State of the Estuary Report 2015

Summary

PROCESSES – Migration Space

Prepared by
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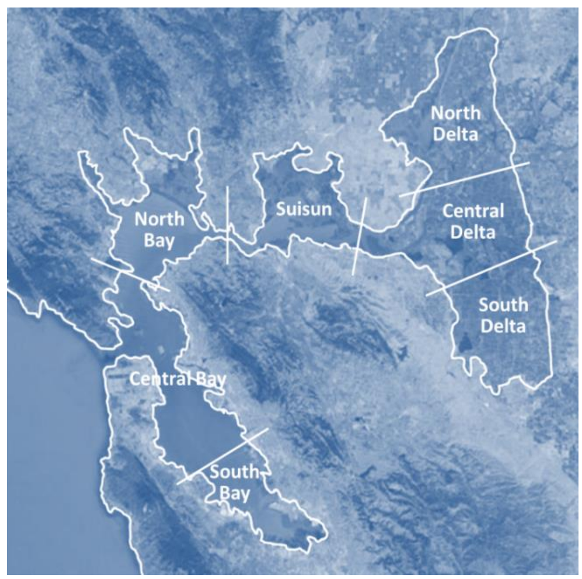
Migration Space Indicator (V3 June 30 2015)

Brief Description of Indicator and Benchmark

Migration space is the upland area between the present-day shoreline of the Estuary and a higher, future shoreline resulting from sea level rise. This report considers two alternative migration spaces, based on the assumption that the Estuary rises either two feet or five feet. Both of these rises in sea level are possible during this century. Migration space excludes all existing tidal areas as well as any reclaimed areas, such as salt ponds in South San Francisco Bay or diked farmlands in the Delta that would be flooded without their dikes or levees. However, migration space includes all areas of landfill within the historical limits of the Estuary that are above the future shorelines. The total area of migration space is due mainly to the slope of the land immediately adjacent to the Estuary. The space is widest across broad, gently sloping valleys and plains.

This indicator measures the current percentage of undeveloped space, and the percentage of that space that is protected from development. This indicator is based on the need to protect and restore the zone of natural transition from estuarine habitats to terrestrial habitats that is critically important for the ecological and economic health of the Estuary. The indicator has been estimated for each major sub-region of the Estuary.



Sub-regions of the Estuary.

There are no existing benchmarks for migration space. The benchmarks are arbitrarily 50% of the total migration space in each sub-region being undeveloped, and 75% of that undeveloped space being protected. The scoring break between fair and poor scores is arbitrarily set at 40% and 50%, respectively.

Indicator Status and Trend Measurements

Much of the commercial, industrial, and cultural resources of the Estuary are associated with its shore. Shorefront businesses contribute great wealth to the region. The shoreline adjoins the airports, railroads, and highways that are vital to domestic and international commerce.

These uses of the shore have historically overridden concerns for the natural benefits provided by its undeveloped areas. But, there is a growing appreciation that the natural transition zone beautifies the Estuary, supports much of its ecological diversity, and provides abundant recreation. It contributes substantially to the quality of life in the region.

While appreciable amounts of undeveloped migration space exist in some sub-regions, most of the space around the Estuary has been developed, and only a small percentage of the undeveloped space is protected from future development. For the Estuary as a whole, the existing transition zone is not well protected, and opportunities to restore the transition zone are not abundant. Given that much less than half the total migration space is undeveloped, and that less than half the undeveloped space is protected, the overall condition of the migration space is considered poor.

Scientific Interpretation

The migration space indicator represents the ability for the shallow habitats of the Estuary, principally the tidal marshes and mudflats, as well as the associated terrestrial habitats, such as grasslands and forested hillsides, to migrate inland as sea level rises. The shallow estuarine habitats help protect the shore against erosion and flooding due to storm surges or erosive waves generated by high winds. Without protected, undeveloped migration space, the Estuary will rise against the developed landscape, compressing the natural shore into a narrow band of vulnerable habitats with minimal cultural, economic, or ecological value.

The migration space indicator also represents the opportunity for native populations of plants and animals to track appropriate habitat conditions that are also migrating inland and upstream. The rising sea will cause saline conditions in the Estuary to move upstream in local watersheds and toward the Delta. Areas of healthy transition zone are needed in every sub-region of the Estuary to allow the associated plants and animals to migrate along with their required salinities.

The migration space indicator has never been calculated before. There are no data to quantify a trend in the percent of undeveloped migration space that is protected. The overall patterns of development in the region suggest that much of the migration space was developed during the latter half of the last century, before the advent of environmental regulations. Since then the rate of development of the migration space has likely lessened, although the quality of the remaining undeveloped space may be subject to continuing decline due to pollution, over use, biological invasion, and ecological isolation. Furthermore, there is generally more undeveloped space for the two-foot rise in sea level than for the five-foot rise. This reflects the pattern of urban encroachment toward the shoreline. It suggests that there will be less undeveloped space in the future than there is now. For either a two-foot or five-foot rise in sea level, very little of the undeveloped space is protected.

