been used widely to examine marsh response to SLR across San Francisco Bay. The Marsh98 model is based on the mass balance calculations described by Krone (1985). This model assumes that the elevation of a marsh surface increases at a rate that depends on (1) the concentration of suspended sediment in the water column and (2) the depth and duration of inundation by high tides. Marsh98 implements these processes by calculating the amount of suspended sediment that deposits during each period of tidal inundation and sums that amount of deposition over the period of record. Organic material was added directly to the bed elevation at each time step at a constant rate. Marsh98 was implemented in the Fortran programming language, and multiple runs were executed using MatLab v.2010b. For more details see Stralberg et al. (2011).

Calculating the wave attenuation from tidal marsh ecosystems

Along the North Bay shoreline, waves are primarily formed by local winds but wakes from large boats can also be important for causing erosion of marsh edges and the bay shoreline (Lacy and Hoover 2011). Wind speed and fetch (distance over water that wind has consistently blown) are important factors determining the size of wind generated waves. In the San Francisco Estuary, winds are strongest during the summer months and generally blow from the west, with average mid-day wind speeds of 8 m/s recorded (Conomos et al. 1985). In the winter, the prevailing wind is still from the west but winds from the east and southeast are not uncommon (Conomos et al. 1985). In general, wind waves are smaller in the North Bay then other sites in the estuary as the configuration of the North Bay shoreline results in the waves with small fetch when generated with winds from the west. However, sites are still exposed to winds from the south and southeast and from winds generated by wakes from vessels. Unfortunately, we were unable to find a source of wind or wave data with which to create maps of current or future conditions to apply to our existing elevation models. Fortunately, there is evidence that relative wave attenuation is insensitive to small changes in the incident wave height (Lacy and Hoover 2011) allowing us to make some simplifying assumptions as we estimated the wave attenuation throughout the study extent.

We conducted a review of existing research on marsh wave attenuation to assign values to the different vegetation classes. From the literature surveyed (Cooper, 2005; Houser and Hill, 2010; Knutson 1982; Kobayashi, 1993; Lee, 2004; Moller and Spencer, 2002; Moller *et al*, 1996; Moller *et al* 1999; Wayne, 1976), we came up with estimated attenuation values of 6% per meter for high marsh, 3% per meter for mid marsh, 1% per meter for low marsh, 0.1% per meter for mudflats, and 0.001% per meter for subtidal/open water. To represent the uncertainty in this estimate, we created values for both higher-than-expected attenuation and lower-than-expected attenuation by doubling and halving those values, respectively. We turned these values into wave attenuation grids by reclassifying the aforementioned elevation grids with the raster (Hijmans and van Etten, 2012) and rgdal packages in R 2.15.0 (R Core Development Team, 2012) based on their elevation with respect to mean higher high water.

We then used the 'Path Distance' tool in the Spatial Analyst package of ArcGIS 9.3 (ESRI 2010) to find the least-cost path for waves from San Francisco Bay and major streams/rivers to reach sites along the coast. We used wave attenuation (i.e. wave travel cost) grids as the cost surface and the direction to the nearest open water as the horizontal factor to restrict wave movement to within 45 degrees of its direction of propagation. In R, these additive path costs were then turned into estimated wave attenuation values by first dividing the cost to reach each pixel by the distance that pixel was from open water to get an average attenuation and then raising this value to the distance travelled to get the true, multiplicative effect of wave attenuation: a value between 0 and 1 that represented the proportion of incident wave energy dissipated by the marshes. Subtracting the wave attenuation values from one produced the wave retention grids, which show the percentage of a wave's initial energy (upon leaving open water) that remains upon reaching a given pixel.

The amount of energy dissipated by a given marsh area depends not just on the marsh vegetation but on the energy of the wave itself: higher energy waves will lose more energy per meter than will lower energy waves. This is because many of the dissipative forces of marsh vegetation increase proportionally (within limits) to wave energy. Another consequence of this effect is that a 'fresh' wave just encountering the outer edge of a marsh will lose more energy in the first meter of the marsh than the second, more in the second than in the third, and so on and so forth. Most wave attenuation occurs on the outer edges of a marsh, with progressively smaller amounts being dissipated as a wave travels inwards. Therefore, a simple additive sum of attenuation values is insufficient: wave energy decay is best modeled exponentially (Cooper, 2005; Houser and Hill, 2010; Moller and Spencer 2002; Moller et al, 1999). We accounted for this by using the (additive) cost path only as an intermediate step by which we could determine the average attenuation per meter for a given wave path. We then produced a (multiplicative) attenuation value by raising the average to the distance the water had to travel to get there. Things are further simplified when the initial waves are likely to be very similar in height, as in the case of San Francisco Bay. This means that initial wave height can be ignored when calculating the wave attenuation, following the exponential wave decay model presented in Moller et al (1999).

To evaluate the effects of sea-level rise on levees and other shoreline structures, we extracted the estimated wave retention values along them for each attenuation and sea-level rise scenario. We summarized and plotted these values by subwatershed (CalWater) and marsh sites. Similarly, we summarized and plotted habitat composition and estimated bird abundance. Habitat composition was determined by the elevation with relation to mean higher high water and shown by percent cover.

Limitations of our approach

Our projections are limited by two main methodological factors: the assumptions made in producing the elevation grids and the relative simplicity of our attenuation calculations. For the purposes of wave attenuation, the major assumption to note in the elevation grids is that sedimentation rates are applied uniformly across the given input surface. This assumption ignores the spatial heterogeneity in suspended sediment concentrations which occur within a marsh, e.g. higher sediment concentrations are typically found closer to the bay edge and near channels than within the interior of a marsh. Sedimentation and sediment transport are notoriously complex processes and their effects depend on many physical processes, including water flow direction, current velocity, the slope and substrate of the underwater surface, exposure to tidal processes, vortices and other diversions caused by bathymetry, and erosion. Our projections of future wave attenuation are limited to the extent that sedimentation and erosion occur unevenly. This is especially apparent in the formation of channels within marshes: our projections often show channels turning to low or mid-marsh. The net effect is that wave retention is likely to be slightly higher than predicted, as channels are likely to remain and keep assisting wave propagation. For more information on the other – but less potentially confounding – assumptions made in the elevation modeling, please see Stralberg et al. (2011).

The relative simplicity of our attenuation calculations meant that many factors affecting wave attenuation were not explicitly accounted for. Due to the lack of relevant data on conditions in the San Francisco Estuary (e.g. *in situ* measurements of marsh vegetation composition and frictional characteristics, substrate composition, etc), we were unable to use a model that explicitly calculates wave height decay from first principles (e.g. WHAFIS). We instead relied upon data derived from observations at other locations, most which were in Europe and none on the Pacific Coast of the US. While we feel that these are good estimates, they are no substitute for detailed, site-specific parameters. Our calculations also did not explicitly include effects of bathymetry, instead including this in the attenuation coefficients obtained from the literature. Bathymetry can have a large effect on wave propagation, especially when uneven. In particular, scarps at the edge of a marsh (where the water depth decrease sharply) can cause waves to break earlier than they otherwise would have, drastically reducing wave energy in a way that our calculations do not capture.

A final point that bears mention is that these projections are of relative wave attenuation under average (daily mean higher high water) conditions. The resulting figures do not estimate the actual energy or height of waves reaching the shore and thus should not be used to determine the impact forces on levees or other structures. Nor do they directly address flooding risk. Our calculations do not take into account any levee overtopping or failure that might occur: they assume that currently existing levees will be maintained and enhanced as necessary to protect areas behind them from flooding. Finally, these wave attenuation projections are for average conditions and do not indicate what could happen under storm conditions, with a storm surge, higher winds, and larger initial waves.

Modeling tidal marsh bird response to sea level rise

We examined five species for bird abundance: Black Rail (*Laterallus jamaicensis*), Clapper Rail (*Rallus longirostris*), Common Yellowthroat (*Geothlypis trichas*), Marsh Wren (*Cistothorus palustris*), and Song Sparrow (*Melospiza melodia*). We extracted GIS-derived environmental characteristics for current (circa 2010) conditions, including marsh elevation, salinity, and a series of distance metrics at locations where tidal marsh bird observations were made. We used boosted regression tree models to model statistical correlation between observed abundance, corrected for probability of detection, and the environmental predictors (Elith et al. 2008). Statistical models were then used to predict to the GIS layers of projected future conditions to make maps of predicted abundance. The calculated abundances of future bird populations are based upon the marsh elevation projections (discussed above; see Veloz et al. (2013) for more details) as well as salinity. After extracting the abundance for each species in the given polygon, we log-transformed the raw abundance values to allow all five species to be plotted on the same axes. Plots were produced in R with the ggplot2 package (Wickham, 2012).

Results for the North Bay

Summaries by Sub-Watershed

Marsh elevation changes by sub-watershed

We summarized the changes in marsh elevation by sub-watershed (Figure 1). The low sea-level rise/high sedimentation scenario shows watersheds remaining relatively steady in their composition. In contrast, the low sea-level rise/low sedimentation combination shows increases in marsh area at the expense of mudflats (Petaluma River), subtidal areas (Gallinas Creek), and upland areas (Belvedere Lagoon, Old Mill Creek, Ross Creek, and San Rafael Creek).

The high sea-level rise/high sedimentation scenario shows a similar, though more pronounced, trend. All sites show a decrease in mudflats, subtidal areas, and upland areas, with most of the gains going to mid marsh. The high sea-level rise/low sedimentation combination projects that mudflats will increase in area while the rest of the marsh moves upslope and retains a similar footprint (at the expense of upland areas). At the sub-watershed level, both factors (sea-level rise and sedimentation) have significant effects on projected marsh compositions.

In our projections, the amount of suspended sediment in the water column generally plays a larger role than the rate of sea-level rise: the difference in outcomes between the high and low sediment pairs is, on average, greater than the difference in outcomes between the high and low sea-level rise pairs. This is because the majority of the watersheds in the region have high amounts of suspended sediment: 100 or 150 mg/L under the low assumption and 300 mg/L with the high assumption. With these amounts of sediment, our models generally show that marshes can keep pace with sea-level rise and even increase in area for all scenarios but high sea-level rise/low sedimentation. Only in Richardson Bay, with much smaller sediment concentrations (25 and 50 mg/L), does the effect of sea-level rise predominate and vegetated marsh habitat turn into mudflats and subtidal zones.

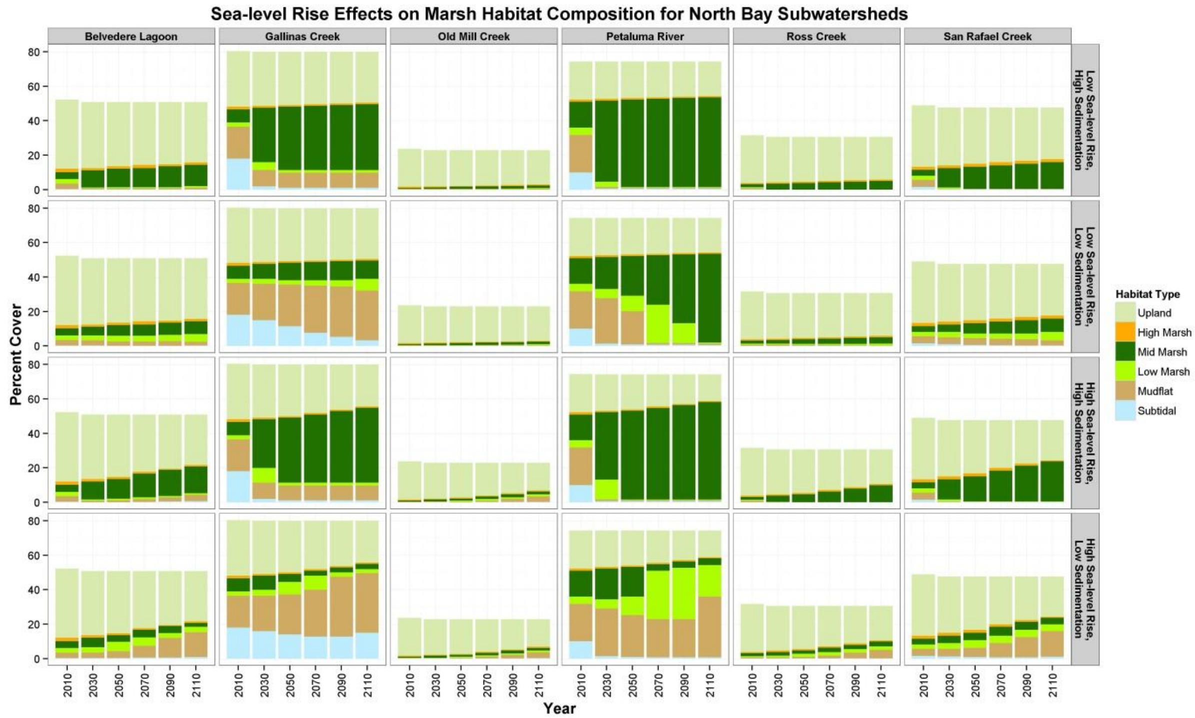


Figure 1. Tidal marsh habitat composition under different sea-level rise scenarios for subwatersheds in North San Francisco Bay. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation. Bars do not always sum to 100% as areas of no data are shown as blank.

Wave retention changes by sub-watershed

We summarized the wave retention along levee edges at the sub-watershed level. At the spatial scale of the sub-watershed, there are very few temporal trends in changes in wave retention, with the exception of increasing wave retention through time for the high seal level rise/ low sediment scenario (Figure 1). Under the high sea level rise/low sediment scenario, we project increasing % wave retention within all sub-watersheds, particularly between 2050 and 2070 (Figure 2).

We project that levees in the Belvedere Lagoon and San Rafael Creek sub-watersheds are consistently more vulnerable wave erosion through 2110. In contrast, we project that levees in the Gallinas Creek and the Petaluma River sub-watersheds have the lowest vulnerability to wave induced erosion. In the Old Mill Creek watershed, we project increasing percent wave retention through time in both sediment scenarios for the high sea level scenario. There is less change through time projected for all other sub-watersheds.

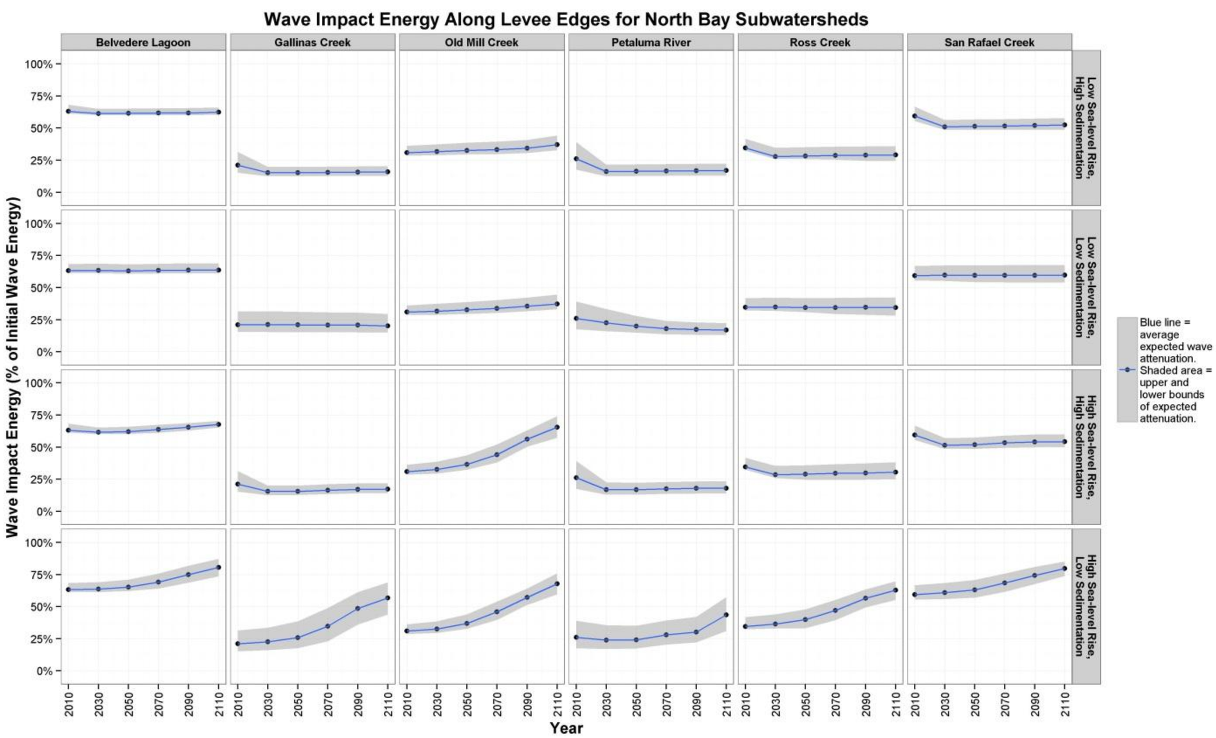


Figure 2. Average remaining wave energy along levee edges summarized by sub-watershed on the North San Francisco Bay shoreline. Low % wave energy remaining indicates that marshes are attenuating wave energy and protecting adjacent levees from erosion. High % wave energy values indicate that tidal marshes are providing less erosion protection.

Tidal marsh bird abundance changes by sub-watershed

We project the higher abundance and greater tidal marsh bird diversity within the Gallinas Creek and Petaluma River sub-watersheds (Figure 3). All five species are projected to occur within these throughout the century within both of these sub-watersheds, except for the high sea level rise scenarios in Gallinas Creek (Figure 3). Black Rail, Common Yellowthroat and Marsh Wren were projected to be largely absent from the other four sub-watersheds (Belvedere Lagoon, Old Mill Creek, Ross Creek, San Rafael Creek). In contrast, we project Clapper Rail and Song Sparrow to occur throughout all sub-watersheds.

Across most scenarios and sub-watersheds, we project Song Sparrow and Clapper Rail abundance to remain stable. The biggest exception to this pattern occurs under the high sea level rise/low sediment scenario across all sub-watersheds and for the high sea level rise/high sediment scenario in the Old Mill Creek sub-watershed (Figure 3). Between 2010 and 2030, we project a sharp increase in Black Rail abundance in the Gallinas Creek across all scenarios and in the Ross Creek sub-watershed for both high sea level rise scenarios. In the Gallinas Creek sub watershed, we project a rapid decline in Black Rail between 2050 and 2070 for the high sea level rise/ low sediment scenario, and between 2070 and 2090 in the high sea level rise/ high sediment scenario.

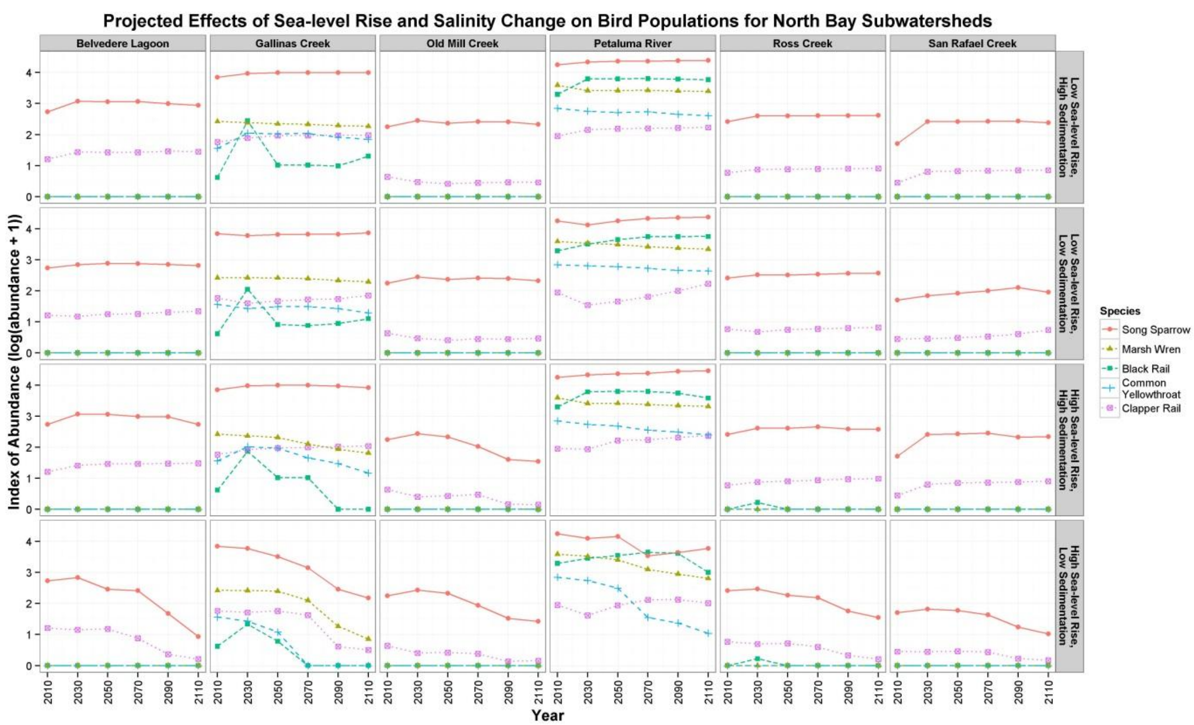


Figure 3. Projected tidal marsh bird abundance (log-transformed) within sub-watersheds on the North San Francisco Bay shoreline under different sea-level rise scenarios.

Summaries of marsh sites by area

Upper Petaluma River

Low sediment = 150 mg/l, high sediment = 300 mg/L

The two sites, Petaluma Dog Park and Gray's Ranch, along the upper Petaluma are both large tidal marsh sites located on the eastern shore of the river (Figure 4). In both sites, we project a large increase in the percent area covered by mid marsh habitat between 2010 and 2110 in all scenarios except for the high sea level rise/low sediment scenario (Figure 5). However, the increase in mid marsh habitat at Gray's Ranch occurs much more slowly for the low sea level rise/ low sediment scenario than in the other two scenarios which show consistent increases. In the high sea level rise/ high sediment scenario we project the percent area mid marsh habitat to increase from 2010 to 2050 at both sites at the expense of high marsh and mudflat habitat. However, between 2050 and 2070, the percent area of mid marsh habitat decreases corresponding with an increase in low marsh habitat at both sites. We project an increase in mudflat habitat at Gray's Ranch by 2110 for the high-sea level rise / low sedimentation scenario.

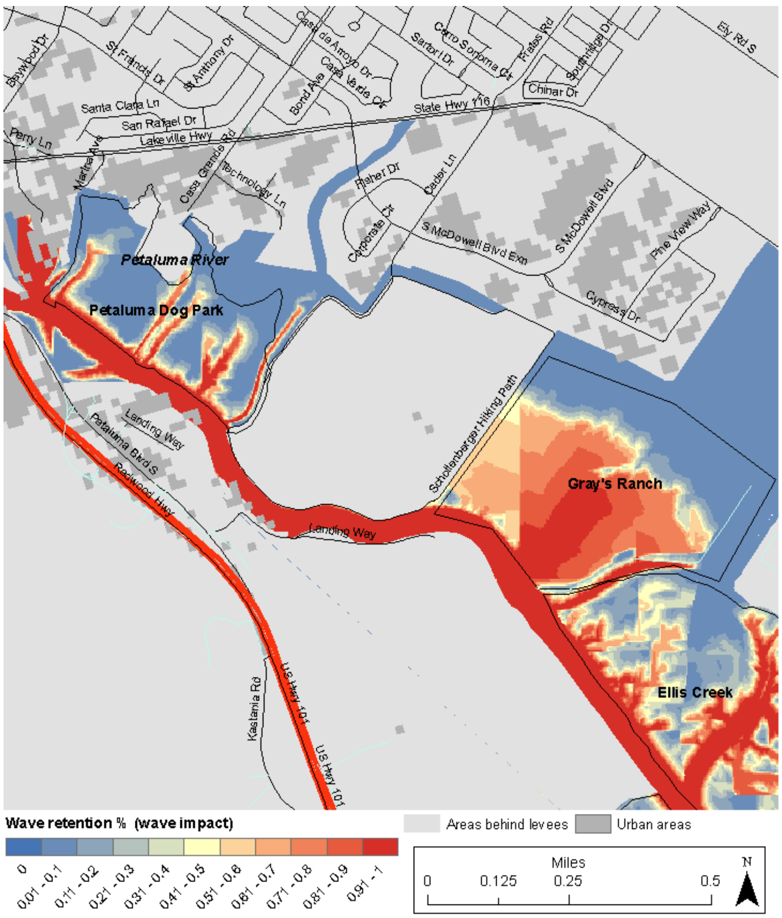


Figure 4. Wave retention (%) based on current (2010) conditions for sites along the upper Petaluma River.

At both sites, we project low wave retention throughout the century (Figure 5). The one exception is the increase in wave retention to 50% (Gray's Ranch) and >25% (Petaluma Dog Park) between 2090 and 2110 for the high sea level rise/ low sediment scenario (Figure 6).