The challenge for the future is to protect the existing undeveloped space, create more of it if possible, and protect it from future development. There are opportunities to meet this challenge in every sub-region of the Estuary. It’s noteworthy, however, that Suisun Bay has the most undeveloped migration space that is unprotected.

Further development of the migration space indicator should be guided by regional experts in land use, sea level rise and its landscape effects, and landscape ecology. There is a critical need to determine the geodetic elevation of the MHHW contour for the Delta. There is also a need to estimate the full extent of the transition zone around the Estuary, and to determine what migration space is needed to conserve the transition zone under different sea level rise scenarios. Scientifically sound criteria will be needed to identify and prioritize opportunities to conserve and restore the transition zone.

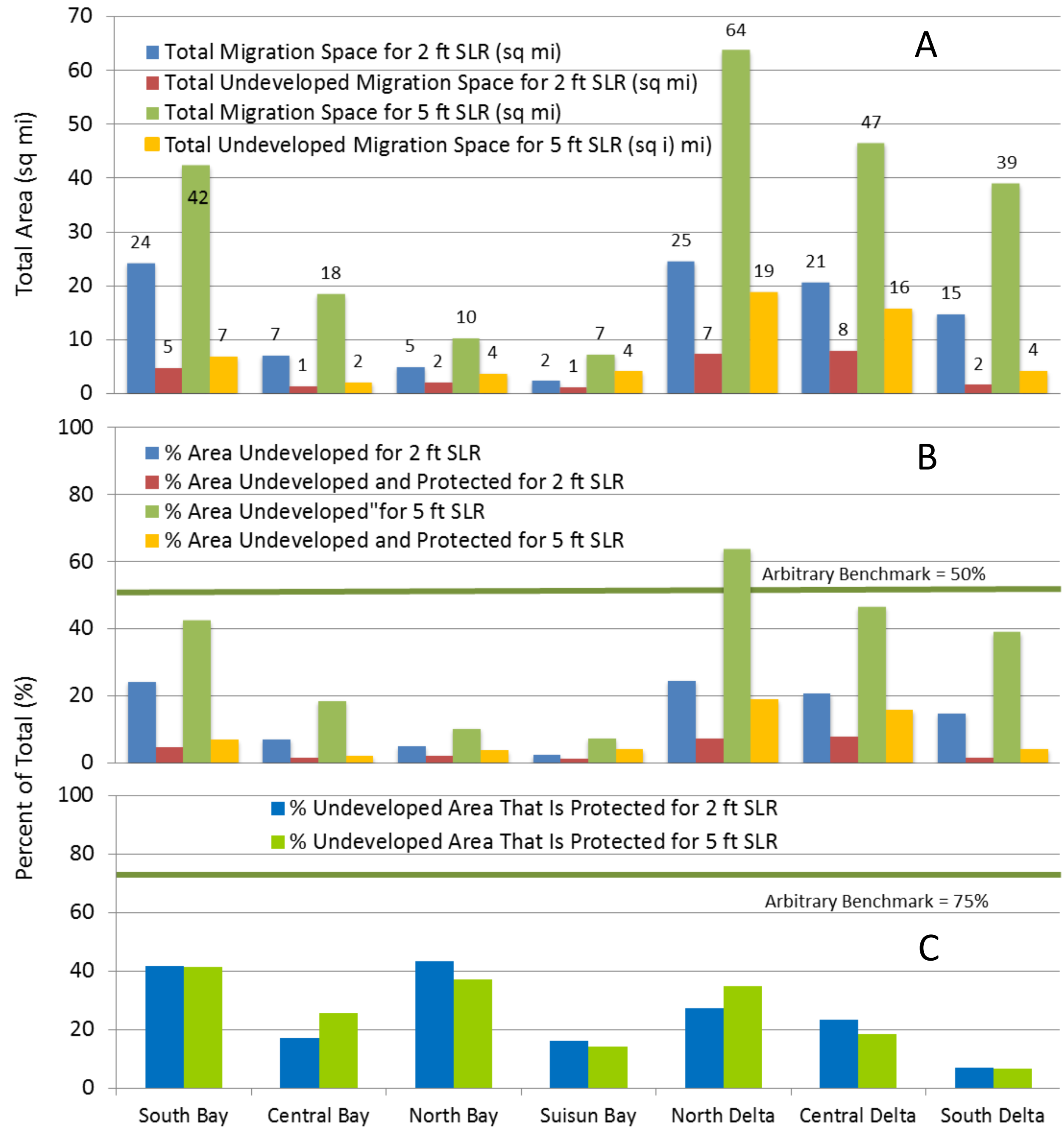


Figure 2. Sub-regional distribution of developed and undeveloped migration space for sea level rise (SLR) of 2-ft and 5-ft, showing (A) total migration space (sq mi); (B) percentage of total migration space undeveloped and protected, showing an arbitrary target value of 50%; and (C) the migration space indicator (i.e., the percentage of the total undeveloped migration space that is protected), showing an arbitrary benchmark of 75%.