We project increases in Black Rail abundance at both sites from 2010 to 2090 for all scenarios. However, for the high sea level rise scenarios we project a decline in Black Rail abundance between 2090 to 2110 (Figure 7). We project that Common Yellowthroat will occur at the lowest abundance at both sites across all scenarios while Black Rail and Song Sparrow occur at the highest abundance.

Figure 5. Marsh elevation projections for sites along the upper Petaluma River. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation.

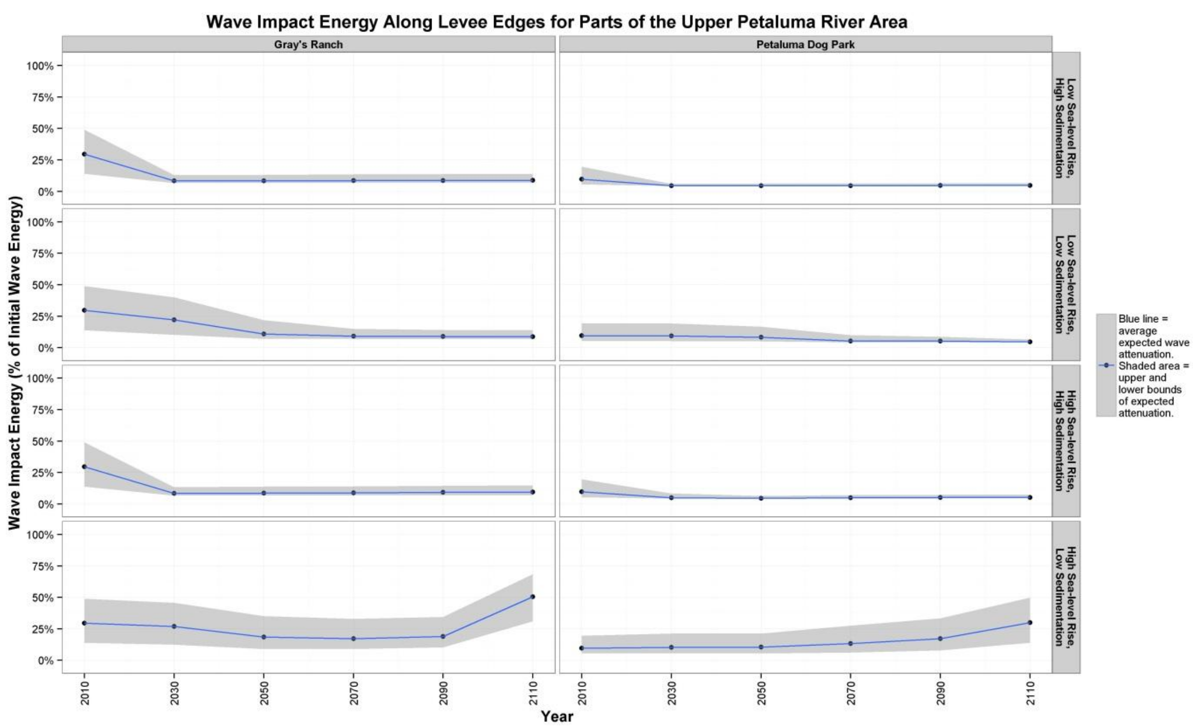


Figure 6. Wave retention (%) along levees for two sites along the upper Petaluma River.

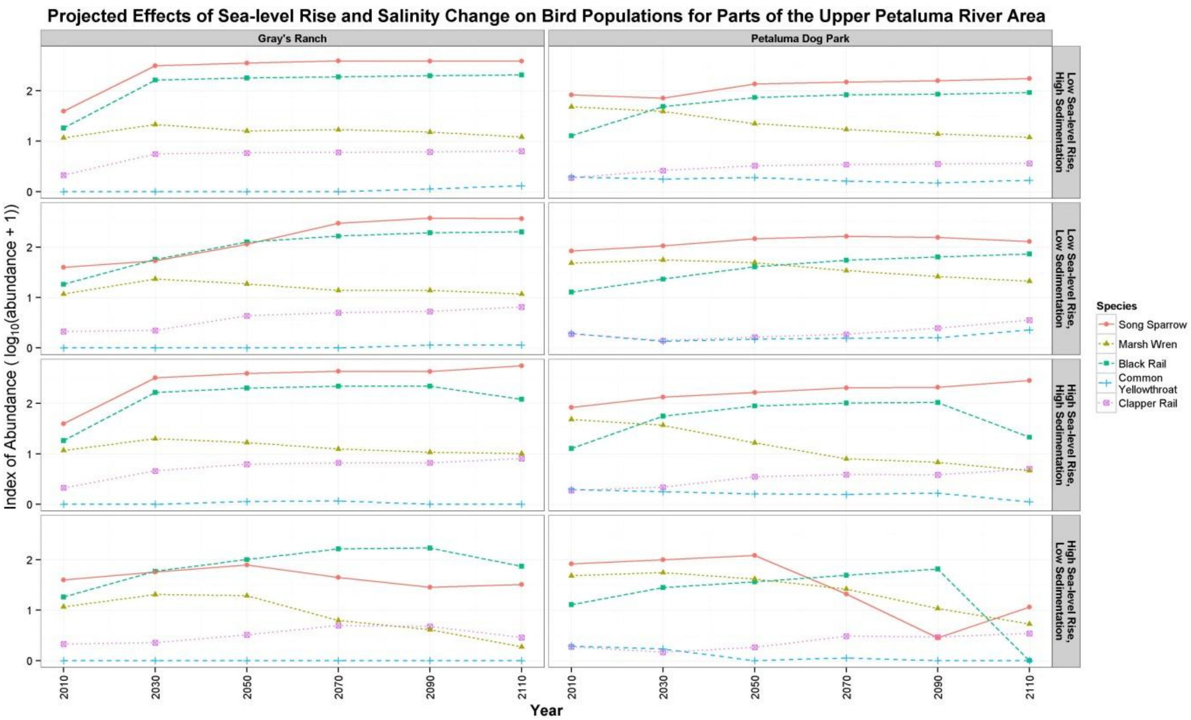


Figure 7. Projected tidal marsh bird abundance (log-transformed) at sites along the upper Petaluma River.

Upper Petaluma River Marshes

Low sediment = 150 mg/l, high sediment = 300 mg/L

Marsh sites on the lower Petaluma River are some of the largest intact marshes remaining in the estuary (Figure 8). Given the relatively high sediment levels present in the Petaluma river, these sites are projected to be very resilient to sea level rise and climate change. We project that tidal marsh will persist through 2110 at all sites but that most of the marsh will transition to low marsh habitat for the low sediment/high sea level rise scenario (Figure 9).

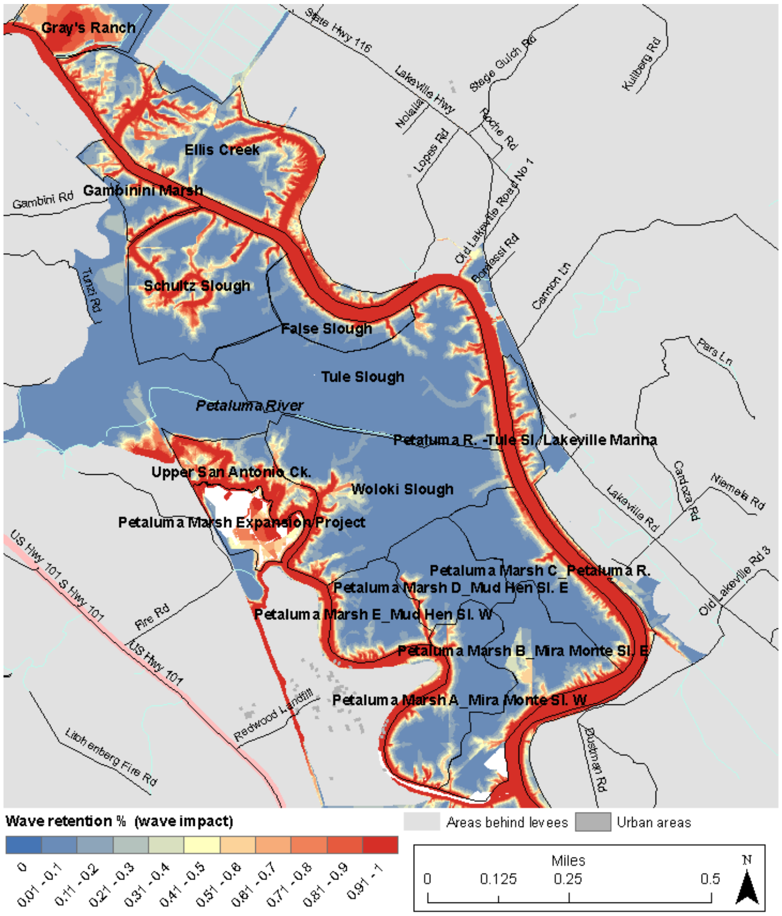


Figure 8. Wave retention (%) based on current (2010) conditions for sites along the lower Petaluma River.

Ellis Creek, Gambinini Marsh, Petaluma Marsh Expansion Project and the Petaluma River/Tule Slough/Lakeville Marina all maintain relatively low wave retention values throughout the century (Figure 10). Some areas such as Upper San Antonio Creek have high wave retention values even under current conditions indicating the vulnerability of levees in these areas to erosion due to sea level rise.

Similarly, all sites are projected to maintain valuable habitat for tidal marsh birds in all scenarios throughout the century at all sites (Figure 11). However, Common Yellowthroats do show a decline in about a third of all the future plots, especially the high sea-level rise/low-sedimentation scenario.

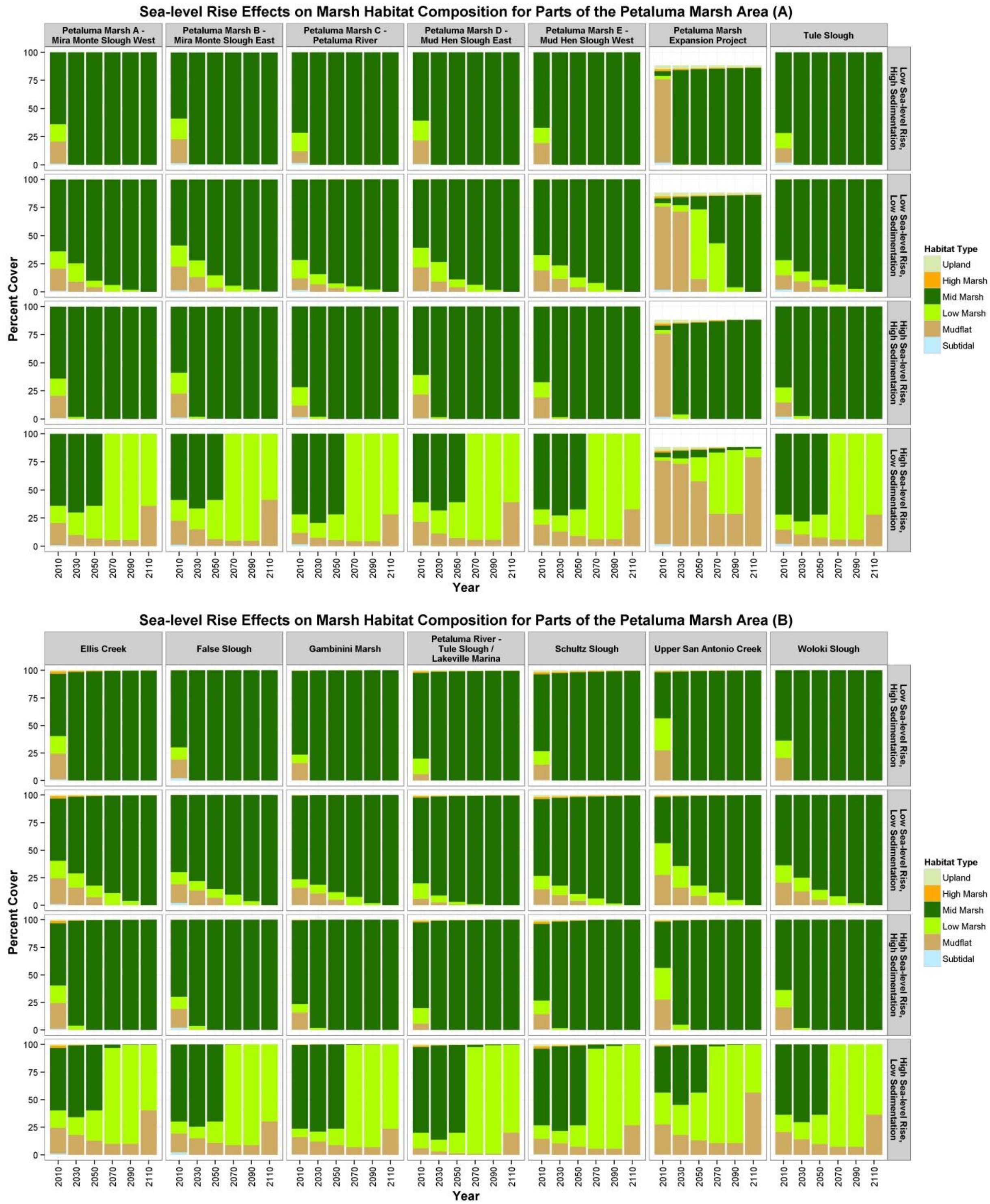


Figure 9. Marsh elevation projections for sites along the lower Petaluma River. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation. Bars do not always sum to 100% as areas of no data are shown as blank.

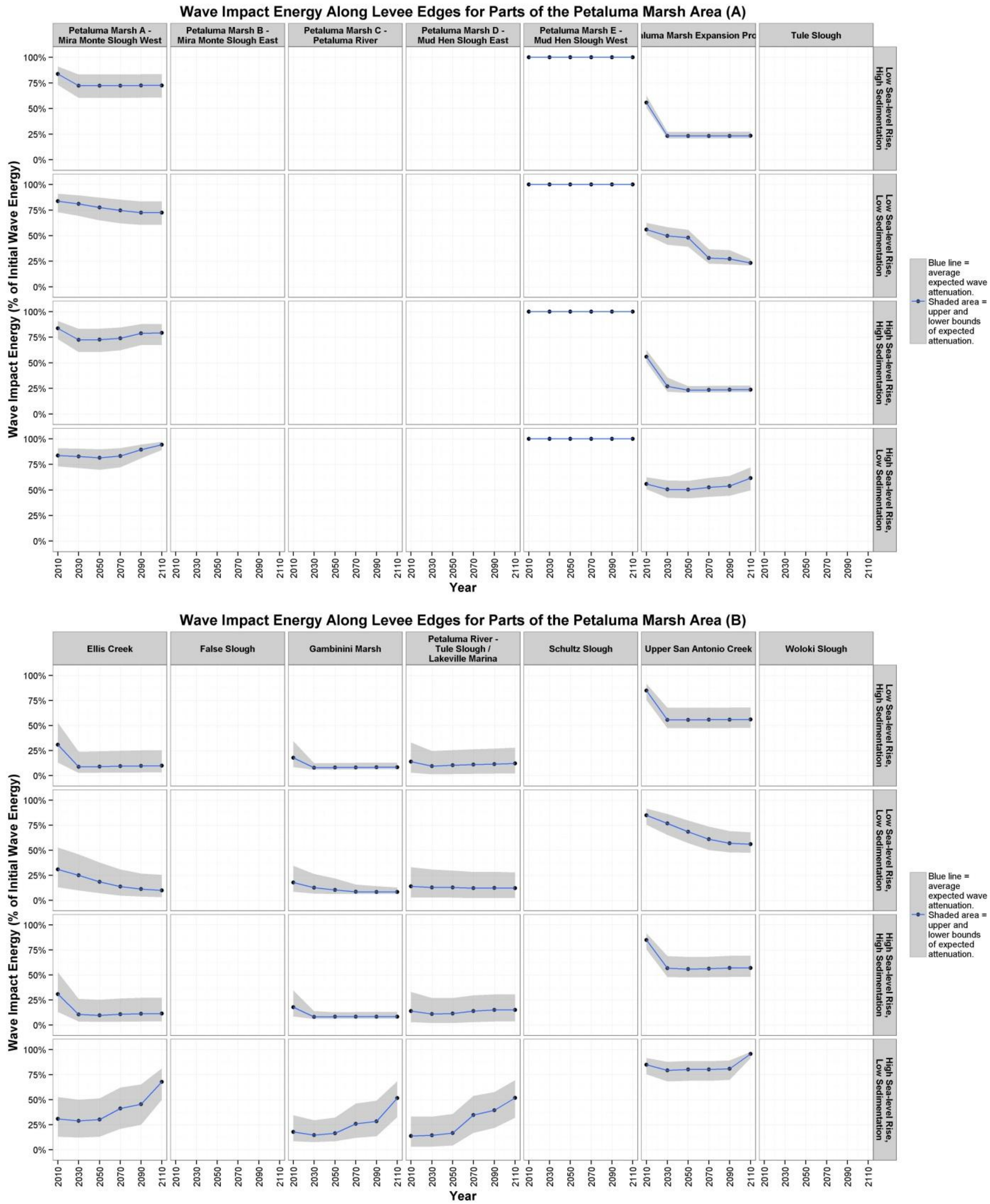
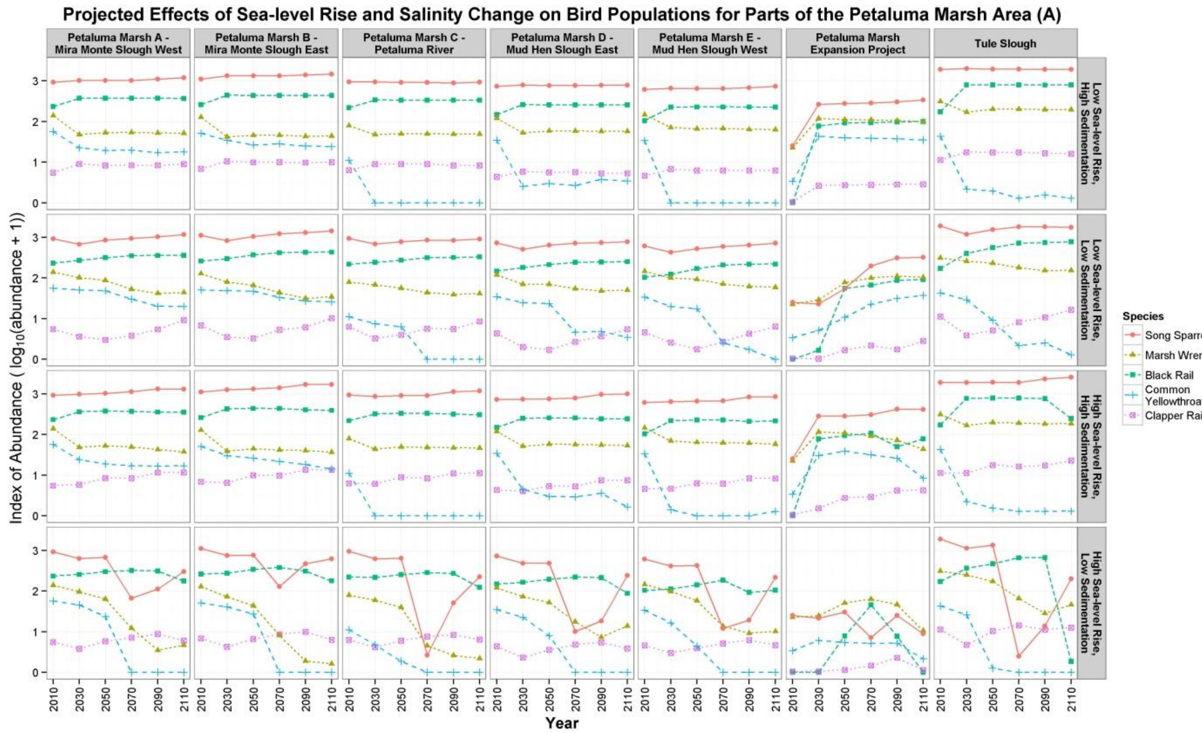


Figure 10. Wave retention (%) along levees for sites along the lower Petaluma River. We were unable to calculate meaningful wave attenuation values for sites with no lines due to areas of no data, not having a direct connection to open water, and/or a lack of levees (or other shore edges) in the site.



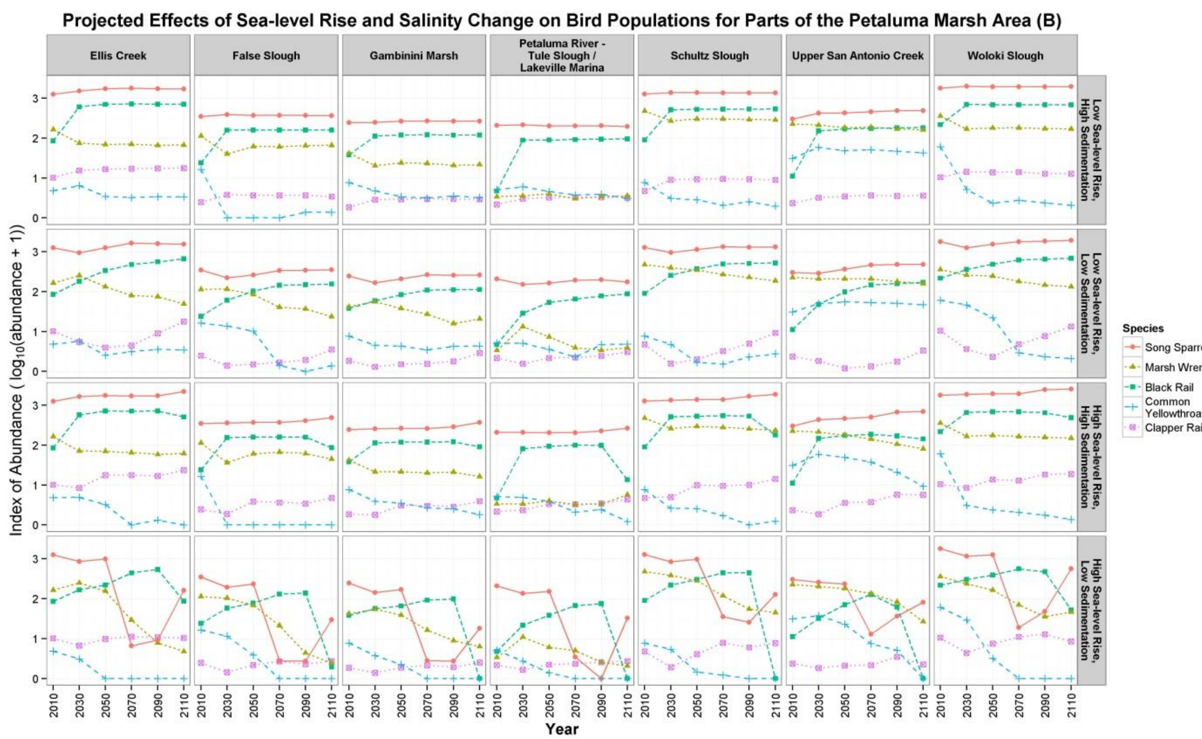


Figure 11. Projected tidal marsh bird abundance (log-transformed) at sites along the lower Petaluma River.