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Technical Appendix

PROCESSES – Migration Space

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Estuary Migration Space
Technical Appendix
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Background and Rationale

The purpose of this indicator is to provide an initial assessment of the scale of opportunity to conserve the natural ecosystem services of the estuarine-terrestrial transition zone by identifying undeveloped areas of migration space around the San Francisco Estuary (the Estuary) into which the transition zone can be allowed to evolve as sea level rises.

Definitions

The shorelines of estuaries have great ecological, economic, and cultural importance (Daily et al. 1997, NOAA 1999, NOAA 2008, BCDC 2011). They have been studied in detail from a variety of perspectives, resulting in particular terminology regarding their natural processes, functions, forms, and structures. The following terms are relevant to this report.

Accommodation Space. For an estuary with an unobstructed connection to the sea, the volume of space between two sea levels is its accommodation space (Jervey 1998, Posamentier and Allen 1999). As sea level rises in an estuary, it fills the accommodation space with sediment and tidal water. Changes in accommodation space are the result of one or more of three processes:

- Rise or fall in global sea level,
- Net sedimentation in the estuary, and
- Tectonic or seismic rise or fall in the floor of the estuary.

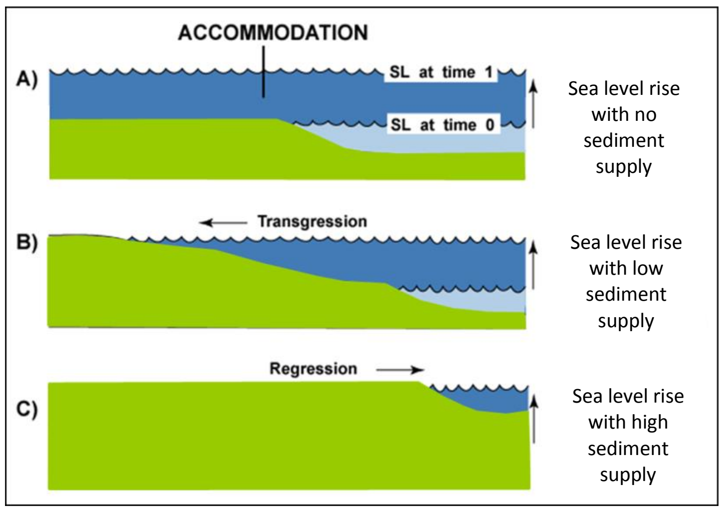

Figure 1. Three possible scenarios for natural changes in accommodation space due to interactions between sea level rise and sediment supply, showing (A) the space filled with water due to sea level rise without sediment input, (B) the accommodation space being filled by estuarine water and sediment (the same figure pertains to the estuary transgressing across former upland as sea level rises), and (C) an abundance of sediment causing the estuary to regress (after Posamentier and Allen 1999).

Interactions among these processes determine whether accommodation space increases, decreases, or remains the same. Earthquakes that raise or lower the floor of an estuary can suddenly and substantially alter its accommodation space (e.g., Gilbert 1907, Byrne et al. 2005). In general, however, the interactions between sea level rise and sediment accumulation regulate accommodation space (Figure 1).

Estuarine Transgression. This occurs when sea level rises relative to the land, causing the shoreline to move inland, and causing the head-of-tide (i.e., the upstream boundary of tidal effects in a river or stream) to move upstream (Pethnic 2000).

Estuarine Regression. This is the opposite of transgression. It occurs as sea level falls relative to the land, causing the estuary shoreline to regress or retreat (World Earth Science. 2003). Regression is common where rivers build deltas into estuaries. Artificial regression results from areas of an estuary that are reclaimed, causing its shoreline to move seaward. Reclamation in the Estuary has reduced its tidal area by about 98% in the Delta (SFEI-ASC 2014) and nearly 85% between the Delta and the Golden Gate (Goals Project 1999).

Transition Zone. The transition zone is defined as the spatial limits of the interactions between terrestrial processes, including runoff, and tidal processes that result in assemblages of plants and animals that are distinct from the adjoining estuarine, riverine, or terrestrial ecosystems (BEHGU 2015). The transition zone varies in width depending on topographic slope and land use constraints. At any given location and time, the width of the transition zone also varies with its function. It tends to be wider for ecological functions, such as support for wildlife, than for physical functions, such as shoreline erosion control.