Lower Petaluma River Marshes

Low sediment = 150 mg/l, high sediment = 300 mg/L

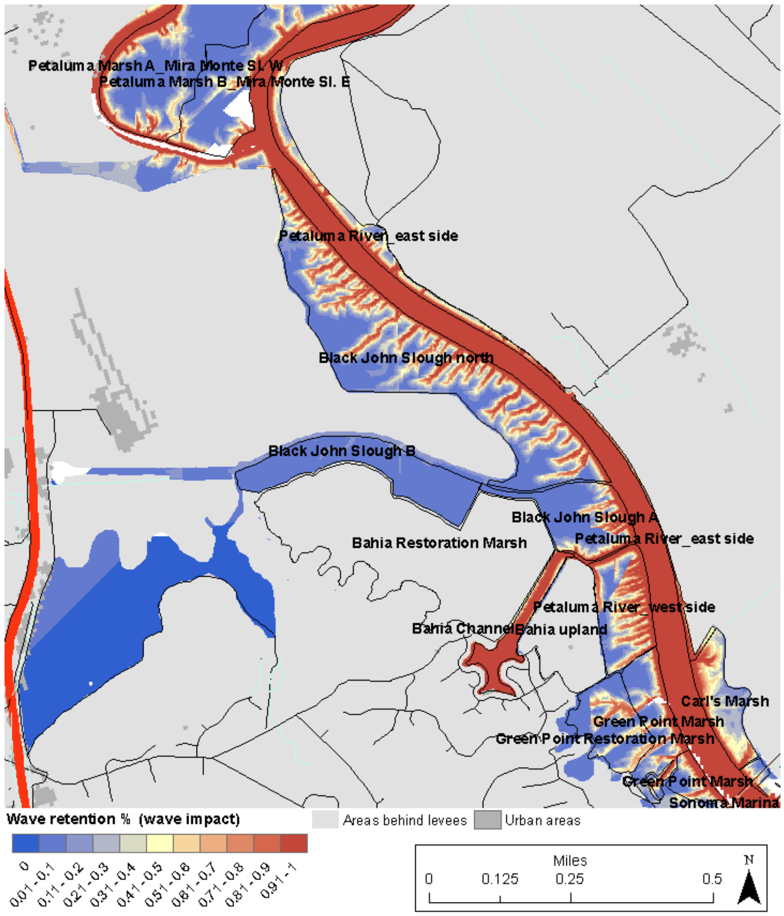
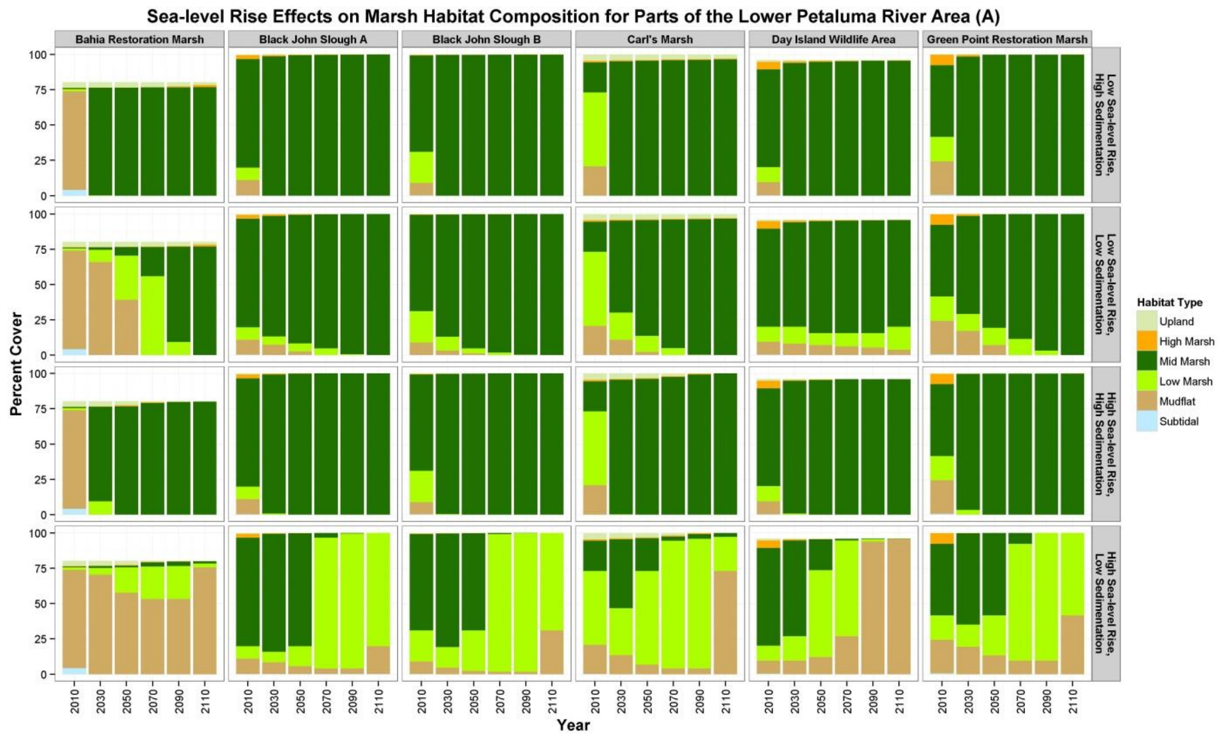


Figure 12. Wave retention (%) based on current (2010) conditions for sites along the Lower Petaluma River.

The Lower Petaluma River Marshes (Figure 12) respond similarly to the Petaluma Marsh sites. For all scenarios except the low sediment/high sea level rise scenario, we project increases of marsh habitat (Figure 13). For the worst case scenario, we project increases in marsh habitat from 2010 - 2050 at most sites, but marshes convert to either low marsh or mudflat between 2050 and 2110. We project an increase in marsh habitat at the Bahia Restoration Marsh from 2010 to 2050 in all scenarios. However, the increases are less pronounced in the low sediment scenarios indicating the importance of sediment to enhance marsh persistence at this site.

Generally, we project that all marsh sites will have very low wave retention values for all scenarios (Figure 14). We do project an increase in wave retention values at some sites between 2090 and 2110 under the low sediment/high sea level rise scenario but wave retention values are relatively low even for this scenario. Thus these marsh sites will likely continue to offer flood protection throughout the next century.

We project that tidal marsh birds will respond similarly to other sites along the Petaluma River with most sites maintaining high habitat value throughout the century under most scenarios (Figure 15). We do project a complete decline of all species at the Dry Island Wildlife Area at 2090 and 2110 for the low sediment/high sea level rise scenario (Figure 14) consistent with the conversion of marshes to mudlfats under this scenario (Figure 13).



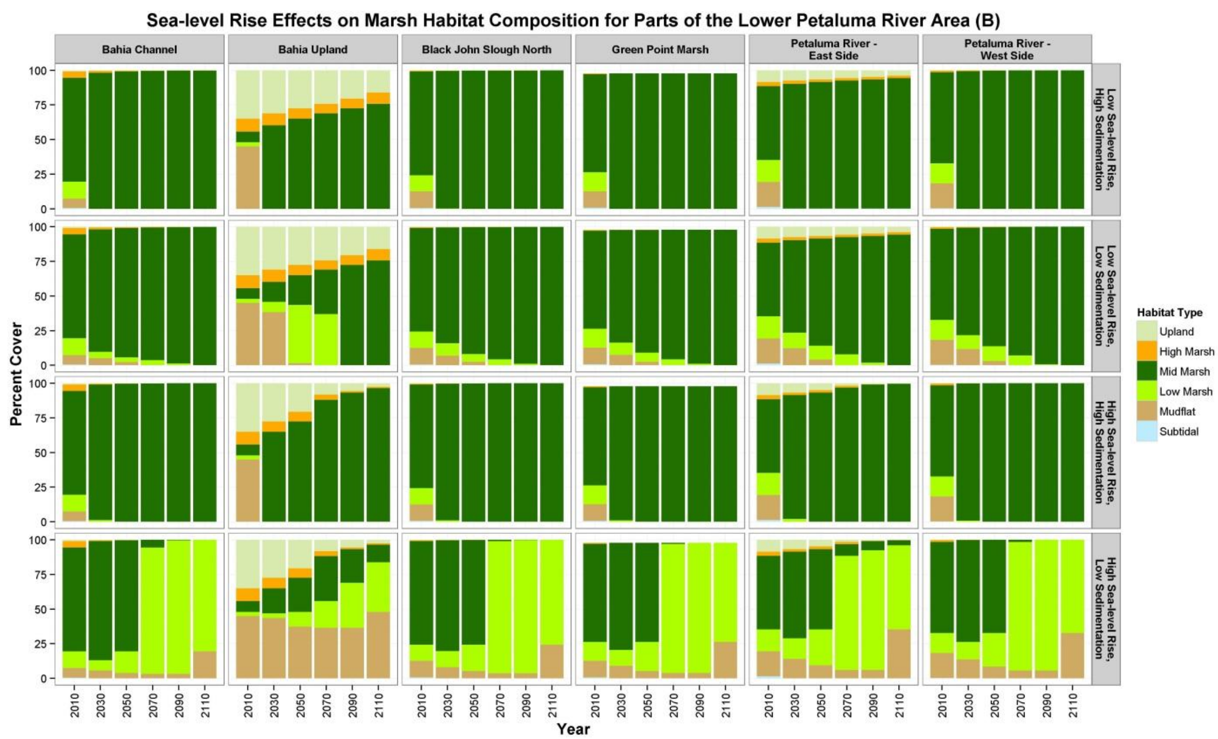


Figure 13. Marsh elevation projections for sites along the lower Petaluma River. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation. Bars do not always sum to 100% as areas of no data are shown as blank.

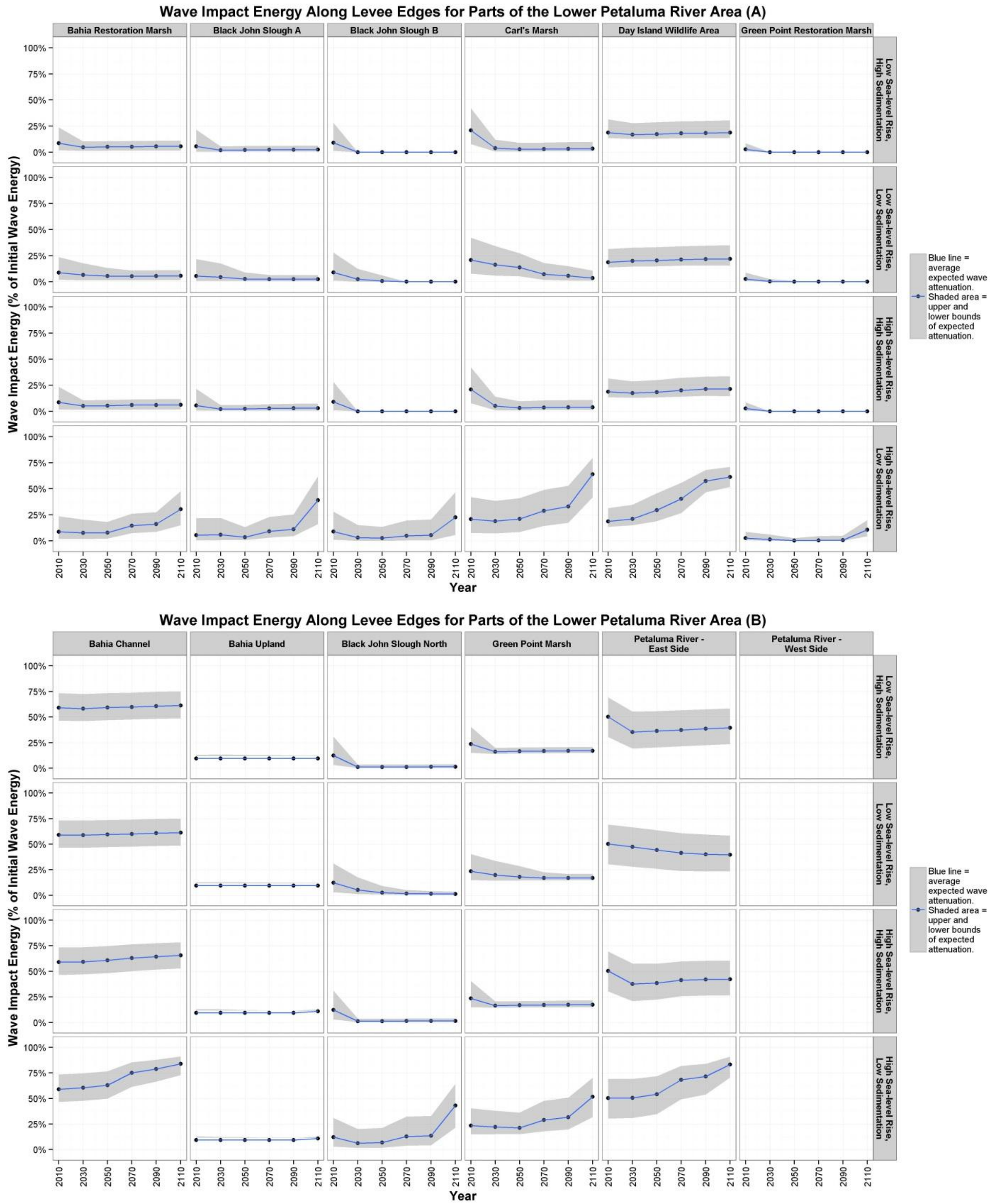


Figure 14. Wave retention (%) along levees for sites along the lower Petaluma River. We were unable to calculate meaningful wave attenuation values for sites with no lines due to areas of no data, not having a direct connection to open water, or a lack of levees (or other shore edges) in the site.

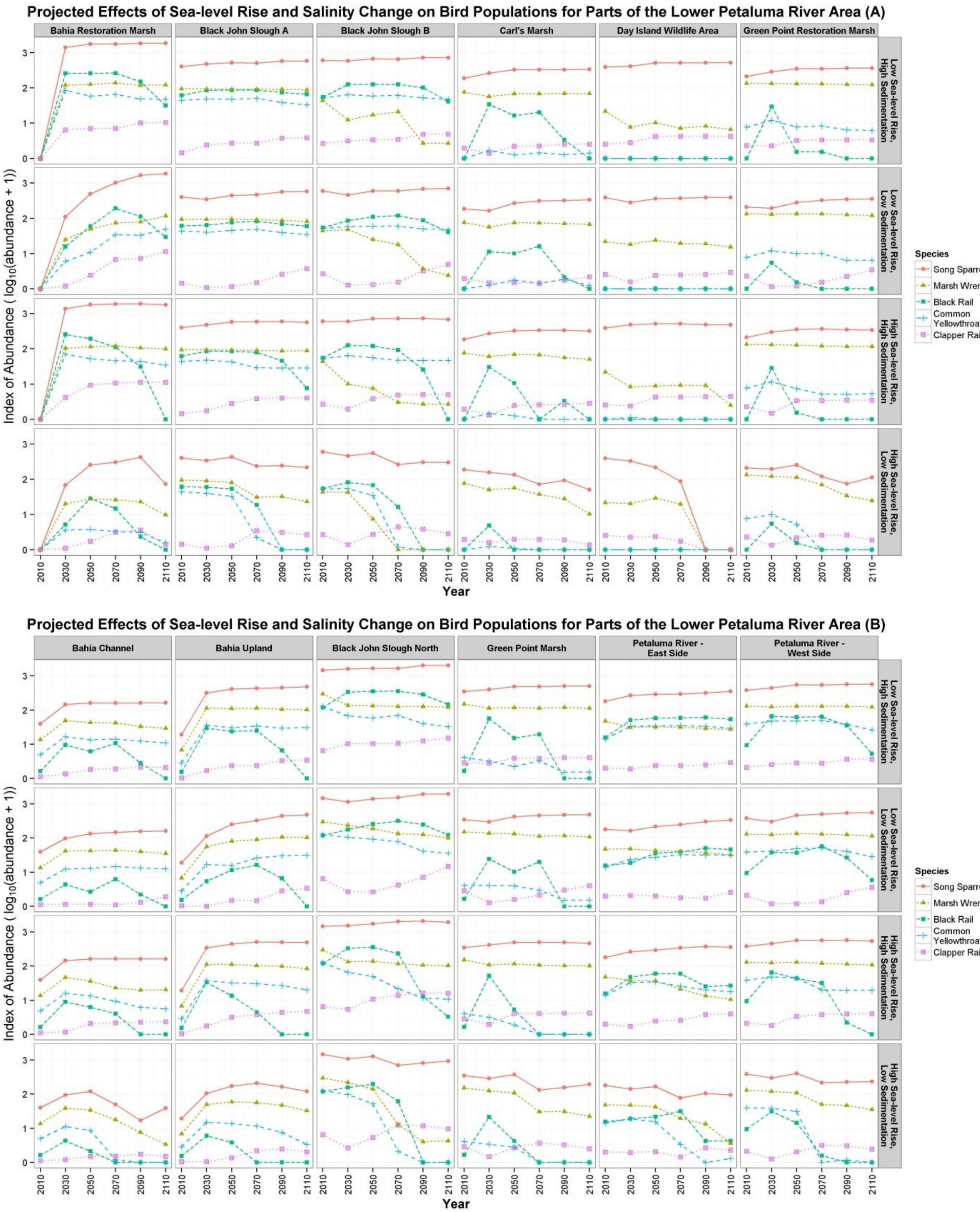


Figure 15. Projected tidal marsh bird abundance at sites along the lower Petaluma River.

Sonoma Baylands/Petaluma River Mouth

Low sediment = 100:150 mg/L, high sediment = 300 mg/L

We project the sites along the north side of the Petaluma RiverMouth (Figure 16) to be relatively less vulnerable to sea level rise. We project tidal marsh habitat to persist at these sites through 2090 for all scenarios. Between 2090 and 2110 we project that the Sonoma Baylands Restoration site will largely convert to mudflat, while the other two sites will be largely converted to a mix of low marsh and mudflat. The size of the marshes within the sites (Figure 16) and the resiliency of the marshes (Figure 17) leads to low wave retention values for all scenarios at all sites (Figure 18). We project consistently low wave retention values for all scenarios at all sites except for a small increase in wave retention between 2090 and 2110 in the low sediment/ high sea level rise scenario (Figure 19).

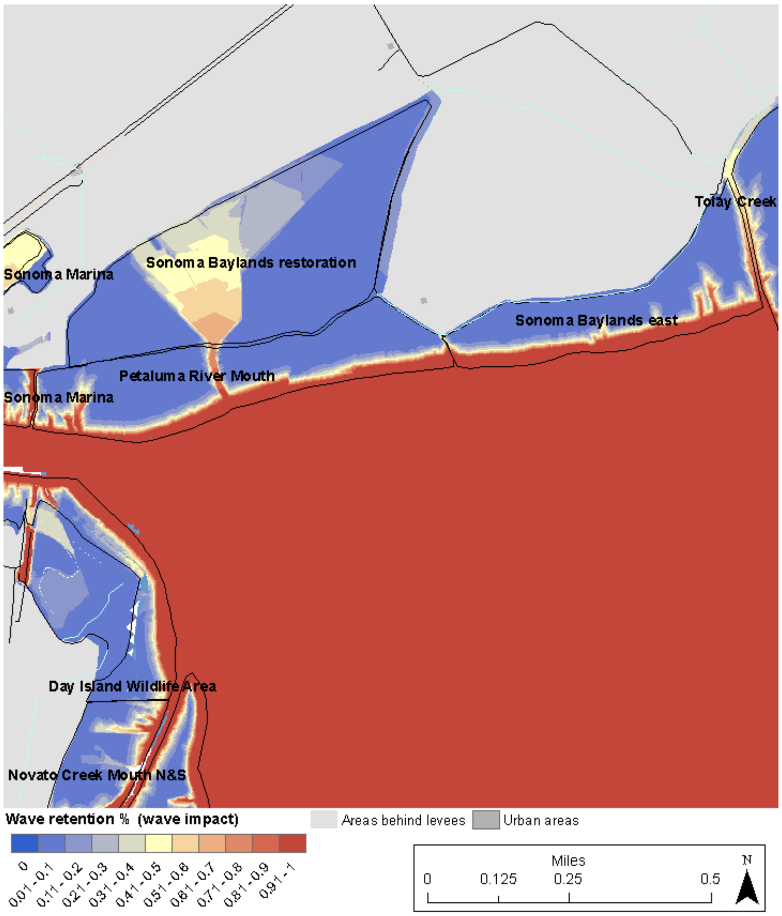


Figure 16. Wave retention (%) based on current (2010) conditions for sites along the Petaluma River Mouth.

We project that all sites have high to moderately high habitat value for all species except Common Yellowthroat (Figure 18). For the other species, we project little change in the number of birds that could potentially occur at these sites except for Black Rail which we project to increase in abundance from 2010 to 2030 and then decline with the rate of decline dependent on site or scenario (Figure 19).

Figure 17. Marsh elevation projections for sites along the Sonoma Baylands/Petaluma River Mouth. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation.

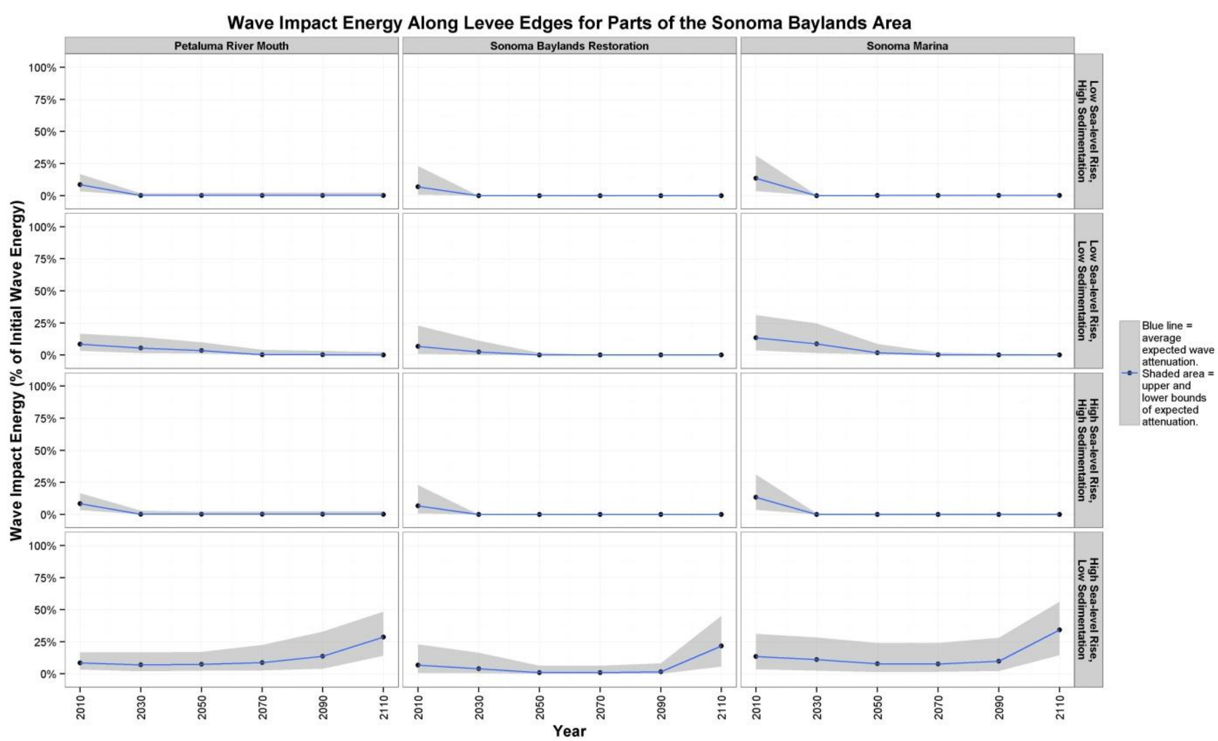


Figure 18. Wave retention (%) along levees for sites along the Sonoma Baylands/Petaluma River Mouth.

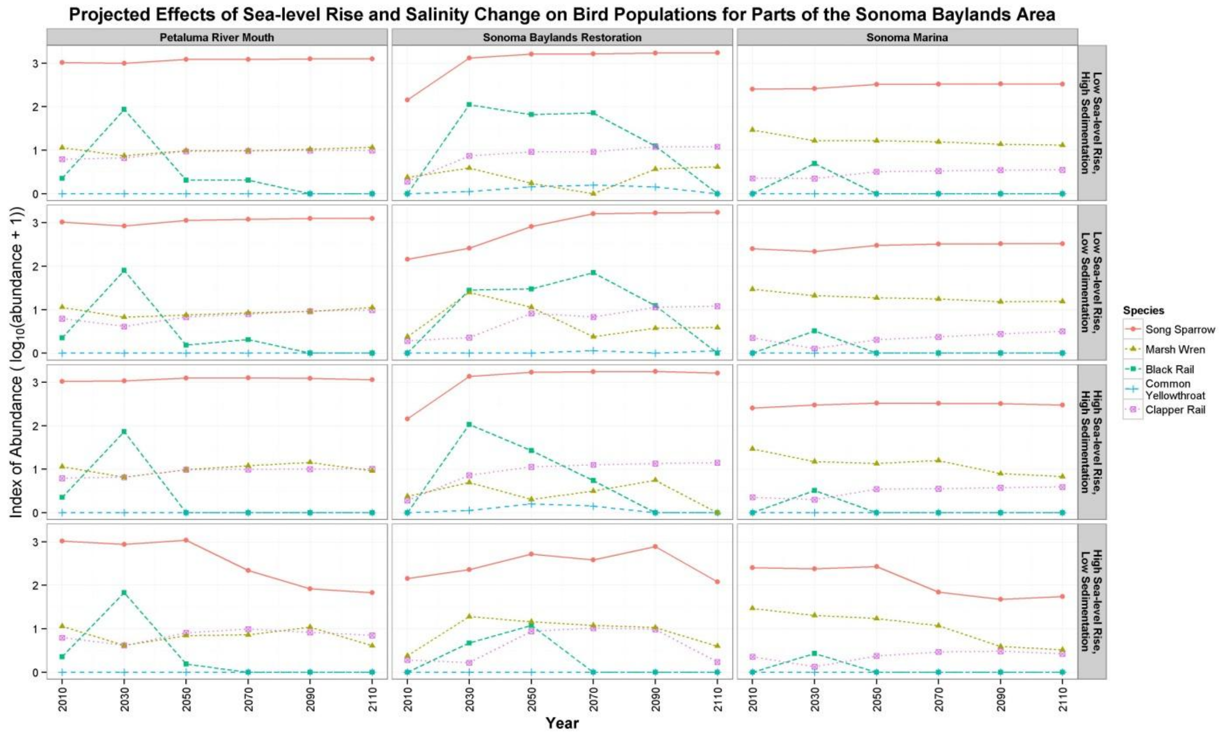


Figure 19. Projected tidal marsh bird abundance at sites along the Sonoma Baylands/Petaluma River Mouth.