Migration Space. For the purposes of this indicator, migration space is defined as the upland area landward of the historical shoreline of the estuary that would be flooded by the Estuary due to sea level rise in the absence of levees, dikes, or other water control structures. Migration space is therefore the landward component of accommodation space. The size of the space varies as sea level rises, and is affected by topographic slope and land use constraints. It does not include any existing tidal areas of the Estuary. Nor does it include any reclaimed areas, such as salt ponds in South San Francisco Bay (south Bay) or diked farmlands in the Delta, which would be flooded by tidal waters under the present-day sea level, if their levees or dikes were beached. However, it includes any areas of artificial fill within the historical limits of the Estuary that would remain above tidal waters for a specified sea level rise. This definition of migration space is consistent with the concept of marsh migration zone used elsewhere (Heberger et al 2009, Klausmeyer et al. 2013)

Why is migration space important?

The migration space is an area of great ecological, economic, and cultural importance. Under modest sea level rise, it encompasses many of the important historical landmarks and archeological sites of the Bay-Delta region, housing for more than 300,000 people, shorefront businesses of great monetary value, and ports that are vital for the economic health of the State. It also delimits the possible extent of the future transition zone. Industry, cultural heritage, and ecological diversity are concentrated along the shoreline, and are directly threatened by accelerated sea level rise (Gleick and Maurer 1990, Heberger 2012, Rodgers et al 2015, BEHGU 2015). Efforts to plan for sea level rise are largely focused on the migration space.

As sea level rises, the built landscape along the shoreline will need to be protected in place, or intentionally moved out of the way through managed retreat (sensu Townsend and Pethick. 2002). The ecological functions of the shoreline cannot stay in-place. They depend on the natural interplay among estuarine, terrestrial, and riverine processes that will move inland as sea level rises. They must be allowed to move into undeveloped areas of the migration space though natural migration or managed realignment (sensu Rupp-Armstrong and Nicholls 2007). The ecological health of the Estuary depends on providing adequate areas of undeveloped migration space to sustain an ecologically healthy transition zone (BEHGU 2015).

Overview of the Migration Space Indicator

The migration space indicator is a fundamental step toward a Bay-Delta regional tool to conserve and restore the natural ecosystem services of the transition zone. Efforts to plan for sea level rise are just beginning (BCDC 2011, ULI 2015) and the economic, technological, engineering, and scientific aspects are evolving rapidly. At this early stage of planning, three technical recommendations about migration space present themselves:

- Improve models for predicting estuarine flooding including extreme flood events;
- Model the landward extent of the transition zone for its various services; and
- Use the models of future estuarine flooding and transition zone extent, plus maps of land cover, habitat, and infrastructure to identify opportunities to conserve and restore the ecosystem services of the transition zone.

Implementing the latter recommendation involves overlaying maps of migration space onto maps of land cover. Mapping the migration space can be complicated by many factors, including local variations in sea level through space and over time (e.g., Knowles 2010, Holleman 2013), the technical difficulty of relating tide height to inland elevation (e.g., NOAA 2010, Kenny et al. 2011), the influence of topographic relief on flood pathways (e.g., Pelletier et al. 2005), and land use change that affects flooding patterns. Furthermore, the existing landscape will change as sea level rises. Developing models to predict estuarine flooding that account for landscape changes caused by the flooding will be an additional challenge.

A variety of scientific and technological efforts are underway to assess regional sea level rise (Table 1 below). Local analyses of migration space are also emerging (TNC 2013, Riordan Seville 2014). These efforts and others will evolve as the need for them becomes clearer and the related science and technology continue to advance. There are also efforts to coordinate these activities (e.g., Adapting to Rising Tides www.adaptingtorisingtides.org/; Lifting the Fog, http://coastaladaptation.org/liftingthefog/; Bay Area Ecosystems Climate Change Consortium, www.baeccc.org; Surging Seas http://sealevel.climatecentral.org/responses/plans).

As realistic models of future local estuarine flooding are being developed, and even afterward, more basic models will be useful to inform regional and local planning. At this time, none of the modeling efforts extends throughout the Estuary, although plans for that are pending. The migration space indicator presented here is an early step toward a Bay-Delta regional planning tool. There are important next steps that must be taken for the tool to better meet the need for planning and tracking migration space health (see Assumptions and Uncertainties below).

Table 1. Prominent efforts to model sea level rise or estuarine hydrodynamics for the San Francisco Estuary entirely or in part. Main source: Related Tools Comparison – California; http://sealevel.climatecentral.org/ssrf/related-tools-comparison-CA.