Novato Creek

Low sediment = 100 mg/L, high sediment = 300 mg/L

We project sites along Novato Creek (Figure 20) to all respond to increasing sea level rise rates in a similar fashion. In all scenarios except for the low sediment/ high sea level rise scenario, we project increases in mid marsh habitat at the expense of all other habitat types (Figure 21). In the low sediment/ high sea level rise scenario, we project declines in mid marsh habitat starting between 2050 and 2070. Between 2070 and 2090, we project almost an almost complete transition of marsh habitat to mudflat or subtidal habitat.

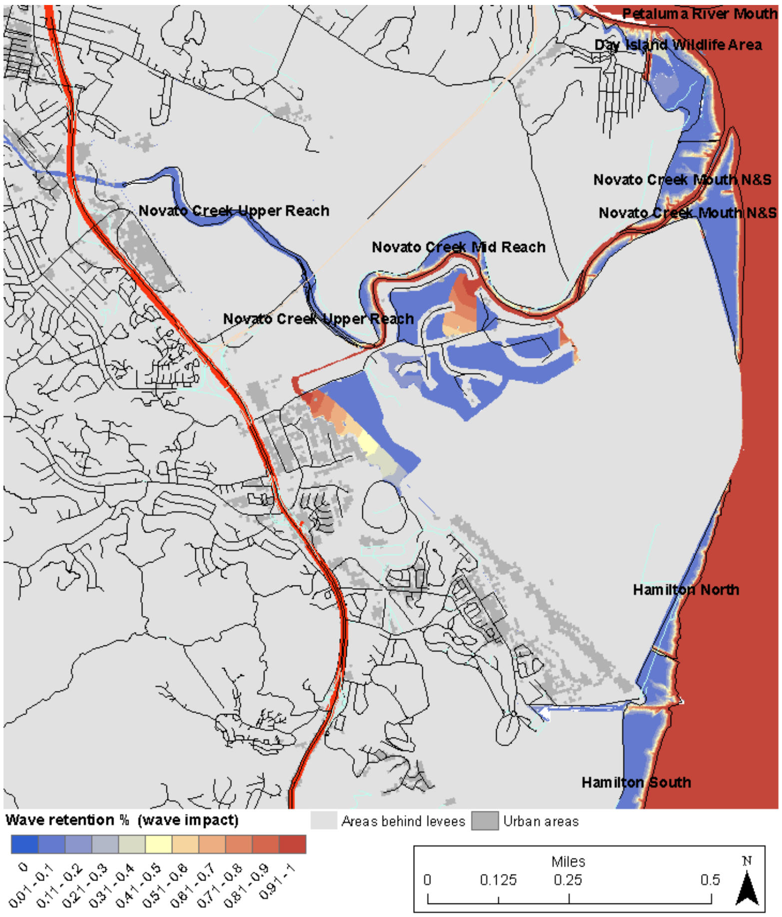


Figure 20. Wave retention (%) based on current (2010) conditions for sites along Novato Creek.

Similar to other sites in our North Marin sub-region, we project large sensitivities to the sediment scenarios with less sensitivity to the sea level rise scenario. With suspended sediment concentrations of 300 mg/L, we project that sites are resilient to high rates of sea level rise.

Our wave retention projections follow a similar pattern as the elevation projections (Figure 22). We project a decrease in wave retention for the high sediment scenarios between 2010 and 2030 (Figure 23). In all scenarios except the low sediment/ high sea level rise scenarios, we project relatively stable wave retention values along levees throughout the century. However, at all three sites, we project increasing wave retention values along levees in the low sediment/ high sea level rise scenario, particularly between 2070 and 2090.

In general, we project that all three sites along Novato will provide high quality habitat for the tidal marsh bird species (Figure 24). However, we do not project all species to be represented at all sites. For example, we don't project Common Yellowthroat to occur at the Novato Creek mouth but the species is projected to occur at the other two sites.

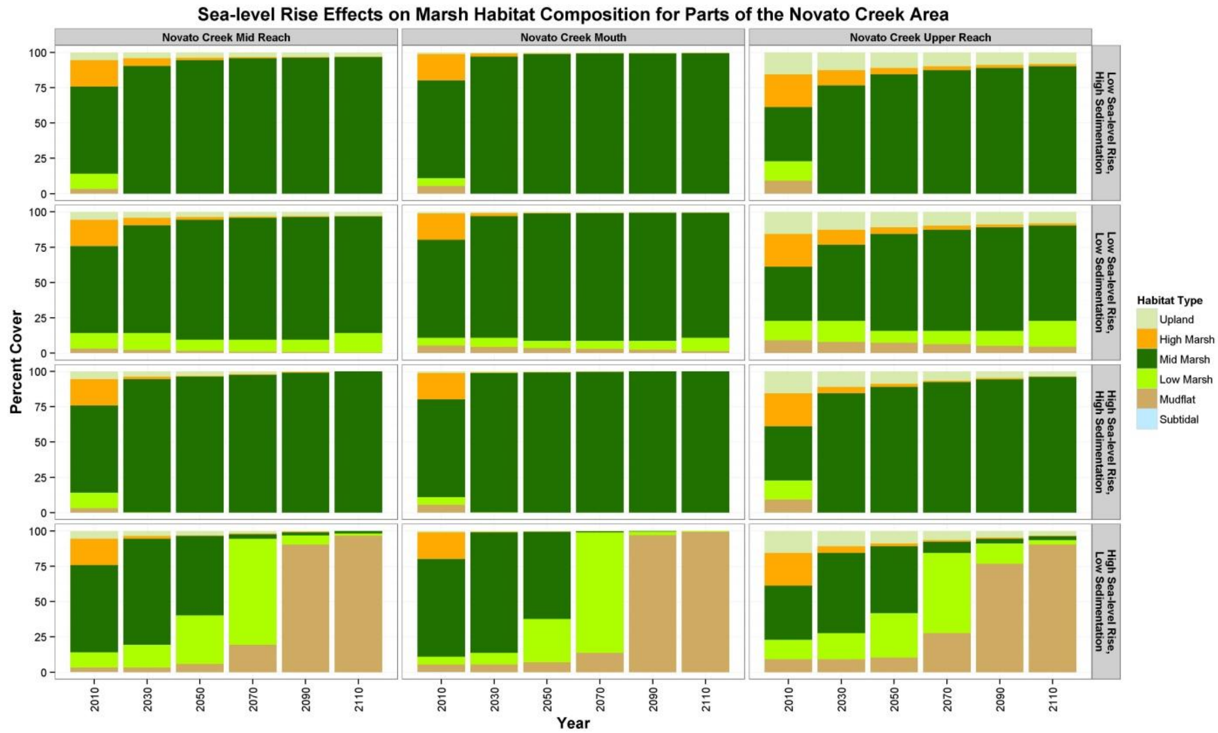


Figure 21. Marsh elevation projections for sites along Novato Creek. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation.

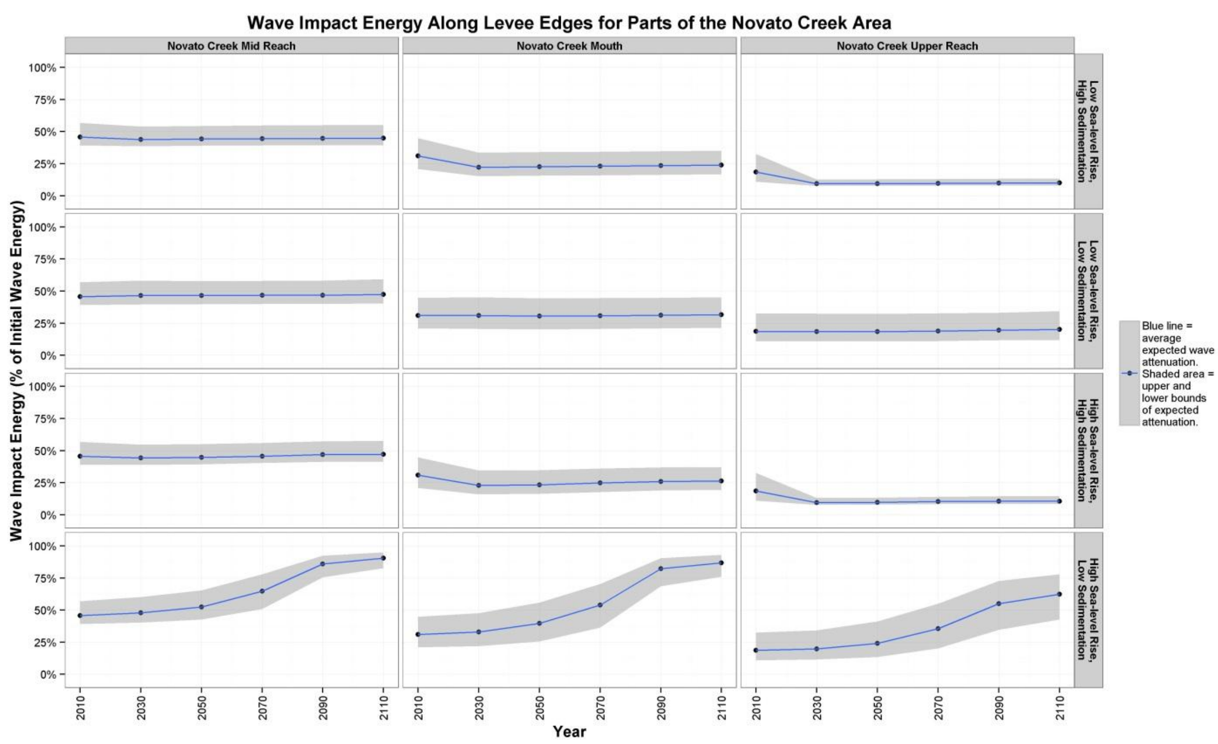


Figure 22. Wave retention (%) along levees for sites along Novato Creek.

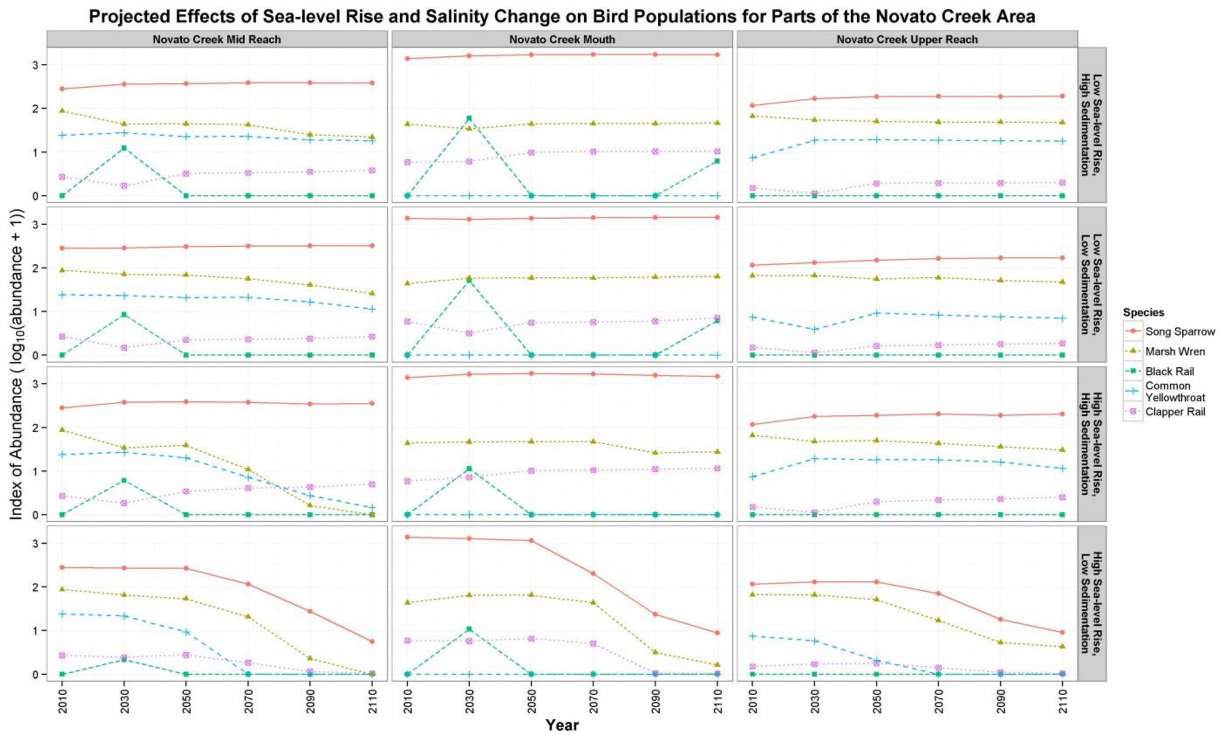


Figure 23. Projected tidal marsh bird abundance at sites along Novato Creek.

Gallinas Creek

Low sediment = 100 mg/L, high sediment = 300 mg/L

We project that sites along Gallinas Creek (Figure 24) will have broadly similar responses to sea-level rise. Under all but the high sea-level rise/low sedimentation scenario, we project that all six marshes will be almost entirely composed of mid marsh by 2030 and later (Figure 25). With such a high concentration of suspended sediment (300 mg/L), we project that sites are resilient to high rates of sea level rise—sea-level rise is only predicted to outpace sedimentation under the high sea-level rise/low-sedimentation scenario. Assuming this worst-case scenario, however, has all plots becoming over 90% mudflat by 2070 or 2090.

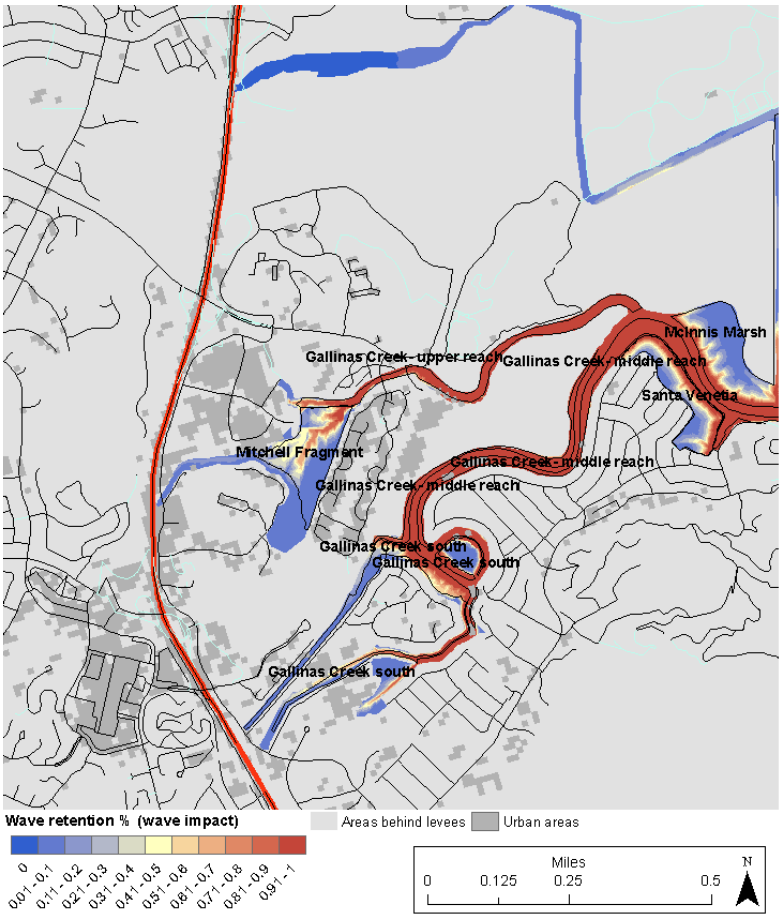


Figure 24. Wave retention (%) based on current (2010) conditions for sites along Gallinas Creek.

As the marsh habitat composition is relatively stable under the first three scenarios, so too are projected wave retention (Figure 26) and bird abundance (Figure 27) essentially constant from 2030-2110. However, the high sea-level rise/low-sedimentation scenario projects rapidly increasing wave retention and precipitous drops in bird abundance for all marshes. Under this combination, only three sites retain enough marsh to support any birds whatsoever, and only a remnant population of song sparrows at that.

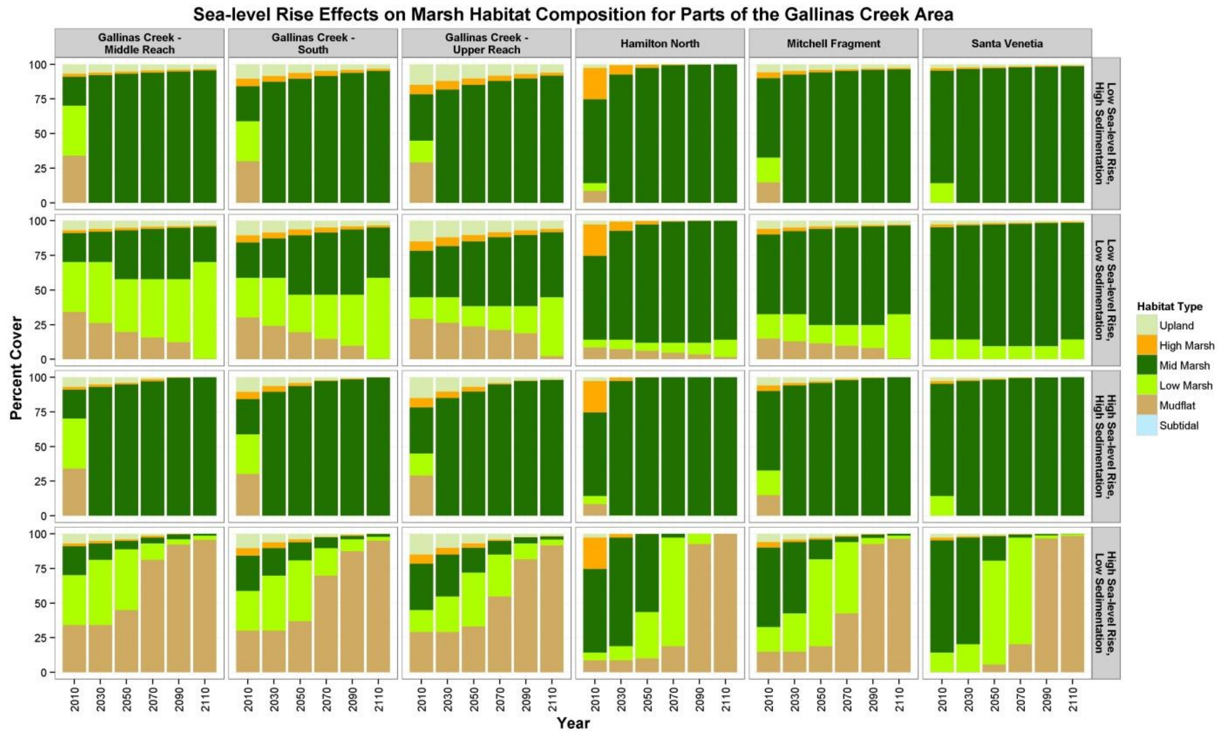


Figure 25. Marsh elevation projections for sites along Gallinas Creek. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation.

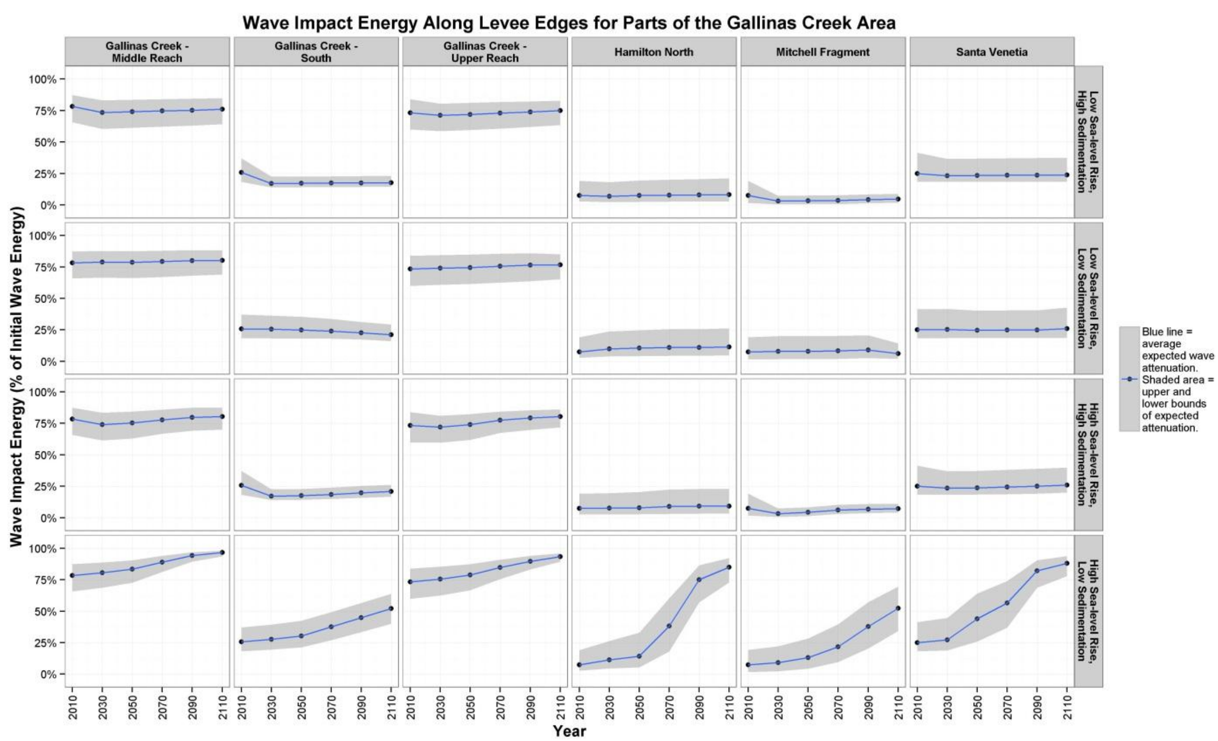


Figure 26. Wave retention (%) along levees for sites along Gallinas Creek.

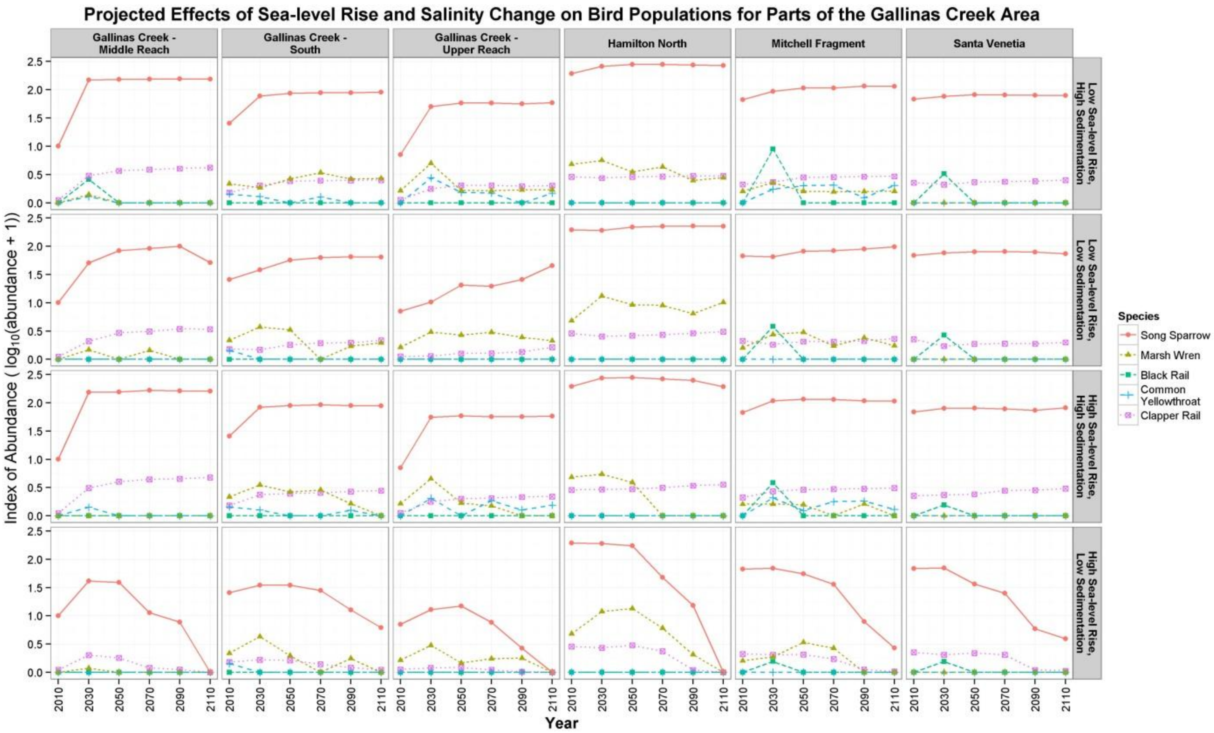


Figure 27. Projected tidal marsh bird abundance at sites along Gallinas Creek.

Gallinas Creek Mouth

Low sediment 100 mg/L, high sediment = 300 mg/L

We project that sites along the shore near the mouth of Gallinas Creek (Figure 28) will respond almost identically to those upstream. Marsh composition is projected to be similar across the first three scenarios, with all sites dominated by mid marsh habitat (Figure 29). However, when high sea-level rise is paired with low sedimentation, all four sites are projected to turn first into low marshes and then mudflats: under this scenario, all four sites will be over 90% mudflat in either 2090 or 2110. The amount of sediment in the water is the most important factor as to whether these sites keep up with sea-level rise or fall behind and turn to mudflats.

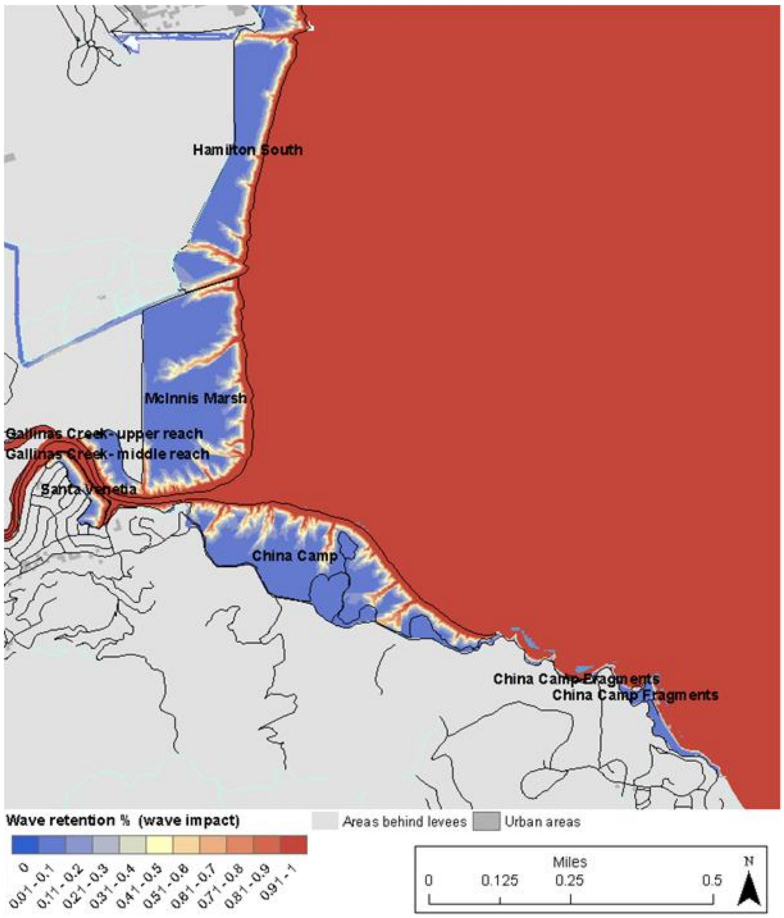


Figure 28. Wave retention (%) based on current (2010) conditions for sites along the shore near the mouth of Gallinas Creek.

The size and composition of these marshes currently provide a good buffer against incoming waves, with projected wave retention near 0% (Figure 30). This protection is projected to remain essentially steady for all scenarios except high sea-level rise/low sedimentation, where retention is projected to increase to upwards of 50% by the end of the century.

All sites except the China Camp Fragments currently have habitat suitable for a relatively large population of Song Sparrows and moderate populations of Marsh Wrens and Clapper Rails (Figure 31). These populations are projected to remain relatively steady under all but the high sea-level rise/low-sedimentation combination, which shows large declines for all species present.

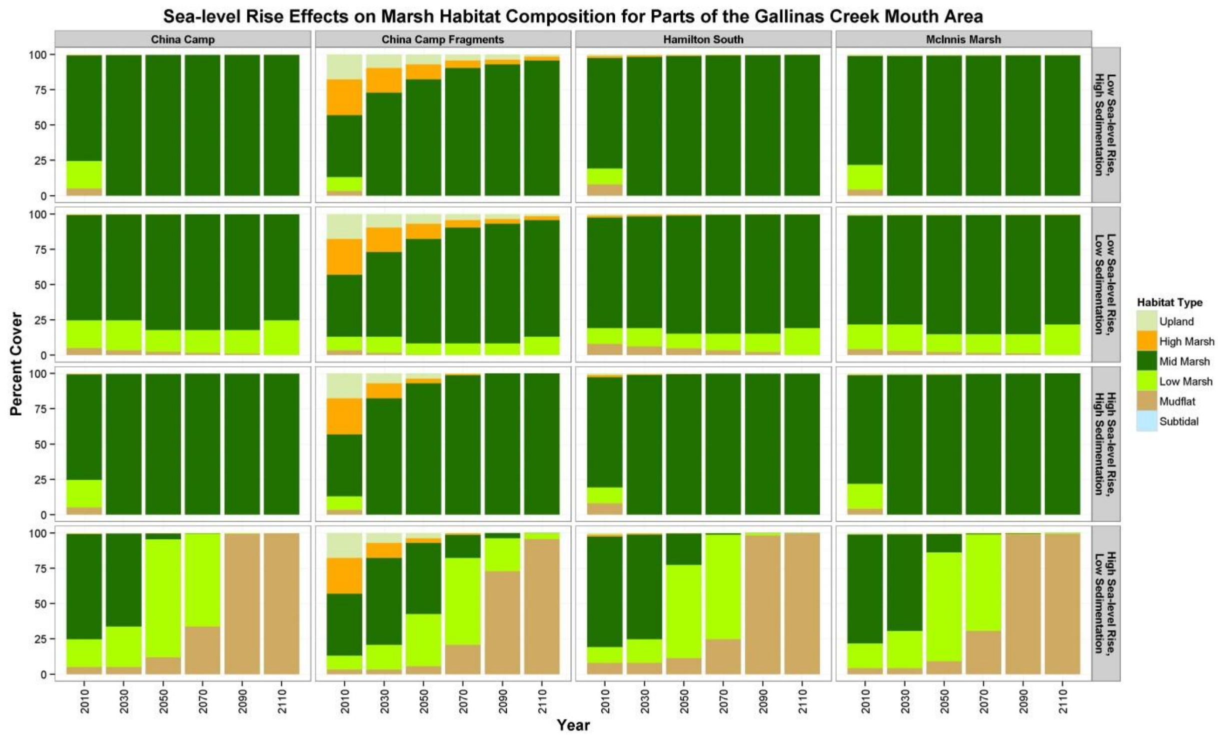


Figure 29. Marsh elevation projections for sites along the Gallinas Creek mouth. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation.

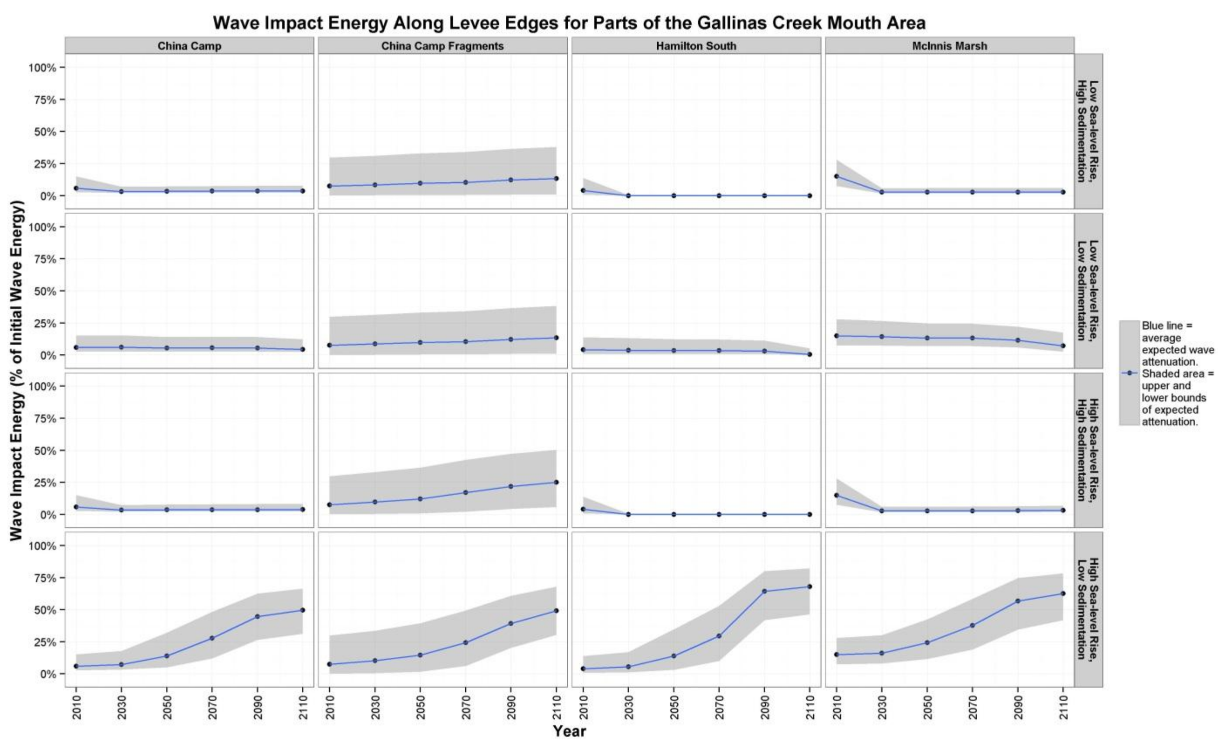


Figure 30. Wave retention (%) along levees for sites along the Gallinas Creek mouth.

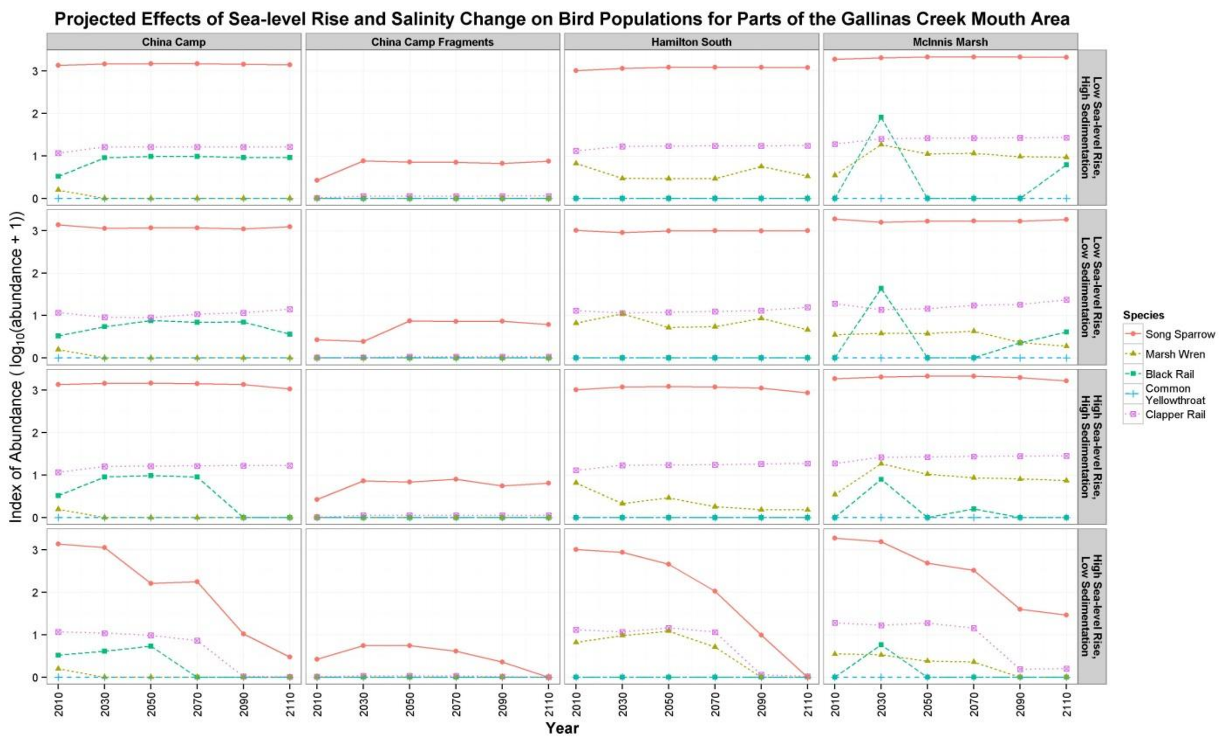


Figure 31. Projected tidal marsh bird abundance at sites along the Gallinas Creek mouth.

San Rafael

Low sediment 100 mg/L, High sediment 300 Mg/L

We project that marshes in the San Rafael area (Figure 32) will persist unless confronted with the high sea-level rise/low sedimentation scenario. Under the two scenarios of high sedimentation, vegetated areas of the marsh are predicted to expand greatly at the expense of mudflat, subtidal, and upland zones (Figure 33). The low sea-level rise/low-sedimentation scenario also projects marsh expansion, though much more gradually. Mid marsh increases the most for these three scenarios. Only in the high sea-level rise/low-sedimentation are these sites projected to be overtaken by rising waters, with mudflat comprising 75% or more (of areas with data) for all sites by 2090 or 2110.

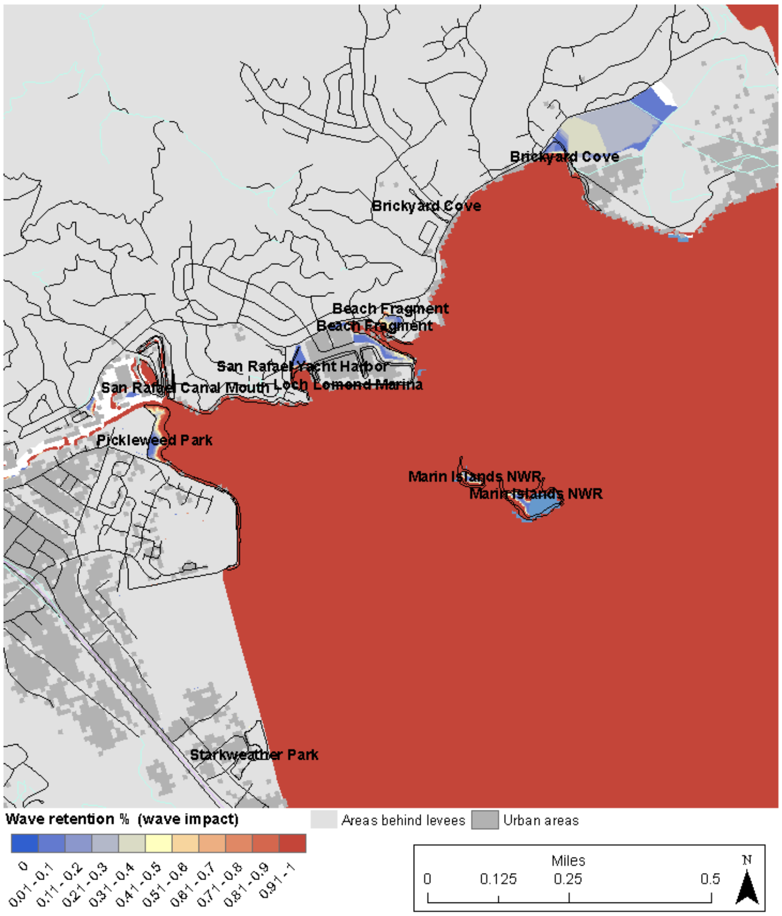


Figure 32. Wave retention (%) based on current (2010) conditions for sites in San Rafael.

Under current conditions, wave retention is moderately high to high at all sites but Starkweather Park (Figure 34). The high wave retention values are due to the narrow width of marshes within this region. Wave retention is projected to remain almost constant across the first three scenarios but increase dramatically under the high sea-level rise/low-sedimentation scenario as marshes turn to mudflats.

These sites currently have habitat suitable for a moderate number of Song Sparrows, with Pickleweed Park and San Rafael Creek Mouth also potentially home to Clapper Rails (Figure 35). These two species are projected to increase in abundance for the first three scenarios but drop off precipitously under the high sea-level rise/low-sedimentation scenario.

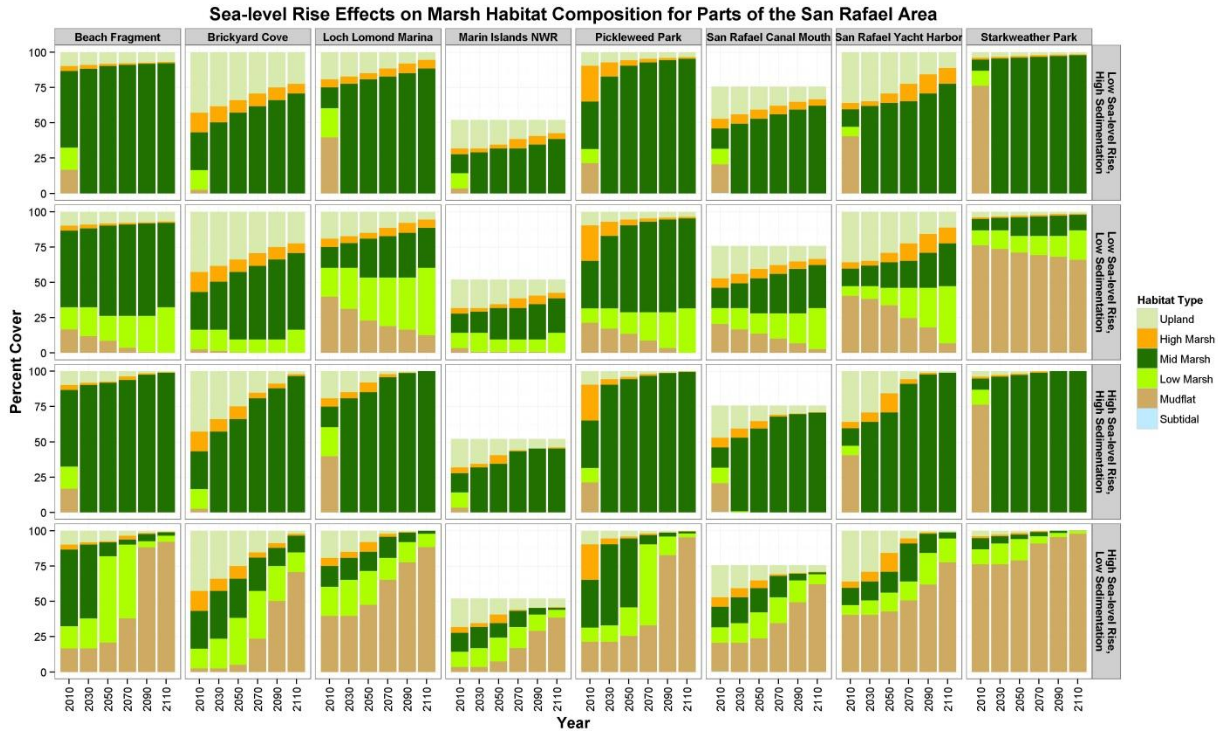


Figure 33. Marsh elevation projections for sites in San Rafael. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation. Bars do not always sum to 100% as areas of no data are shown as blank.

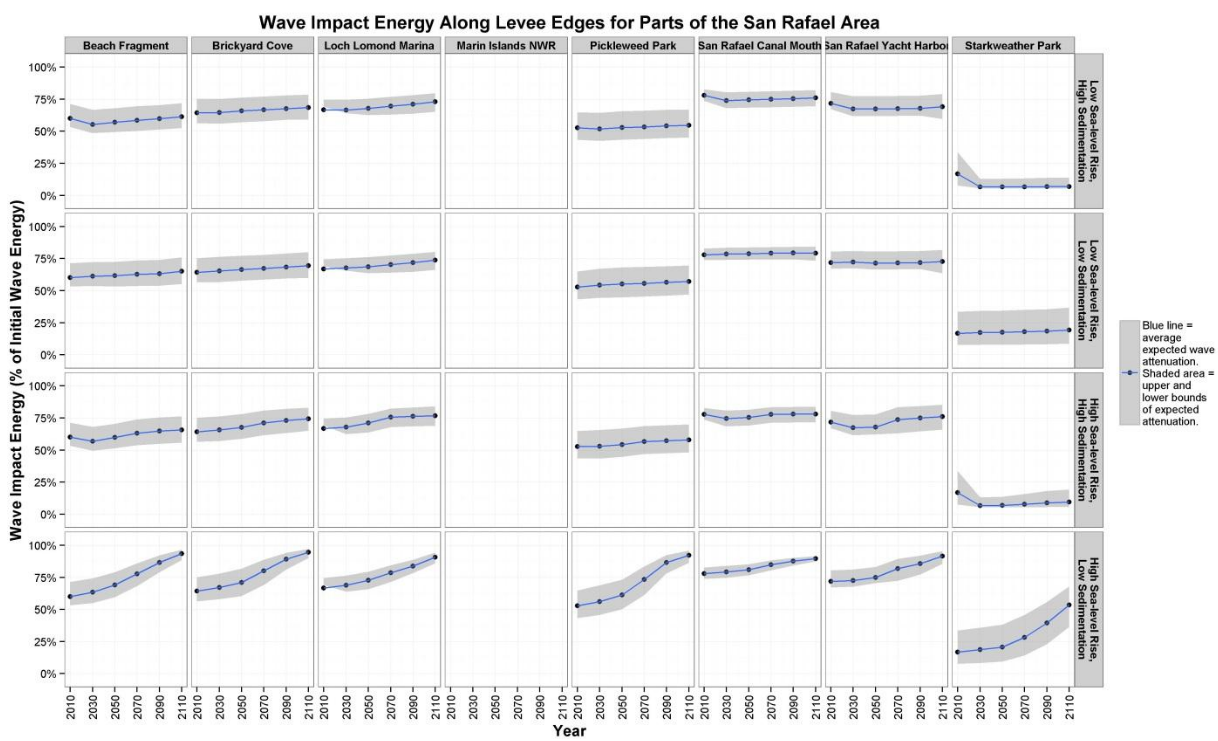


Figure 34. Wave retention (%) along levees for sites in San Rafael. We did not calculate wave retention for Marin Islands NWR due to a lack of data.

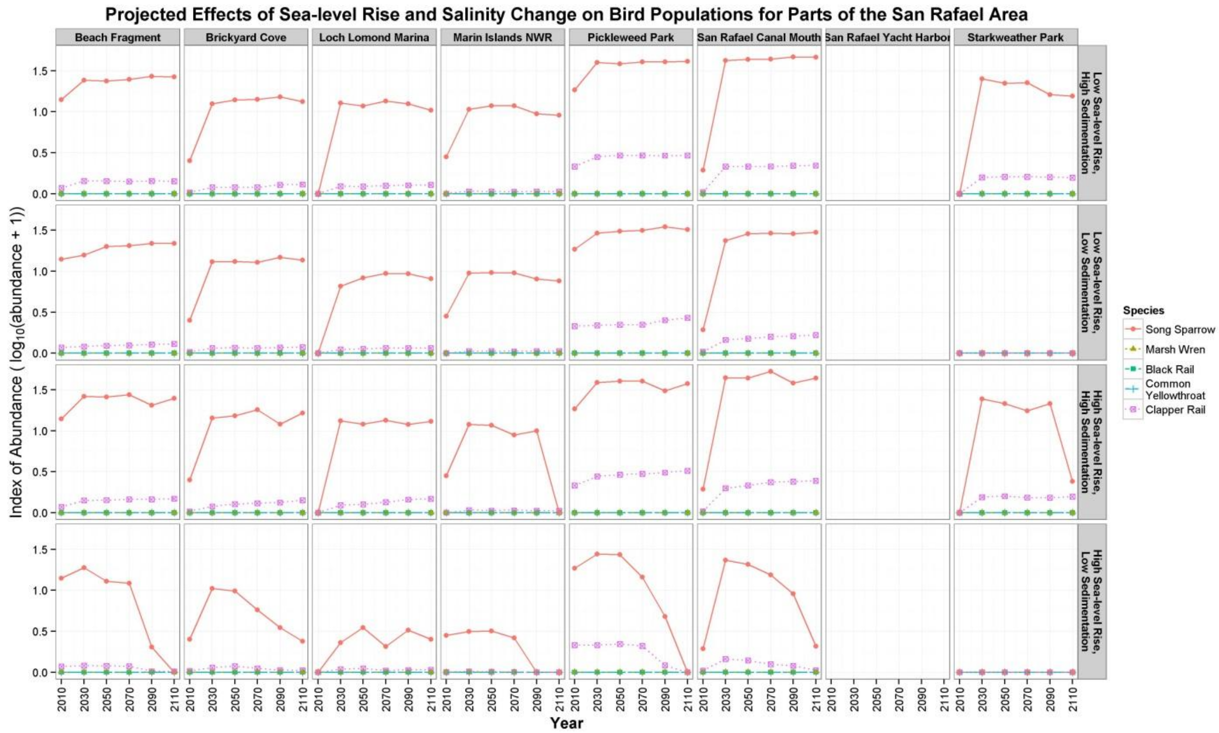


Figure 35. Projected tidal marsh bird abundance at sites in San Rafael. There was no data for projecting bird abundance at the San Rafael Yacht Harbor due to the artificial nature of the site.