	Climate Central - Surging Seas Risk Finder	NOAA Coastal Services Center - Sea Level Rise and Coastal Flooding Impacts Viewer	Pacific Institute - The Impacts of Sea Level Rise on California's Coast	Cal-Adapt - Exploring California's Climate	Our Coast, Our Future	SUNTANS
URL	http://sealevel.climatecentral.org/	http://coast.noaa.gov/slr/?redirect=301ocm	http://pacinst.org/publication/the-impacts-of-sea-level-rise-on-the-california-coast/	http://cal-adapt.org/sealevel/	http://www.pointblue.org/outage.html	http://sourceforge.net/projects/suntans/
Purpose/ Description	Provides public multi-part web tool to help communities, planners, and leaders conduct a screening-level analysis of sea level rise and coastal flood risks, using 1) detailed searchable maps; 2) analysis of over 100 variables for 1000s of communities; 3) community comparisons; and 4) local sea level and flood risk projections.	A visualization tool for coastal communities showing potential impacts from sea level rise and coastal flooding as well as a planning level tool.	Provides access to sea-level rise scenarios generated by the Pacific Institute, ESA PWA and the U.S. Geological Survey as part of the CA Energy Commission's Public Interest Energy Research Program (PIER). The tool shows the threat of coastal erosion and inundation due to flooding over three depths based on a 100 year flood scenario.	Provides access to sea-level rise flooding scenarios generated by the Pacific Institute, ESA PWA and the U.S. Geological Survey as part of the CA Energy Commission's Public Interest Energy Research Program (PIER). The tool shows the threat of inundation due to flooding over three depths based on a 100 year flood scenario.	A collaborative, user-driven project focused on providing San Francisco Bay Area coastal resource and land use managers and planners locally relevant, online maps and tools to help understand, visualize, and anticipate vulnerabilities to sea level rise and storms.	The Stanford unstructured-grid, non-hydrostatic, parallel coastal ocean model. For simulation of non-hydrostatic flows at high resolution in estuaries and coastal seas. Requires a grid generator and ParMETIS (if run in parallel).
Scope	National	National	California	California	Bodega Head to Half Moon Bay and SF Bay	Adaptable

	Climate Central - Surging Seas Risk Finder	NOAA Coastal Services Center - Sea Level Rise and Coastal Flooding Impacts Viewer	Pacific Institute - The Impacts of Sea Level Rise on California's Coast	Cal-Adapt - Exploring California's Climate	Our Coast, Our Future	SUNTANS
Release Yr	Rolling: 2013 -2014	2012 (West Coast of US)	2009	2011	2013 Half Moon Bay to Bodega; 2014 SF Bay	Ongoing
Organization/ Sponsor	Climate Central	NOAA Coastal Services Center	California Energy Commission, California Environmental Protection Agency, Metropolitan Transportation Commission, California Department of Transportation, and the California Ocean Protection Council	California Energy Commission; UC-Berkeley Geospatial Innovation Facility	Point Blue Conservation Science; USGS; Gulf of the Farallones National Marine Sanctuary; Coravai LCC	Stanford University Environmental Fluid Mechanics and Hydrology Program
Sea Level Rise Scenarios	Up to 10 feet in 1-foot intervals above local high tide line (Mean Higher High Water)	Up to 6 feet in 1-foot intervals above local high tide line (Mean Higher High Water)	Current water levels, 19", 39" and 55" inundation	Current water levels, 19", 39" and 55" inundation	Total of 40 combinations of sea level rise and storm scenarios that include 0-2 m SLR in 25 cm increments plus a 5 m extreme, and 4 storm scenarios: no storm, annual, 20 year, and 100 year	

	Climate Central - Surging Seas Risk Finder	NOAA Coastal Services Center - Sea Level Rise and Coastal Flooding Impacts Viewer	Pacific Institute - The Impacts of Sea Level Rise on California's Coast	Cal-Adapt - Exploring California's Climate	Our Coast, Our Future	SUNTANS
Inundation Model	Modified bathtub approach, modeling hydrologic connectivity and locally adjusted Mean Higher High Water levels.	Modified bathtub approach, modeling hydraulic connectivity and locally adjusted Mean Higher High Water levels.	Bathtub approach	Bathtub approach	USGS Coastal Storm Modeling System (CoSMoS)	
Point of Contact	Dan Rizza: drizza@climatecentral.org	John Rozum: john.rozum@noaa.gov	Matthew Heberger mheberger pacinst.org	Kevin Koy: kkoy@berkeley.edu; Susan Wilhelm: susan.wilhelm@energy.ca.gov	Kelley Higgason: kelley.higgason@noaa.gov	Oliver Fringer fringer@stanford.edu

Methods and Data Sources

This approach to develop the migration space indicator delineates the boundaries of alternative migration spaces for the entire Estuary based on two future sea level rise scenarios, and quantifies areas within the two spaces that could be dedicated to migration of the natural estuarine-terrestrial transition zone. The approach is very similar to that taken in other efforts for sub-regions or selected locations within the Estuary (e.g., CLN 1.0). The basic details of the methodology, including the sources of data used in the indicator, are presented below.

Seaward Boundary.