Corte Madera Creek

Low sediment = 100 mg/L, high sediment = 300mg/L

Sites along Corte Madera Creek (Figure 36) respond very similarly to one another, with sediment concentration having a larger effect than sea-level rise rate. Under all scenarios but high sea-level rise/low-sedimentation, vegetated marsh areas are projected to outpace rising waters and expand in size (Figure 37). For the two high sediment scenarios, this increase is mostly in mid marsh habitat, at the expense of mudflats and upland areas. For the low sea-level rise/low sedimentation scenario, both mid and low marshes are projected to expand. Under the high sea-level rise/low sedimentation combination, mudflats are expected to dominate these sites by the end of the century, with vegetated marshes mostly squeezed out. All scenarios show a decrease in the projected high marsh areas.

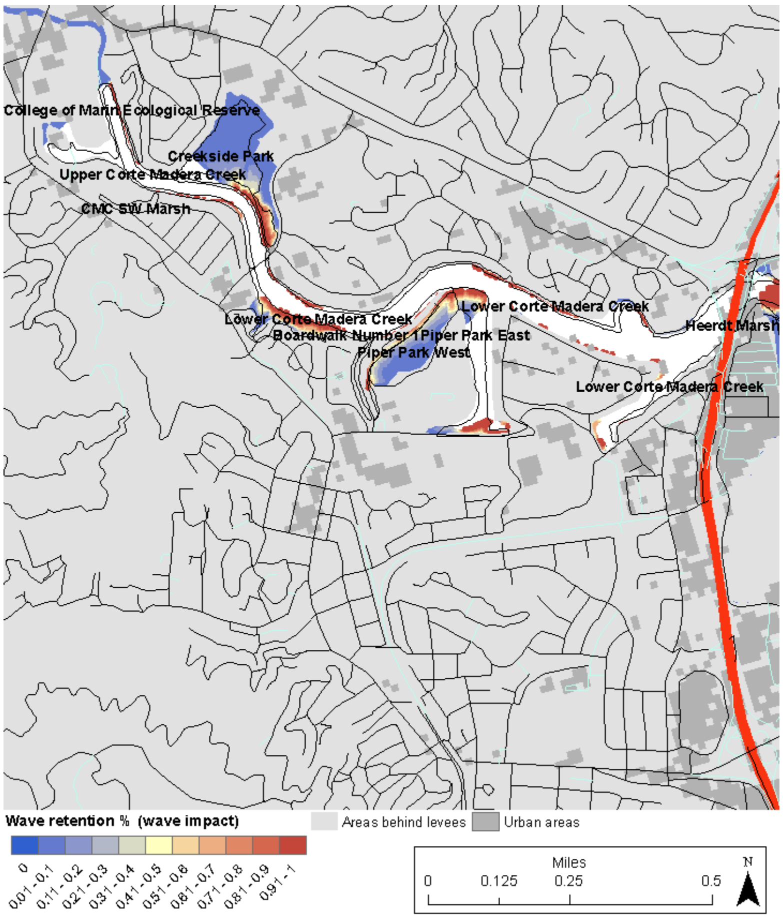


Figure 36. Wave retention (%) based on current (2010) conditions for sites along Corte Madera Creek.

Wave retention is projected to remain relatively steady for all sites under the first three scenarios (Figure 38). Wave retention is projected to increase dramatically under the high sea-level rise/low sedimentation scenario for those sites not already near 100%.

All sites along Corte Madera Creek are projected to be suitable for moderate numbers of Song Sparrows, and most for a very small population of the Clapper Rail (Figure 39). Under the first three scenarios, bird abundances are projected to remain relatively constant, though several sites do show an increase from 2010 to 2030. Clapper Rails and Song Sparrows are both projected to decrease under the final scenario of high sea-level rise and low sedimentation: Clapper Rails disappearing from all sites by 2110 and Song Sparrows from about half.

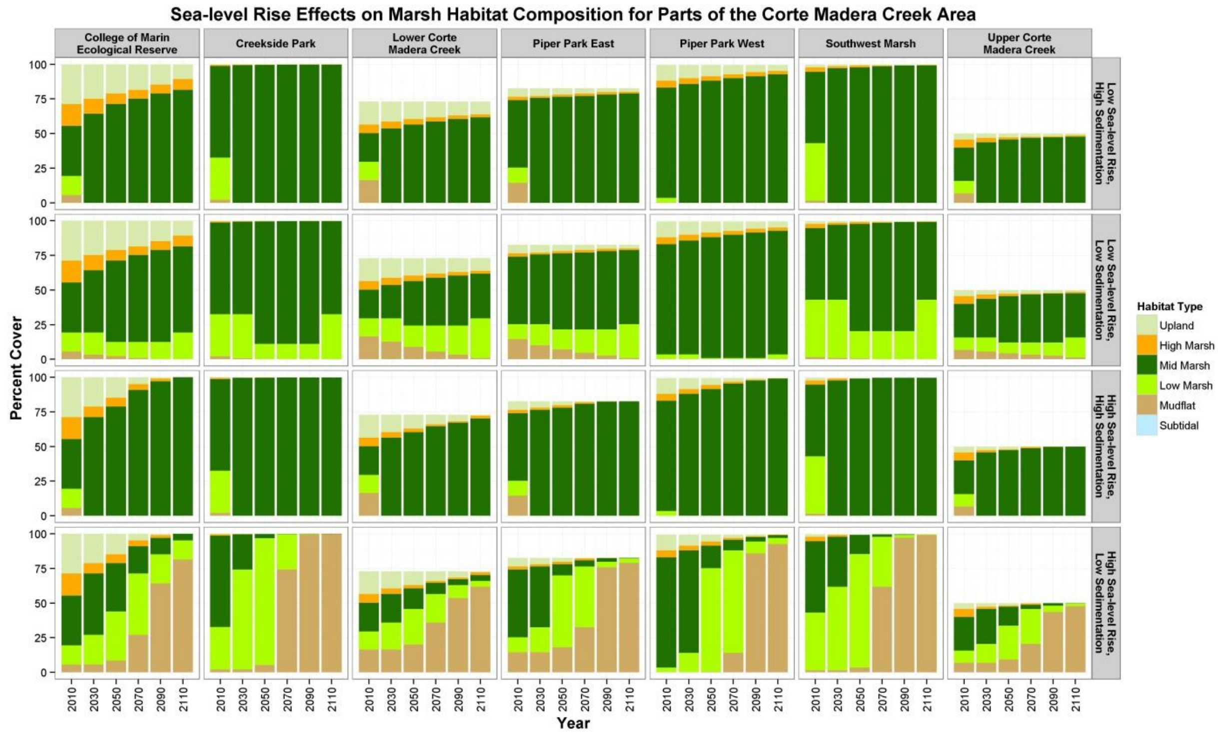


Figure 37. Marsh elevation projections for sites along Corte Madera Creek. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation. Bars do not always sum to 100% as areas of no data are shown as blank.

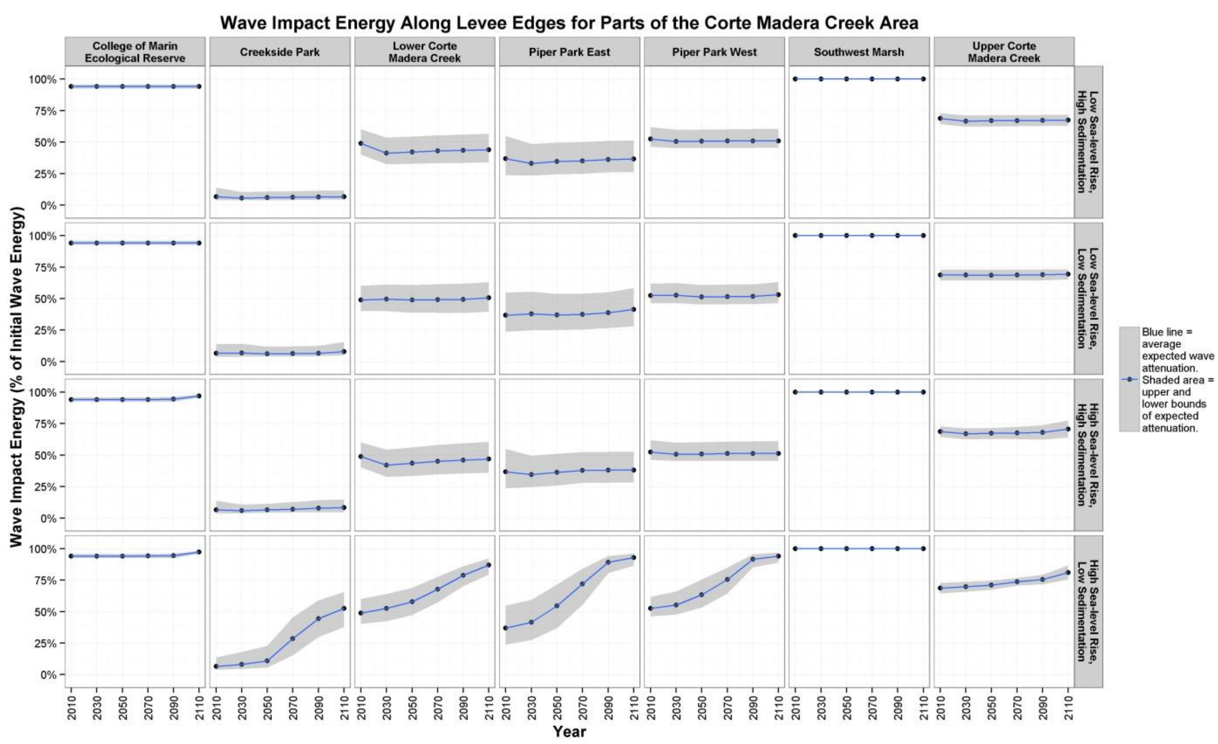


Figure 38. Wave retention (%) along levees for sites along Corte Madera Creek.

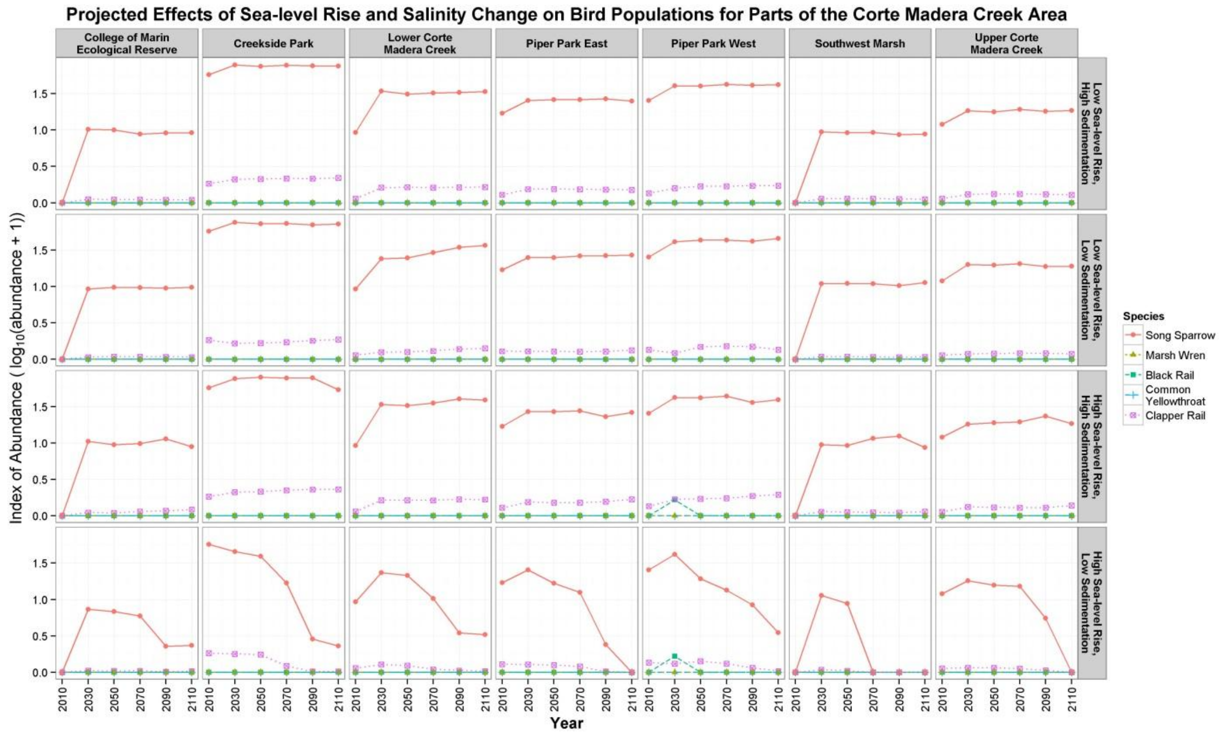


Figure 39. Projected tidal marsh bird abundance at sites along Corte Madera Creek.

Corte Madera Shore

Low sediment = 100 mg/L, high sediment = 300mg/L

The sites along the Corte Madera shoreline (Figure 40) have a different composition than most of the sites we've looked at previously. The majority of the sites currently have substantial mudflats, with those at the Corte Madera Creek Mouth and Marta's Marsh making up the largest percentages of their sites (Figure 41). Despite that, we project that the sites will respond in a similar way to those along the Corte Madera Creek. Under the two scenarios with high sedimentation, mid marsh grows at the expense of all other habitat classes. For the low sea-level rise/low sedimentation scenario, we project that low marshes will expand most, extending into areas previously covered by mudflats. However, when high sea-level rise is coupled with low sedimentation, we project an expansion of mudflats across the board. Curiously, this growth in mudflats isn't seen until 2070.

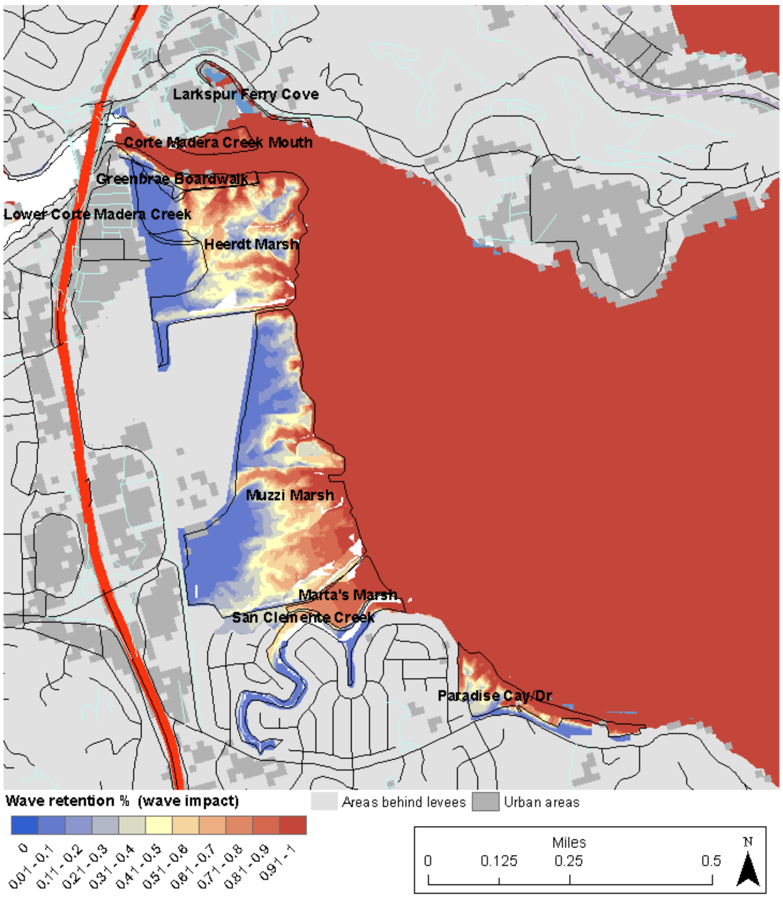


Figure 40. Wave retention (%) based on current (2010) conditions for sites along the Corte Madera shoreline.

Wave attenuation is largely constant across time and marsh composition for the first three scenarios (Figure 42). The final scenario, with high sea-level rise and low sedimentation, projects increases in wave retention as marshes shrink.

All sites but the Larkspur Ferry Cove are projected to have habitat suitable for moderate Song Sparrow populations and low Clapper Rail populations (Figure 43). We project that these two species will be relatively stable for the first three scenarios. Under the final scenario of high sea-level rise and low sedimentation, however, we project rapid decreases in abundance for these two species starting around 2050 which culminates in their removal from all sites by 2110.

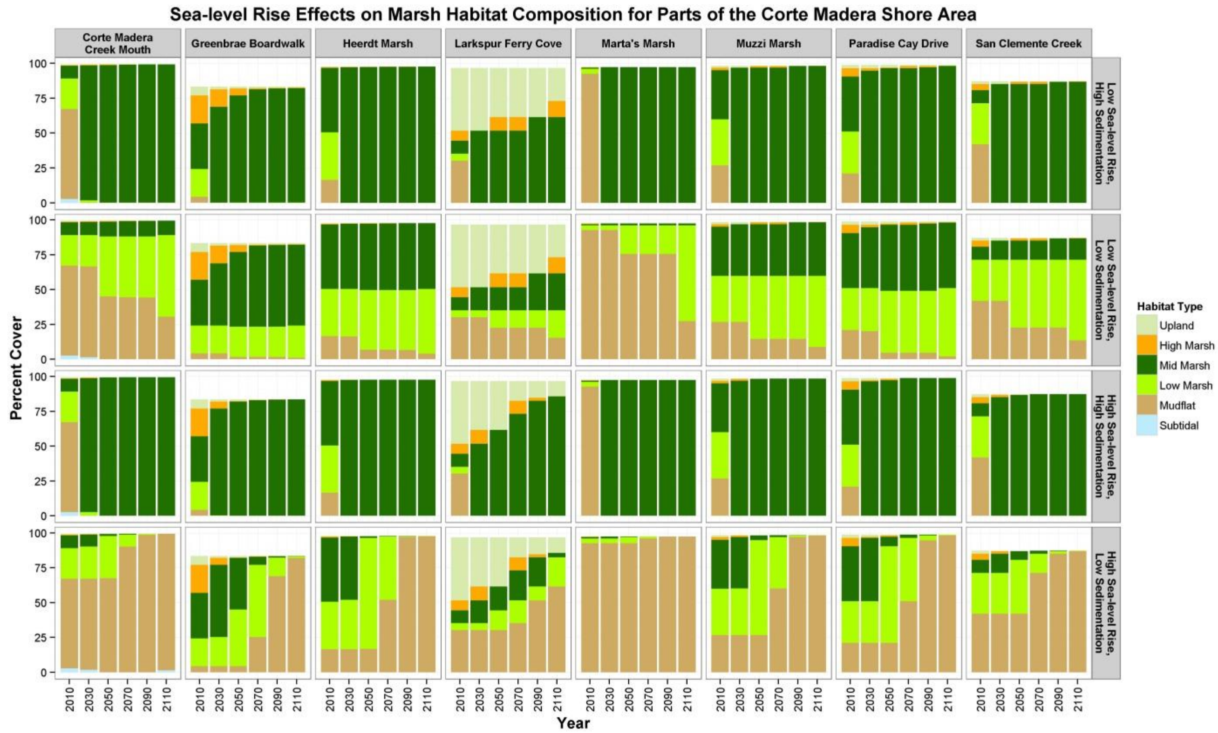


Figure 41. Marsh elevation projections for Corte Madera Shore sites. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation. Bars do not always sum to 100% as areas of no data are shown as blank.

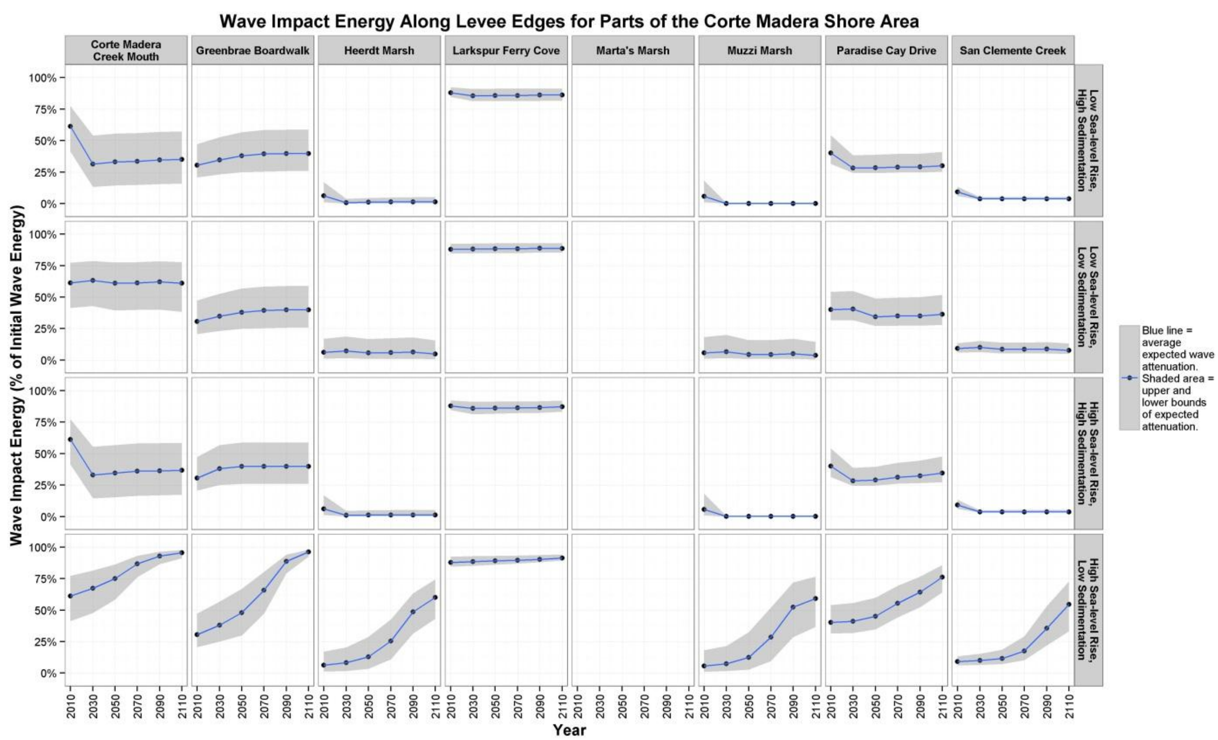


Figure 42. Wave retention (%) along levees for sites along the Corte Madera shoreline. We were unable to calculate meaningful wave attenuation values for Marta's Marsh due to areas of no data and a lack of levees (or other shore edges) in the site.

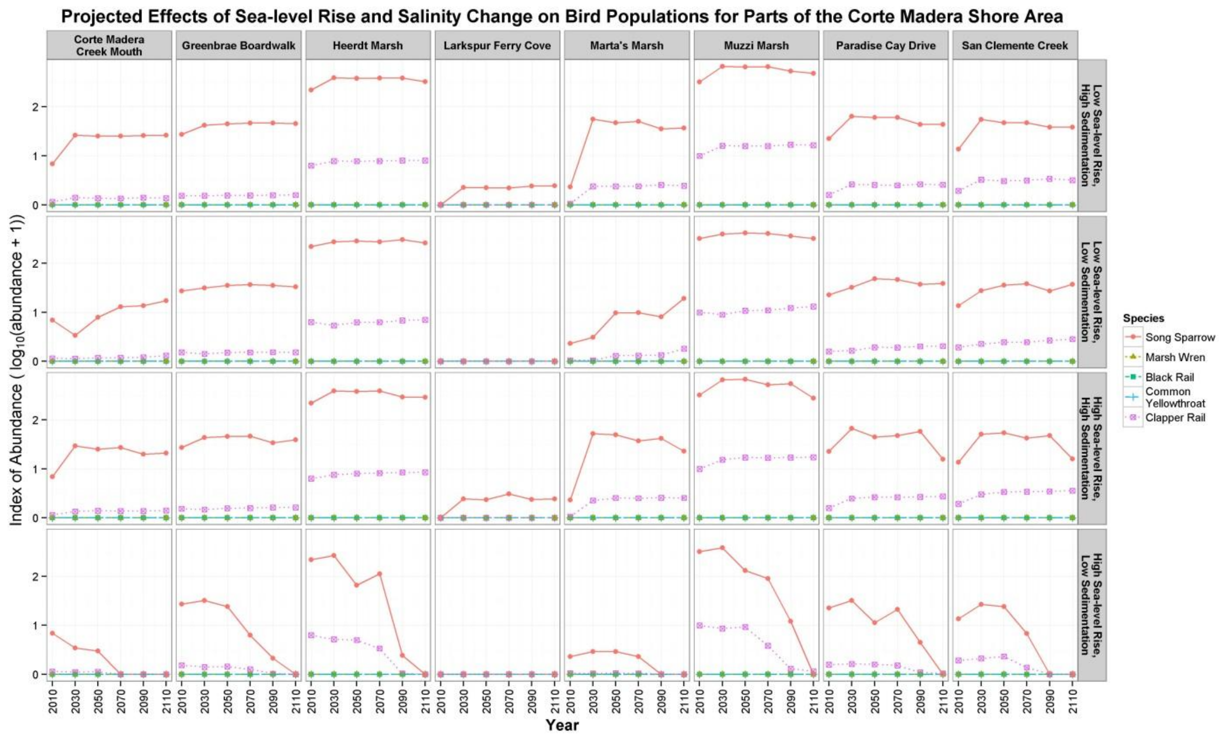


Figure 43. Projected tidal marsh bird abundance at sites along the Corte Madera shoreline.