For the Bay Area, a modern shoreline was created that ignores the levees of reclaimed estuarine areas that would be flooded under existing sea level if these levees were breached. The shoreline was derived from the Modern Baylands layer of the Bay Area Aquatic Resource Inventory (BAARI) by dissolving the bay, channel, diked baylands, tidal flats and tidal marshes (http://www.sfei.org/sites/default/files/SFEI%20MAPPING%20STANDARDS_08092011_v8_0.pdf). The resulting shoreline is essentially the historical (pre-settlement) shoreline updated to account for sea level rise over the last two centuries, and to account for artificial fill other than levees that is above the selected future sea levels. It is assumed that this shoreline corresponds to local Mean Higher High Water tidal datum (MHHW). This boundary corresponds well to the MHHW contour plus the diked "low-lying areas" derived by NOAA (NOAA 2010).

For the Delta, a modern shoreline was created that ignores the levees of reclaimed estuarine areas following a simple multi-step process. A line was derived from the historical Delta tidal habitats layer (SFEI-ASC 2014) of the CA Aquatic Resources Inventory (www.ecoatlas.org/data/#cari) by dissolving the water and tidal features. The resulting shoreline is essentially the historical (pre-settlement) shoreline. It is assumed to correspond to present-day local MHHW, although it has not been adjusted for historical sea level rise.

Landward Boundary

The landward limit of the migration space was estimated throughout the Estuary for two future sea levels, +2 ft and +5 ft above present-day MHHW. These heights are generally consistent with the heights recently used to explore sea level rise effects on Bay Area intertidal habitats (BEHGU 2015)[1].

Generally, the process used to estimate future landward boundaries of estuarine flooding can be described as a bathtub approach or linear superposition method (NOAA 2010, Marcy et al. 2011). For many reasons, sea level varies in height along the shoreline of an estuary, relative to a common geodetic datum. To represent this variation, it should be modeled as a spatially variable water surface. In addition, the elevations of this surface must be referenced to the same vertical datum as the land surfaces (i.e., NAVD88). There are currently two primary ways this surface can be created. The first and simpler approach is to covert the MMHW tidal datum derived for well-gauged tide stations to NAVD88, and then interpolate the surface between the stations. The second and more accurate approach is to use NOAA's vertical datum conversion software, VDatum (http://vdatum.noaa.gov/) for a dense array of points along the shoreline. Both approaches were incorporated into the migration space indicator.

[1] The future sea level values used in the Baylands Ecosystem habitat Goals Update (BEHGU 2015) are 52 cm (1.7 ft) and 165 cm (5.4 ft). These values were rounded to the nearest whole foot because other data incorporated into the migration space indicator do not support the spatial resolution denoted by increments of elevation less than about one foot. For example, sea level data provided by NOAA is based on 1-ft increments of sea level rise.

For the Bay Area, the areas denoted as "high confidence" in the NOAA Sea Level Rise and Coastal Flooding Impacts Viewer (http://coast.noaa.gov/slr/) for the +2-ft and +5-ft sea levels were adopted (http://coast.noaa.gov/digitalcoast/tools/slr). According to the documentation for the viewer (Marcy et al. 2011), where VDatum was available, it was used to covert MHHW into elevations relative to NAVD88. A linear superposition method was used to raise the resulting grid of elevation points in 1-ft increments of sea level rise up to 6 ft above present-day MHHW. Because tidal datum transformations in VDatum extend only slightly beyond the present-day MHHW shoreline, interpolation and extraction routines to extend the MHHW surface inland were done according to methods suggested in NOAA (2010). Where VDatum was not available, methods outlined in NOAA (2007) were used to interpolate between NOAA tide gages for which the relationship between MHHW and NAVD88 had been resolved.

A much simpler and less accurate method was used in the Delta. The NOAA sea level rise data have not yet been developed for the Delta, and insufficient data were available to apply the NOAA method of VDatum conversion from tidal to geodetic elevations. The elevation of the seaward boundary (see above), which was assumed to correspond to the local MHHW, was further assumed to have a tidal elevation of 6.4 ft NAVD88, based on reckonings reported for a single station at Cache Slough by the CA Department of Water Resources (DWR) http://baydeltaconservationplan.com/Libraries/Dynamic_Document_Library/2D_Hydrodynamic_Modeling_of_the_Fremont_Weir_Diversion_Structure_with_average_Westside_tributary_flows.sflb.ashx. In other words, the sea level surface was assumed to have one elevation relative to NAVD88 throughout the Delta.

Land Cover

All assessments of land cover depended on the 2011 National Land Cover Database of USGS (NLCD 2011; http://www.mrlc.gov/nlcd2011.php) and the California Protected Areas Database of the Green Info Networks (CPAD; http://www.calands.org/).

These two datasets (NLCD 2011 and CPAD) were the basis for deciding areas of migration space that could be devoted to the conservation of the estuarine-terrestrial transition zone. The decisions involved value judgements about the relative likelihood of different land covers being left undeveloped or being converted from developed to undeveloped status (Table 1). It is assumed that any land coves categorized as undeveloped can be devoted to the transition zone. All areas designated as protected in the CPAD are assumed to be undeveloped. The assignment of land covers to these categories can be revised at any time.