Richardson Bay

Low sediment = 25 mg/L, high sediment = 50 mg/L

Unlike many of the other North Bay areas, sites in Richardson Bay (Figure 44) are projected to be relatively insensitive to sedimentation and thus more vulnerable to sea-level rise. Sediment levels in Richardson Bay are not only low, do not vary much between our low vs. high sedimentation assumption. As a result, marshes in Richardson Bay lose ground to sea-level rise under all scenarios, even with the most optimistic combination of low sea-level rise and high sedimentation (Figure 45). All eight sites show an increasing amount of mudflat and subtidal zones across time. This increase first occurs at the expense of upland areas as marshes migrate upslope but the marsh quickly runs into barriers that prevent further upward movement. Under scenarios of high sea-level rise, we project that subtidal and mudflat zones will cover over 95% of the area at each site but Blackie's Pasture by 2110.

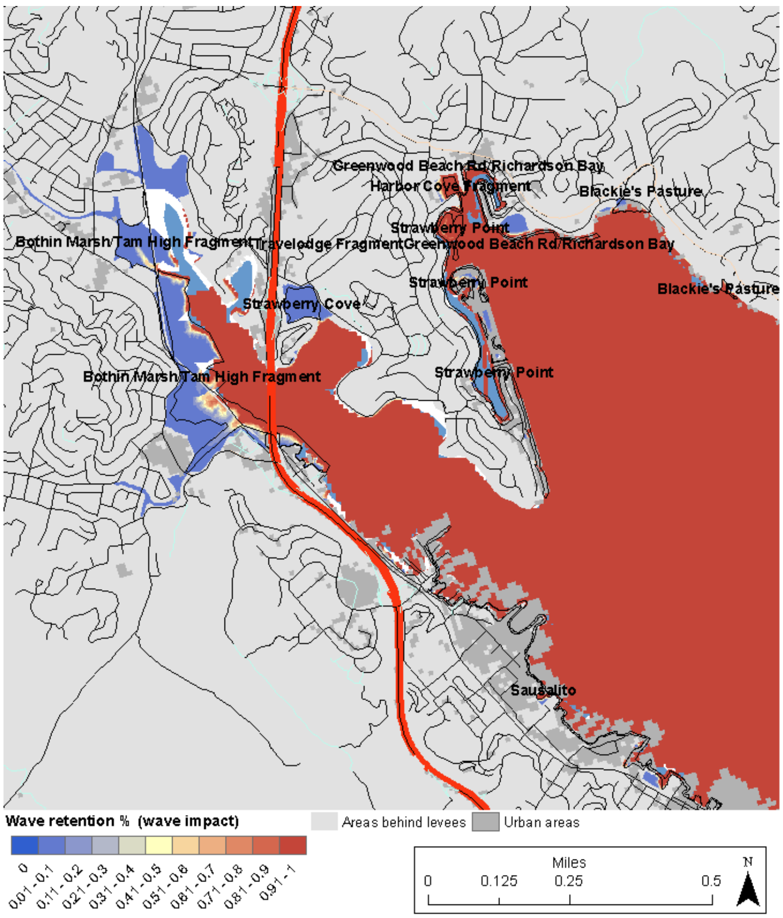


Figure 44. Wave retention (%) based on current (2010) conditions for sites in Richardson Bay.

Wave retention starts out relatively high for over half of these sites (Figure 46), mostly because these sites tend to be narrow. Wave retention increase across all scenarios as marshes turn to mudflats and subtidal areas, but the increase is most pronounced for the two scenarios including high sea-level rise.

With the exception of Bothin Marsh, Song Sparrow is the only species projected to be present under any scenario, and only at relatively low abundances (Figure 47). Bothin Marsh is projected to be suitable for a moderate number of Song Sparrows in addition to a small population of Clapper Rails. Under both scenarios with low sea-level rise, bird abundances are projected to be generally stable or increasing. Both scenarios of high sea-level rise project bird populations decreasing, most to zero by 2110.

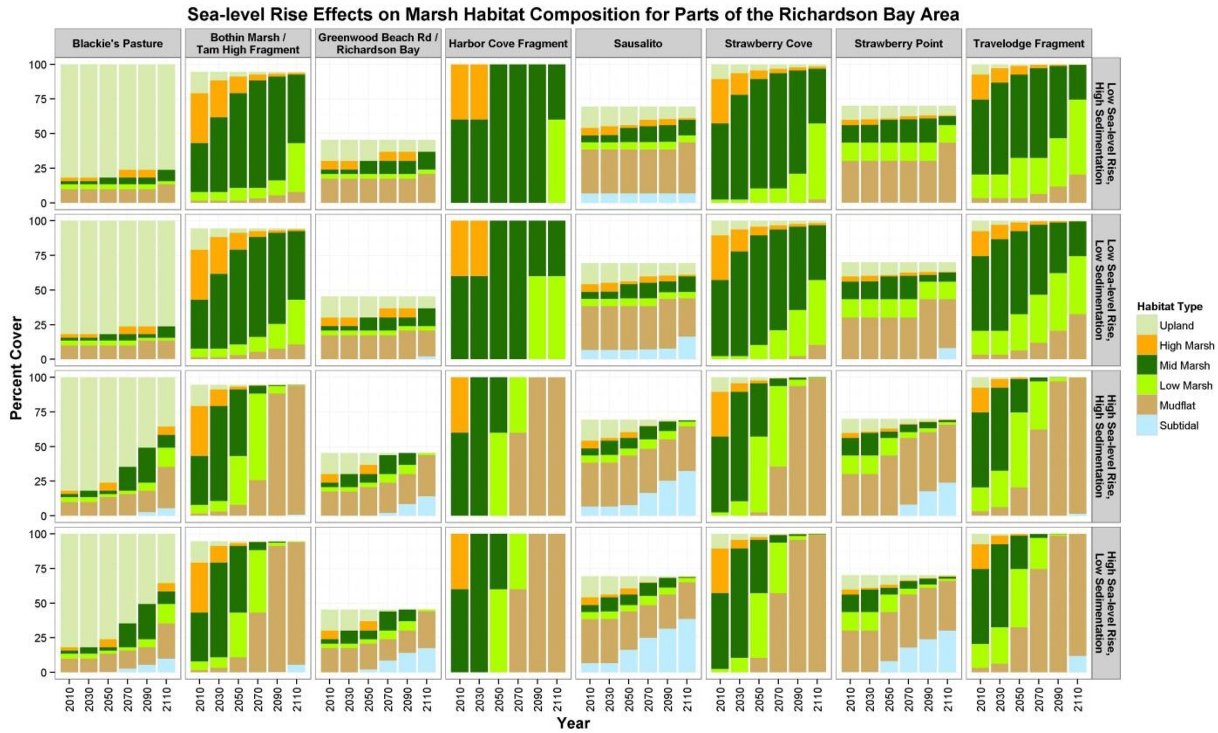


Figure 45. Marsh elevation projections for sites in Richardson Bay. The relative amount of projected sedimentation vs. sea-level rise determines future marsh elevation. Bars do not always sum to 100% as areas of no data are shown as blank.

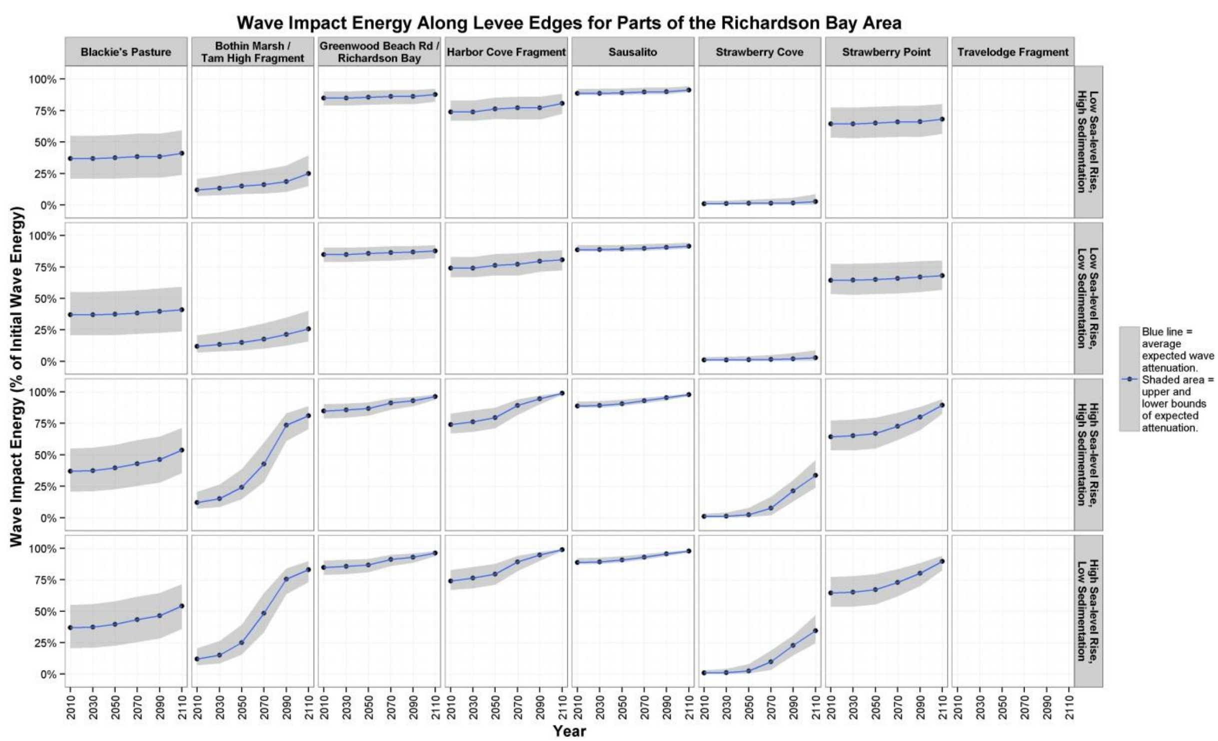


Figure 46. Wave retention (%) along levees for sites in Richardson Bay. We did not calculate wave retention for the Travelodge Fragment as it is not connected by open water to the Bay.

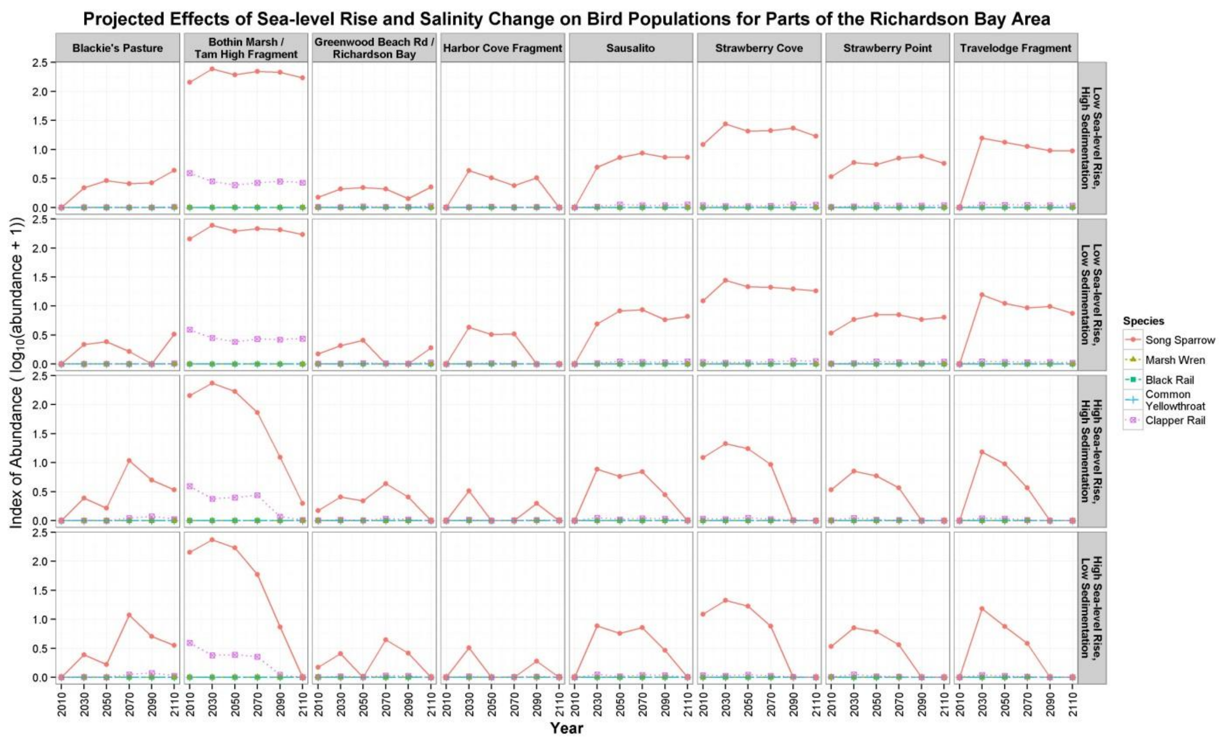


Figure 47. Projected tidal marsh bird abundance at sites in Richardson Bay.

Case studies

Here we provide the results for three case studies which were chosen based on stakeholder needs. The case studies are meant to illustrate how the decision support tool can be used to conduct a vulnerability analysis to sea level rise.

Vulnerability assessments are usually comprised of three components: 1. Exposure or the amount of change a place or species experiences. 2. Sensitivity or how much a location or species changes in response to exposure. 3. Adaptive capacity or the ability of a location or species can adjust to accommodate future changes. For these analyses, the exposure was prescribed by the differences in each of our future scenarios of sea level rise and suspended sediment. We estimate sensitivity of tidal marsh ecosystems by looking at the changes in marsh elevation, wave impact and tidal marsh bird abundance in response to each scenario in the sections above. Finally, we estimate adaptive capacity in several ways. We assume that marshes have some adaptive capacity if they persist under the high sediment scenario because our models indicate that active sediment management could ensure marsh resilience to sea level rise. We also assume that active sediment management is more likely to be successful in areas with naturally high levels of suspended sediment concentrations. We also include in our assessment of adaptive capacity an analysis of the land use adjacent to present day marshes. This analysis shows what types of land uses occupy potential marsh habitat if levees are removed or realigned in the future and marshes are restored or transgress upslope. However, in highly urbanized areas, there is unlikely to be the political will to implement an “abandon and retreat” strategy, where current infrastructure is removed to allow tidal marsh restoration or transgression, so we assume adaptive capacity is lower for these land cover types. Similarly, owners and managers of agricultural areas may be unwilling to abandon their lands to tidal influences resulting in a lower estimate of adaptive capacity. However, there have been cases within the north bay where agricultural lands are being restored to tidal marsh (e.g. Sonoma Baylands) and thus we assign a moderate estimate of adaptive capacity to agricultural land cover types. We assume that developed open space areas have moderately high levels of adaptive capacity as the public and decision makers may be more willing to accept a conversion of these land cover types to tidal marsh habitat. Finally, we assume that vegetated and grassland areas have the highest adaptive capacity as the conversion to tidal marsh habitat in these areas will be a change from one habitat type to another. We assume that stakeholders will be less likely to be opposed to this type of habitat conversion. We assign an ordinal ranking of vulnerability by combing our estimates of site sensitivity and adaptive capacity to each case study site.

Methods

We looked at three case study areas in the Bay including 1) Inner Richardson Bay, 2) Gallinas Creek, and 3) Novato creek (Figure 47).

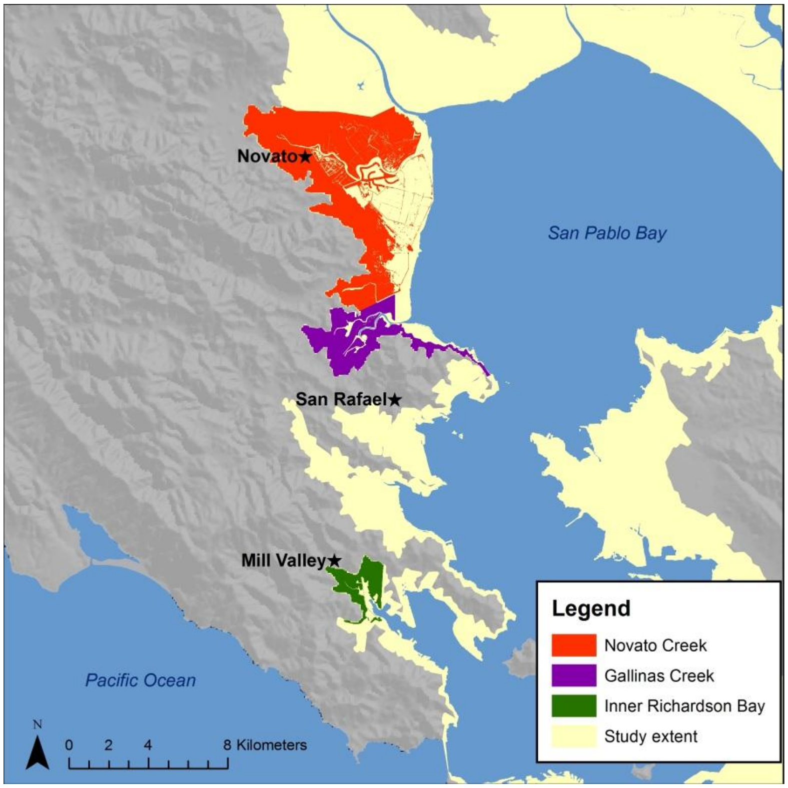


Figure 47. The geographic regions covered in our case studies.

Adaptive Capacity

We examined land use adjacent to present day marshes and the potential for marsh expansion into these areas. While there is relatively little land available for natural marsh expansion, much more land is available that is currently blocked from tidal inundation (e.g., behind levees; Stralberg et al. 2011). Here we examine these blocked areas to get a sense of the potential for marsh expansion given levee removal or realignment. While urban areas are unlikely to be abandoned to allow marsh expansion, we include them in our analysis for comparative purposes.

Within each study area we calculated the total area that would reach marsh habitat type elevations assuming the same sediment and organic matter accumulation used within the marsh98 model. Calculations were run using the Tabulate Area tool in ArcGIS 9.3.1 (ESRI 2009). We summarized the results by land use type using satellite data and land cover types available from the Multi-Resolution Land Characteristics Consortium (Fry et al. 2006). This data set, called the National Land Cover Database (NLCD), is comprised of 16 land cover types applied across the United States and is produced at a 30 m resolution. To match our elevation layers, NLCD was resampled to a 5 m resolution using a “nearest neighbor” technique in ArcGIS. We aggregated the land cover types within the study areas into 7 classes (Table 1).

Table 1

NLCD Type	Description*	Aggregation class
Developed, Open Space	Impervious surfaces account for less than 20% of total cover.	Developed, Open Space
Developed, Low Intensity	Impervious surfaces account for 20% to 49% percent of total cover.	Developed, Low Intensity
Developed, Medium Intensity	Impervious surfaces account for 50% to 79% of the total cover.	Developed, Medium Intensity
Developed, High Intensity	Impervious surfaces account for 50% to 79% of the total cover.	Developed, High Intensity
Deciduous Forest	Dominated by deciduous trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover.	Vegetated
Evergreen Forest	Dominated by evergreen trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover.	Vegetated
Mixed Forest	Neither deciduous nor evergreen species are greater than 75% of total tree cover.	Vegetated
Shrub/Scrub	Dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation.	Vegetated
Woody Wetlands	Forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.	Vegetated
Emergent Herbaceous Wetlands	Herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.	Vegetated
Grassland/Herbaceous	Gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation.	Grassland
Pasture/Hay	Pasture/hay vegetation accounts for greater than 20% of total vegetation.	Cultivated
Cultivated Crops	Crop vegetation accounts for greater than 20% of total vegetation.	Cultivated

* See http://www.mrlc.gov/nlcd06_leg.php for more details

Inner Richardson Bay

There is one existing marsh site within inner Richardson Bay which provides flood protection to human infrastructure landward of the site and habitat for tidal marsh bird species (Clapper rail and Song Sparrow). Our models show that the amount of mid marsh habitat will decrease for all scenarios, including a complete loss of mid and high marsh habitat by 2110 for either high sea level rise scenario (Figure 45). The resulting loss of marsh habitat will lead to an increase in wave impacts along levee edges in all scenarios, including a retention of >75% of wave energy in either high sea level rise scenario by 2110. Similarly, we project that the loss of marsh habitat will lead steep to declines in tidal marsh bird populations in the high sea level rise scenarios (Figure 47). Together this indicates that the tidal marsh ecosystems and nearby human communities may be exposed to greater flooding impacts in the future, particularly for high sea level rise scenarios (Figure 48).

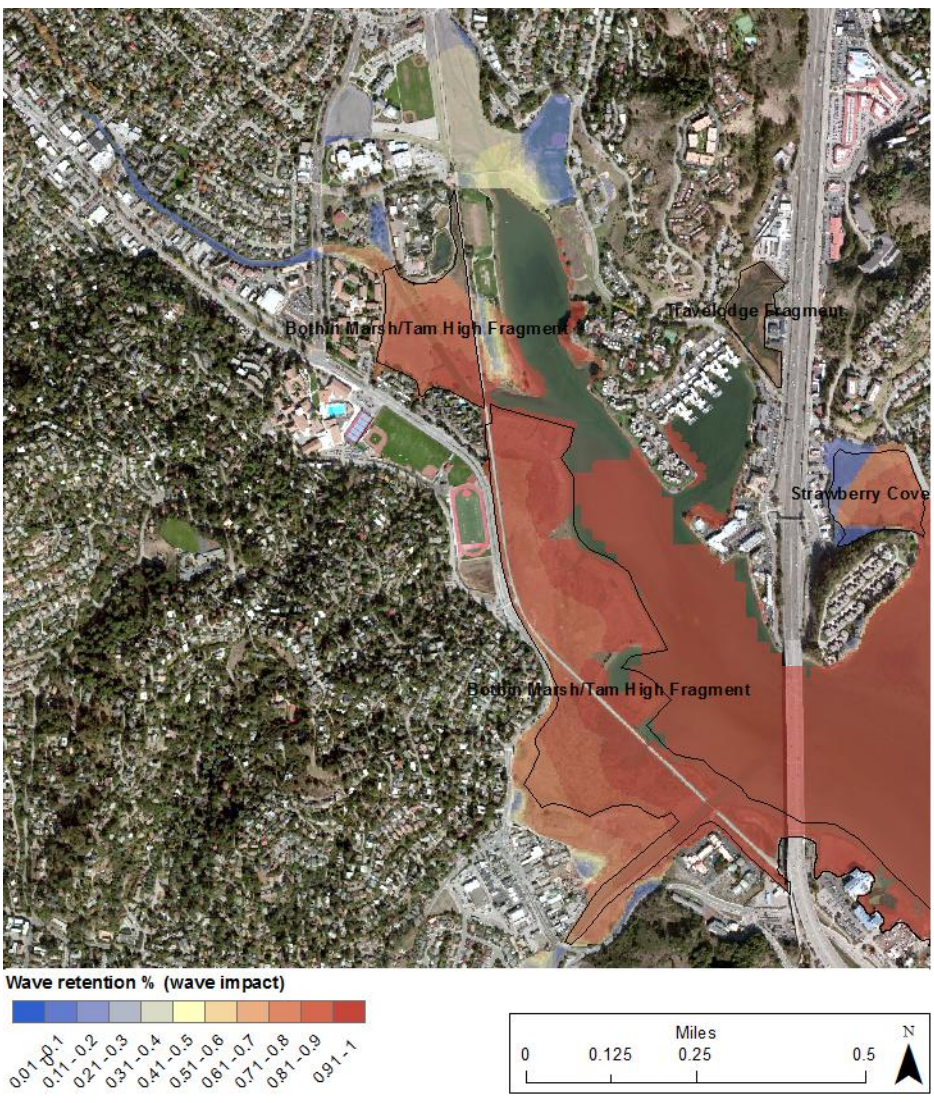


Figure 48. Wave retention (%) for a high sedimentation/high sea level rise scenario at 2110 within inner Richardson Bay. Note the limited opportunities for marsh transgression because of the extensive surrounding development

We estimate that the adaptive capacity of inner Richardson Bay is relatively low. First, observations indicate that Southern Marin County has relatively low suspended sediment concentrations (Stralberg et al. 2011) and our models show that the existing sediment levels will not be sufficient to allow marsh accretion to keep pace with high rates of sea level rise. This means that it will be more difficult than in higher sediment areas for managers to actively manage sediment within the region to promote marsh accretion. Additionally, the surrounding landscape is highly urbanized (Figure 48) and a majority of the area with potential future marsh habitat occurs within moderate to high intensity developed areas (Figure 49). Less than 10 acres of vegetated and grassland habitat and less than 15 acres of developed open space exists to accommodate marsh transgression or restoration (Figure 49).