Table 1. Classification of NLCD land cover types as developed or undeveloped.

Categorization of NLCD Land Cover Types as Developed or Undeveloped	
Developed	***Undeveloped***
Developed - Low Intensity	Water - Open Water
Developed - Medium Intensity	Developed - Open Space
Developed - High Intensity	Barren - Barren Land
Planted/Cultivated - Cultivated Crops	Forest - Deciduous Forest
	Forest - Evergreen Forest
	Forest - Mixed Forest
	Shrubland - Shrub/Scrub

	Herbaceous - Grassland/Herbaceous
	Wetlands - Woody Wetlands
	Wetlands - Emergent Herbaceous Wetlands

The areas of developed, undeveloped, and protected lands were quantified for each major sub-region of the Estuary: South Bay (South San Francisco Bay), Central Bay (Central San Francisco Bay) North Bay (San Pablo Bay and the western portion of Carquinez Straight), Suisun Bay (Suisun Bay and the eastern portion of Carquinez Strait), North Delta, Central Delta, and South Delta (Figure 2). Bay sub-regions are based on the Baylands Goals Project (Goals Project 1999). The Delta sub-regions are generally based on patterns of subsidence that distinguish the Central Delta from its northern and southern areas, with the Central Data being more subsided (DWR 1995).

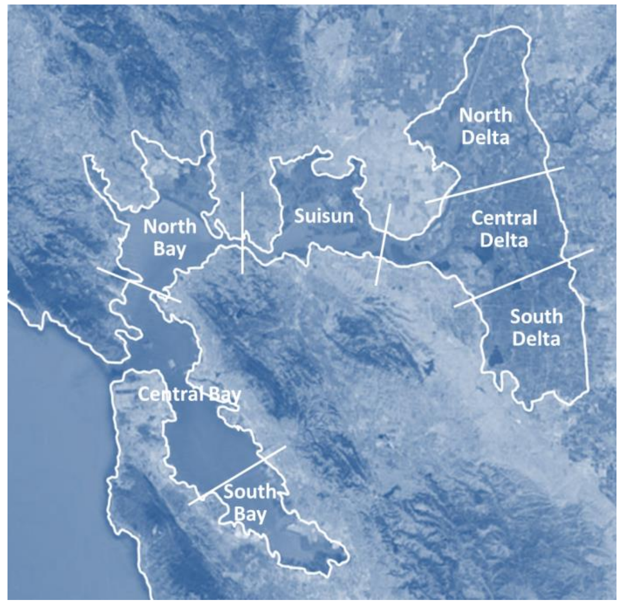

Figure 2. Sub-regions of the Estuary.

Assumptions and Uncertainties

Many assumptions underlie the reported measures of migration space. The most important assumptions are discussed below, along with recommendations for either eliminating them or testing their validity.

Seaward Boundary Location

The seaward boundary of the migration space is assumed to be the MHHW contour. Local MHHW cannot be exactly reckoned without an adequate series of site-specific tide height records. Without such records, the contour must be modelled (e.g., NOAA 2010) or derived from inexact ecological field indicators (Harvey et al 1978).

For the Bay Area and Delta, the seaward boundary (i.e., local MHHW) is assumed to be the historical upland limit of the tides as derived from the historical wetlands datasets of the Bay Area and Delta versions of the California Aquatic Resource Inventory (CARI; the Bay Area version is called BAARI), areas of fill above the projected sea levels. This boundary is based on many collaborating historical records (Collins et al. 1998, Beller et al. 2013, Whipple et al, 2012, SFEI 2014) plus limited local ground-truthing. The assumption that this boundary corresponds to local MHHW is probably conservative. That is, the historical boundary as depicted in BAARI might be slightly higher than the MHHW contour. How much higher depends on the local tide range and the accuracy of the historical records, both of which vary around the Estuary. It might be expected that the depicted boundary is less than 2 ft higher than the actual MHHW contour (Harvey et al 1978, Collins et al. 1998). For existing, low-gradient remnants of the historical, non-diked shoreline, the boundary derived from CARI corresponds closely to the boundary provided by NOAA, plus one foot of seas level rise (Figure 3). Based on their imprecision, and given the purposes of the migration space indicator, the boundaries derived by NOAA and based on CARI are comparable. The boundary provided by CARI is preferable because of its local documentation.