Overall we rank inner Richardson Bay as highly vulnerable to sea level rise. Our models indicate that

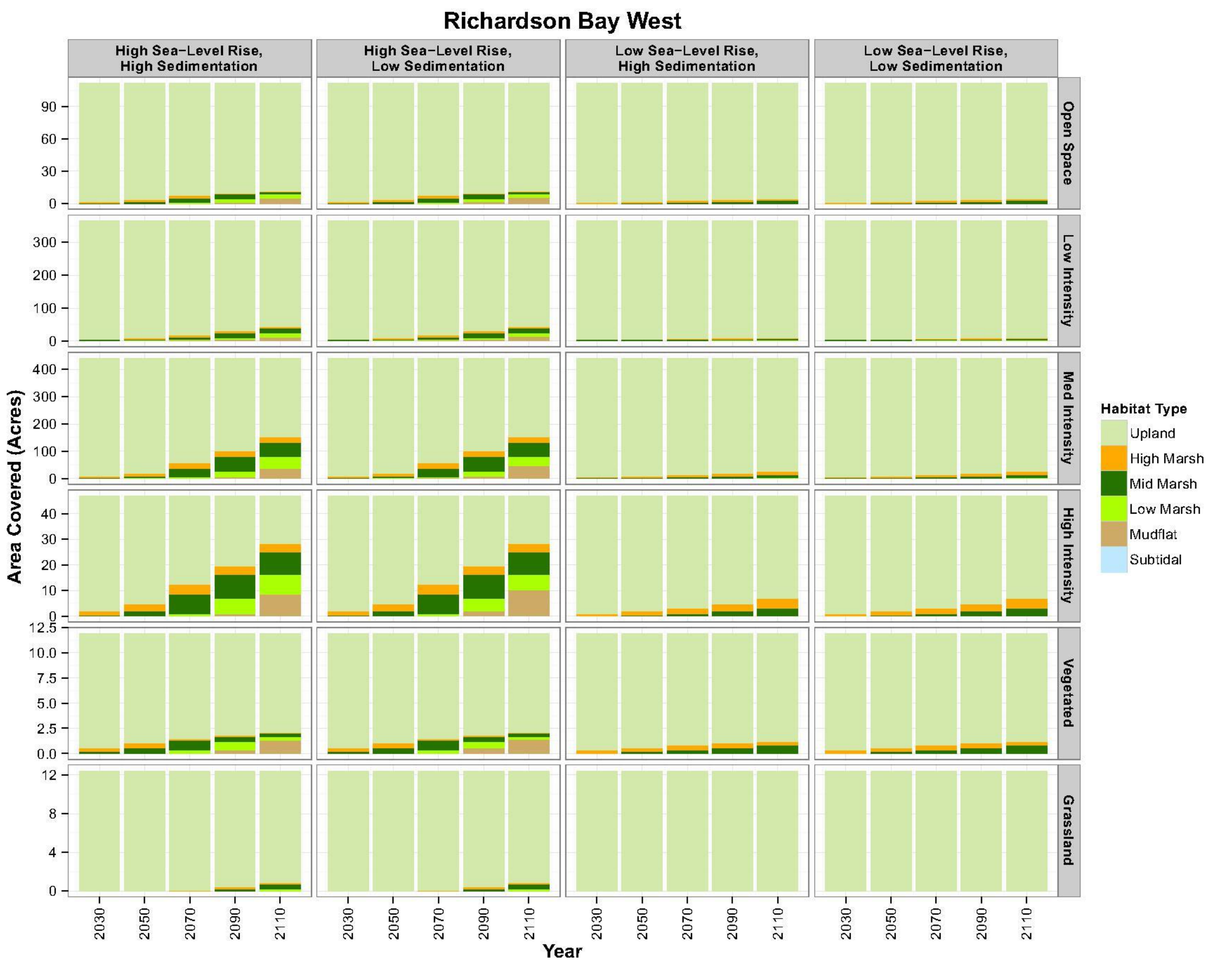


Figure 49. Tidal marsh elevation projections for different landcover types within the inner Richardson Bay region.

existing levees within the region will become increasingly exposed to wave energy and resulting erosion in the future, particularly after 2050. This indicates that increasing levee heights to protect against increasing sea level may be costly due to the need for greater erosion protection. The reliance on tidal marsh habitat in the area for flood protection will require a substantial increase in the amount of suspended sediment with high rates of sea level rise. An abandon and retreat strategy will also be difficult to implement given the highly urbanized geography within the area.

Gallinas Creek

The Gallinas Creek watersheds contains a variety of tidal marsh sites which includes two of the larger marhses within the entire estuary (McInnis Marsh and China Camp) as well as smaller marshes which occur along Gallinas Creek. The Gallinas Creek watershed occurrs within one of higher suspended sediment regions. As a result, we project that the all sites within the watershed will gain tidal marsh acreage by 2110 except under the high sea level rise/low sediment scenario where marshes are projected to convert to mudflat by 2110 consistently throughout the watershed (Figures 25 and 29). Coincidently, the wave impacts along levees adjacent to these sites only increase for the same worse case scenario (high sea level rise/low sediment, Figures 26 and 30). Simarly, we project tidal marsh bird populations to remain constant or increase from 2010 in most cases at sites within the watershed except for the worst case scenario where all species populations decline through the century or are projected to be absent by 2110 (Figures 27 and 31). Together we interept the results to suggest that the sites will have low exposure to sea

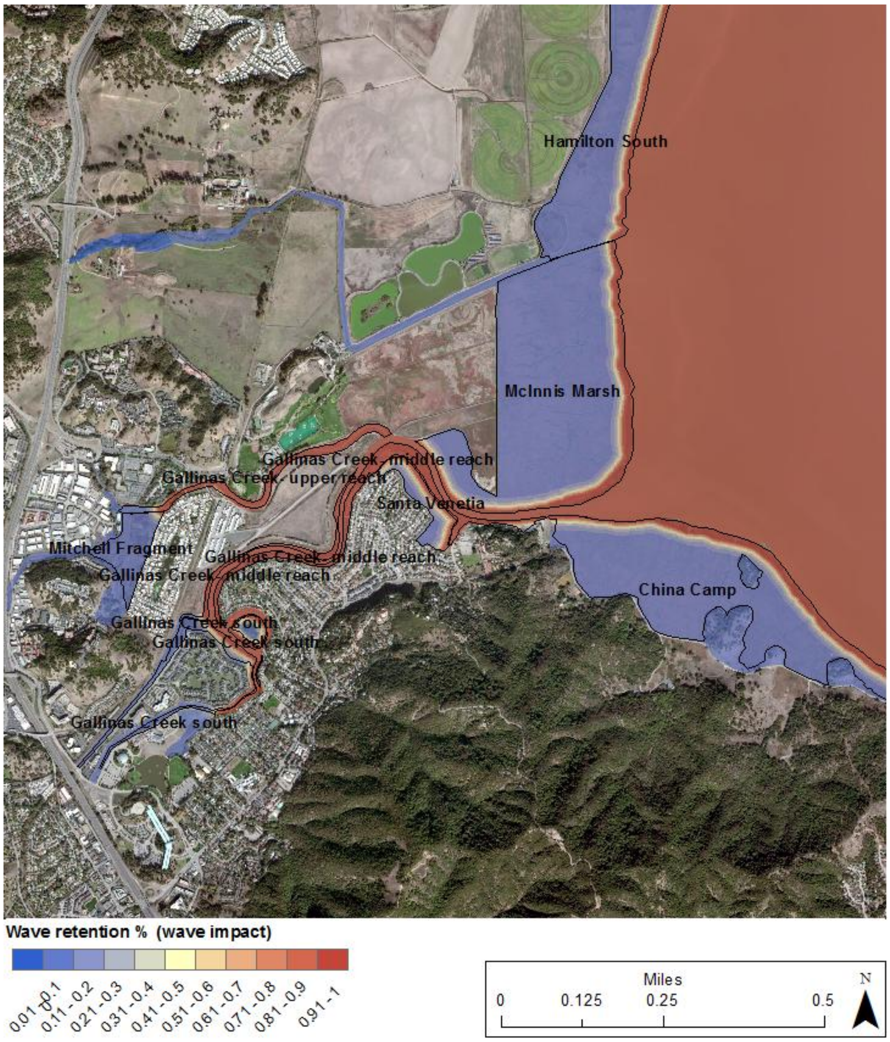


Figure 50. Wave retention (%) within the Gallinas Creek watershed for 2110 using a high sea level rise/ high sediment scenario.

level rise except for the worse case scenario where exposure will be high. We project the populations of tidal marsh species to be sensitive to the worse case scenario. Additionally, we project that the flood

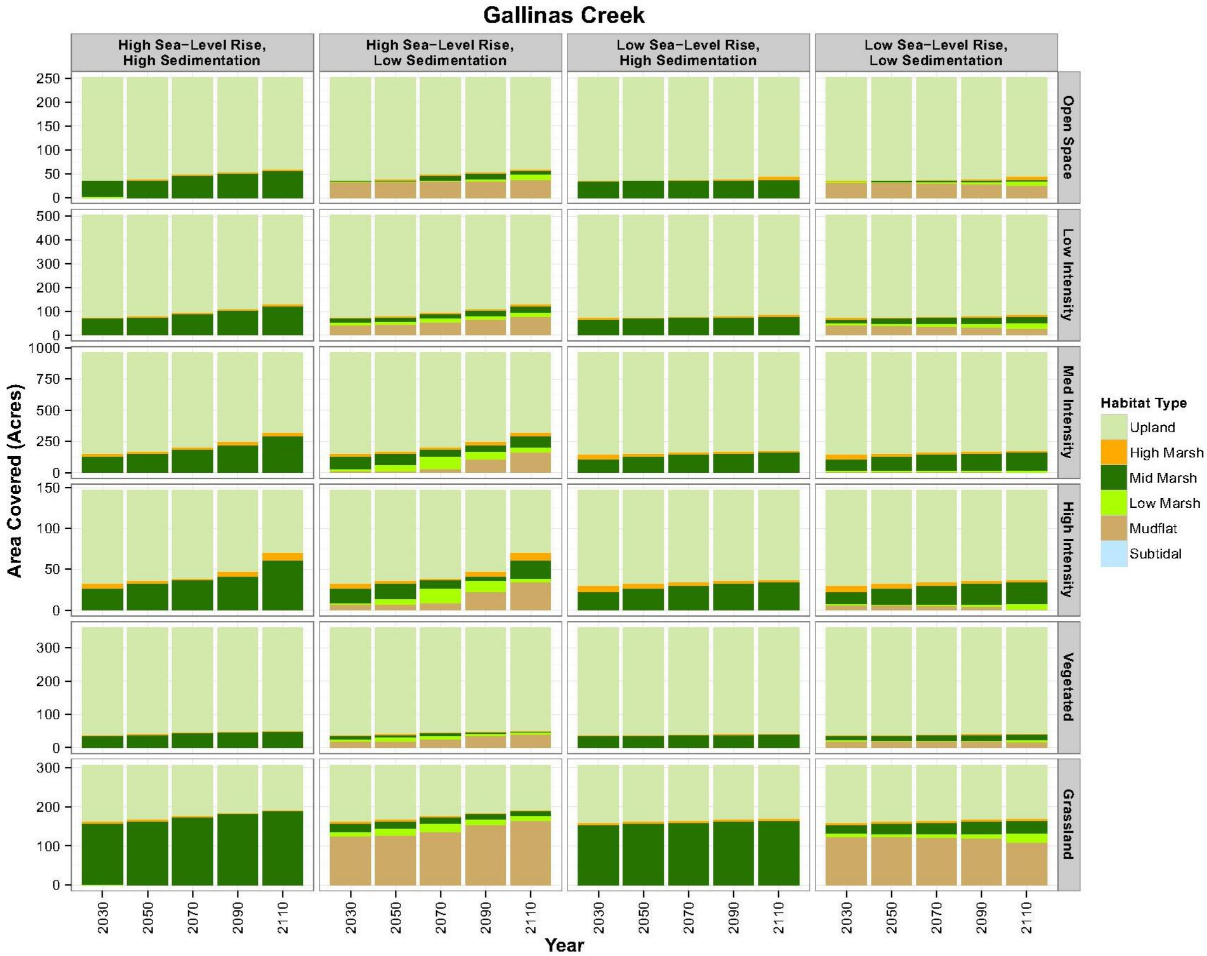


Figure 51. Tidal marsh elevation projections for different landcover types within the Gallinas Creek watershed.

protection ecosystem services of the marshes may also be senstive to the scenarios. For example, penetrating through the Santa Venetia Marsh are projected to retain more than 75% of their energy for the worse case scenario potentially causing greater erosion to the levee which protects the adjacent residnetial community (Figure 26). However, our models indicate that sediment management could enhance the resilience of the tidal marsh and the ecosystem services that it provides suggesting that there is some adapative capacity within the system. Additionally there are some opportunites to allow marsh transgresstion into grassland and vegetated communities, particularly for the high sediment scenarios (Figure 51). Together we estimate that the Gallinas Creek watershed has a moderate vulnerability to climate change with some options available for adaptation. Future work should explore ways that sediment can be delivered to the marsh systems to promote marsh accretion, particulalry if sea level rise rates approach the curves used in our high sea level rise projections (1.65 m/100 years). Additionally, decision makers could explore altrernatives for levee reallignment, particularly along the north side of the middle reaches of Gallinas creek to allow marsh transgression into currently upland habitat, increasing the habitat for tidal marsh species and possibly providing increased flood protection for the watershed (Figure 50).

Novato Creek

The Novato Creek watershed is similar to the Gallinas creek watershed in which there are larger marshes at the creek mouth and then mostly narrow wetland habitats along the creek. The watershed contains a large diversity of land uses (Also similar to the Gallinas watershed, we applied our highest sediment assumptions (150 – 300 mg/L) in our models for the area. We project that the tidal marsh systems within the Novato Creek watershed are sensitive to sea level rise. For three of four scenarios we project substantial increases in tidal marsh acreage within the waterhsed, however we also project almost complete loss of tidal marsh habitat for the worst case, high sea level rise low sediment scenario (Figure 21). We project wave impacts to remain constant or decline for scenarios in which tidal marsh acreages

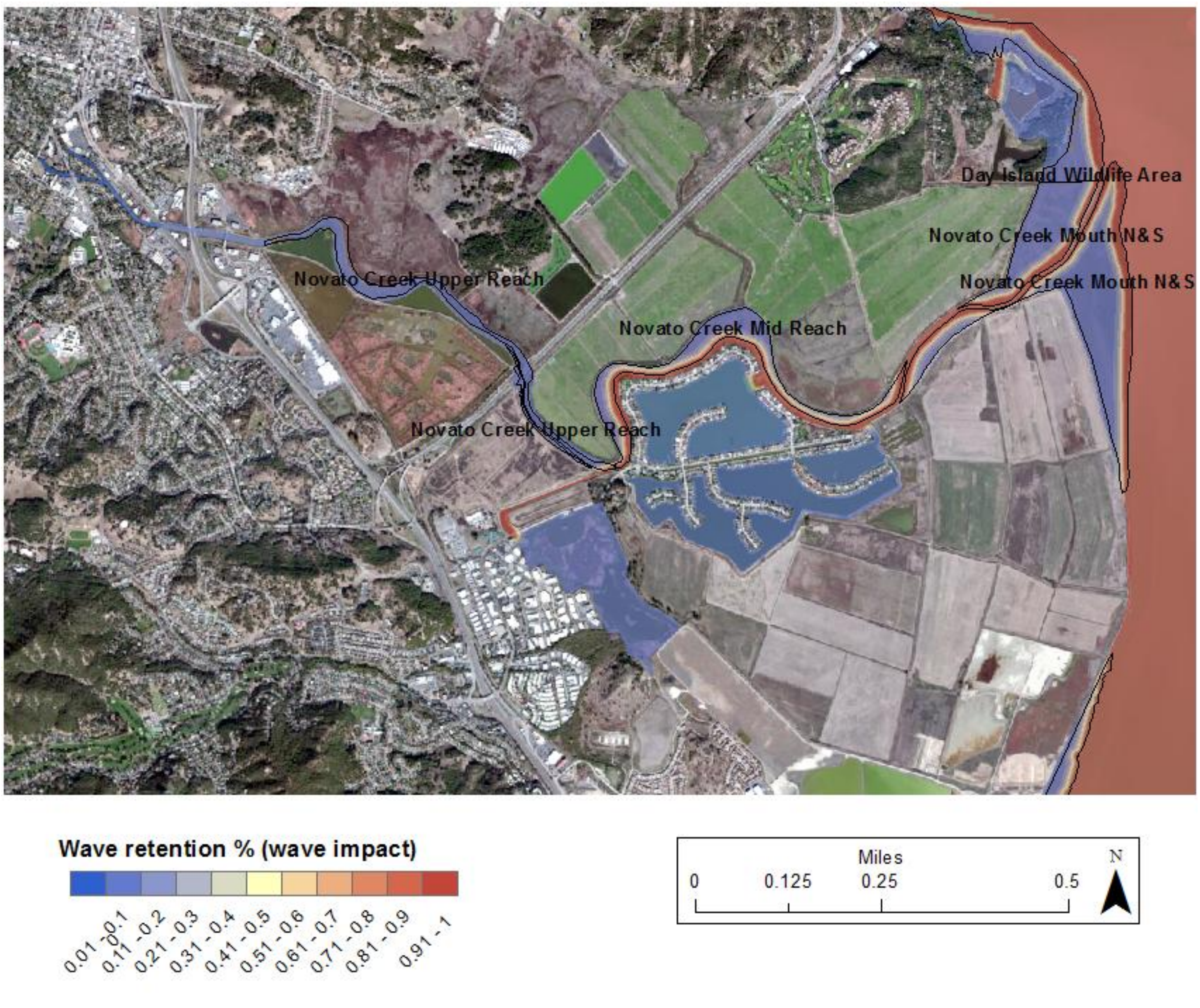


Figure 52. Wave retention (%) within the Novato Creek watershed for 2110 using a high sea level rise/ high sediment scenario.

increase but to increase substantially for the worst case scenario. For example, for the high sea level rise/low sediment scenario, we project almost 100% wave energy reaching levee edges along the middle reach of Novato Creek (Figure 22). We project that the populations of tidal marsh birds largely remain stable through 2110 for the scenarios in which tidal marsh acreage increases but we project consistent declines across species for the worst case scenario (Figure 23).

Like the Gallinas Creek watershed, our models indicate that sediment management could enhance the resilience of tidal marsh ecosystems within the Novato Creek watershed. Our models show that marsh accretion can keep pace with sea level rise if there is enough sediment. The Novato Creek watershed would be a good place to test sediment management actions that could promote long term marsh sustainability.

There is also some potential to promote marsh transgression given the land use types within the Novato Creek watershed. There is a relatively high amount of developed open space, vegetated and grassland acreage within the watershed which could support marsh transgression in the future (Figure 53). However, we project that a large proportion of the potential marsh habitat within these landcover types will only reach mudflat elevations for low sediment scenarios under either sea level rise scenario (Figure 53). We interpret this result as a consequence of subsidence in the area leading to very low initial elevations, some areas behind levees are currently at subtidal elevations. Still, we believe that there are adaptation opportunities to promote marsh expansion through levee realignment and restoration within these areas by raising initial elevations as part of restoration plans. We project that there are also over 600 acres of potential future marsh habitat that is currently being used for agriculture within the watershed. Getting agreement from private landowners to allow their land to be restored to tidal marsh habitat may be more challenging than restoring other lands but our models indicate that there are opportunities within the watershed if stakeholders become interested.

For a tidal marsh restoration along Novato Creek to be resilient to sea level rise, management may need to actively manage sediment for high sea level rise scenarios and also raise initial elevations. Tidal marsh restoration could potentially lower flood risks throughout the watershed and increase the populations of tidal marsh species. In summary, we rate the watershed as having moderately high vulnerability but acknowledge that there are adaptation options that could reduce the vulnerabilities.

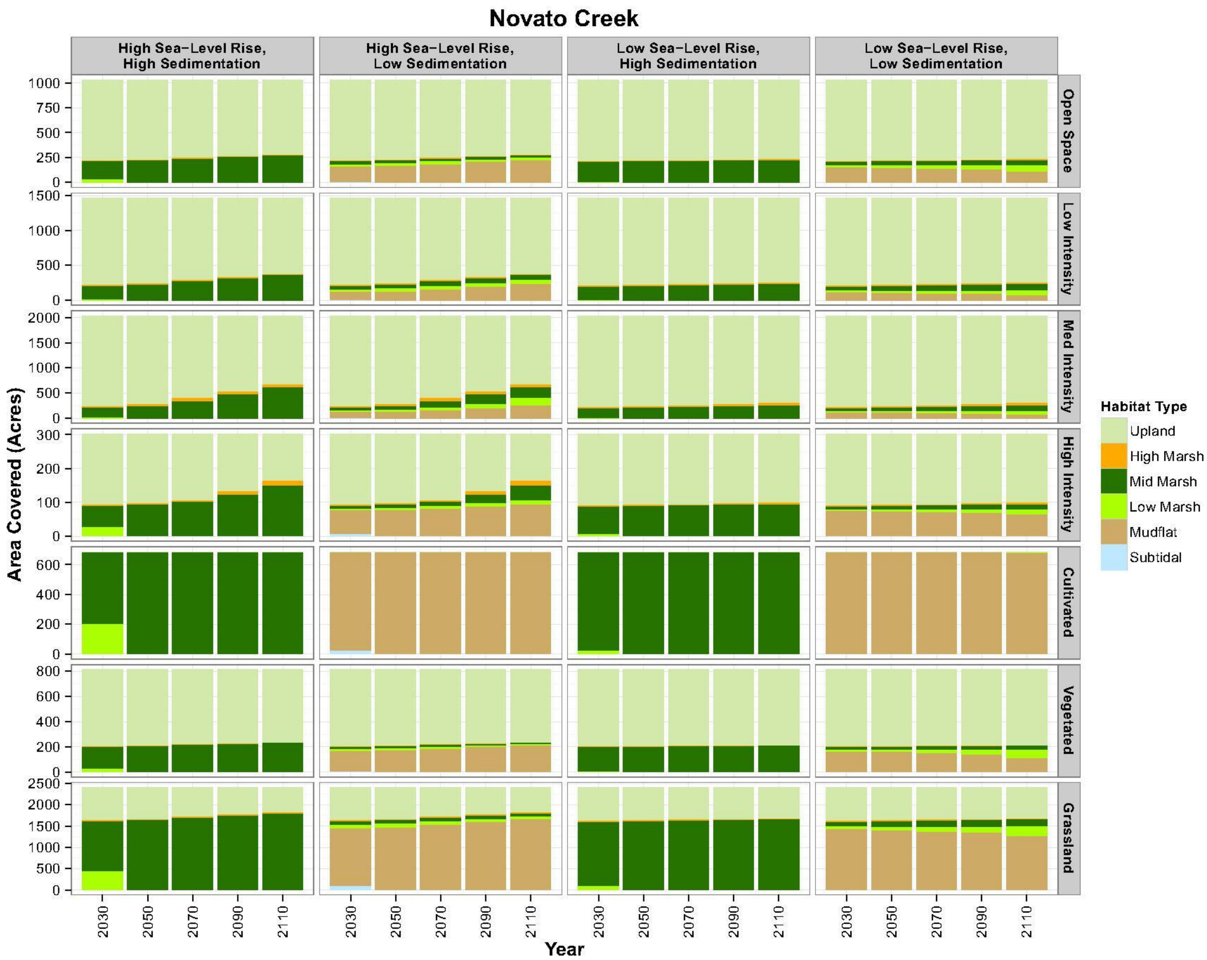


Figure 53. Tidal marsh elevation projections for different landcover types within the Novato Creek watershed

Acknowledgements

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