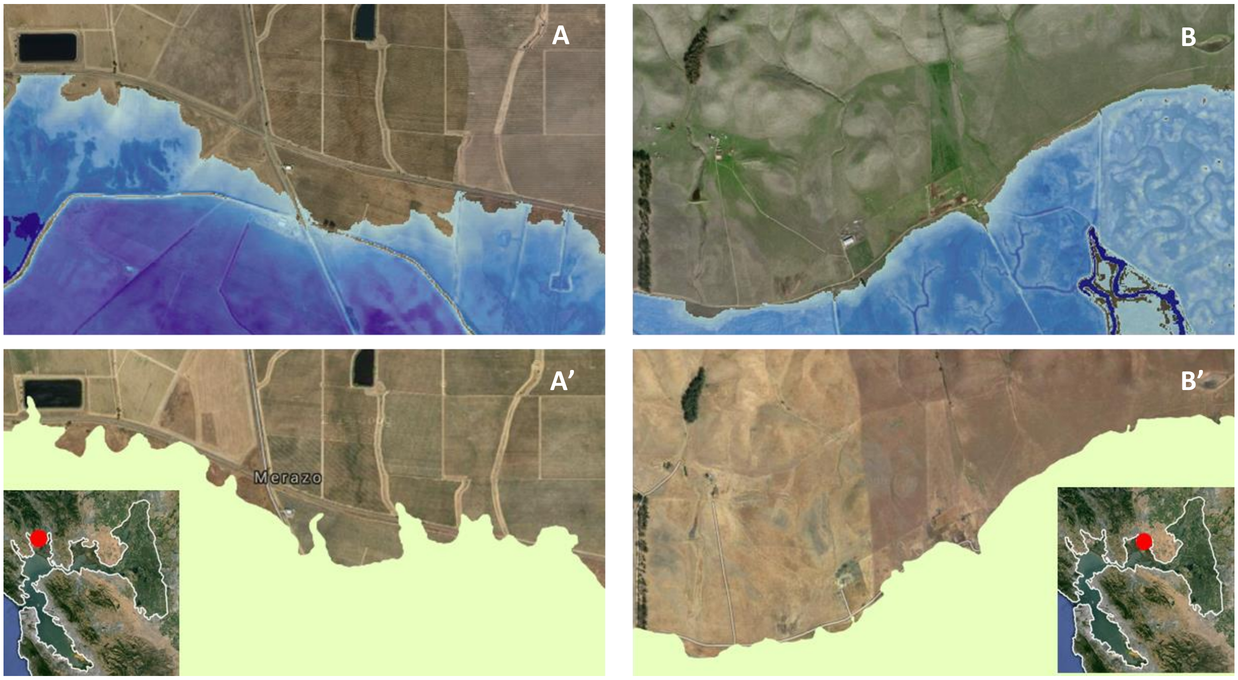

Figure 3. Comparison of seaward boundaries of migration space as represented by the NOAA MHHW contour plus 1 ft of sea level rise, and as derived from the historical tidal wetland boundary provided the CARI (A’ and B’), for areas of remnant natural shoreline in North Bay (A, A’) and Suisun Bay (B, B’).

Seaward Boundary Elevation

For the Bay Area (South Bay, Central Bay, North Bay, and Suisun Bay), the geodetic elevation of the MHHW contour as depicted in BAARI was assumed to be the same as the MHHW contour derived by NOAA (NOAA 2010, Marcy et al. 2011). In other words, the local NAVD88 elevations determined by NOAA for its estimated MHHW contour were transferred to the MHHW contour provided by CARI. This is reasonable, given the close correspondence between the two boundaries (Figure 3).

For the Delta, NOAA has not yet developed an estimated MHHW contour. As discussed above, the MHHW contour was reasonably assumed to be the historical tidal wetland boundary. The geodetic elevation of the MHHW contour has also not been determined, accept for a few locations. The Sacramento-San Joaquin Delta is one notable area along the California coast where VDATUM has not been calibrated (OLS 2012). The best documented reckoning of local MHHW and its conversion to NAVD88 for the Delta or its immediate vicinity pertain to Cache Slough and Sacramento in the North Delta (NAVD88 elevations for MHHW equal 6.4 ft and 7.96 respectively), and Port Chicago in Suisun Bay (MHHW equals 6.04 ft). The Sacramento tide station is near the head of tide on the Sacramento River, and geodetic elevation of MHHW at this station is therefore especially high due to the large and immediate influence of the high river flows. In contrast, the value for Port Chicago is much more removed from such influences because it is outside the Delta. In general, MHHW increases in geodetic elevation with distance upstream through Suisun Bay (DWR 2004). The value for Cache Slough was therefore assumed to be the most representative of the Delta overall. In other words, sea level was assumed to be the same relative to the land surface throughout the Delta, and the MHHW contour was assumed to have the same elevation relative to NAVD888 as reported by DWR for Cache Slough.

This is a large assumption with uncertain effects on the estimates of migration space around the Delta. The difference in NAVD88 elevation of MHHW for the three stations referenced above is less than two feet, which agrees with differences in elevations for MMHW relative to Mean Sea Level of 1929 (NGVD29) reported elsewhere for the Delta (Simenstad et al. 2000, OLS 2012). The reported geodetic elevation for Cache slough is probably within one foot of actual local geodetic elevations, which is comparable to the expected error of estimated MHHW contour in the Bay Area.

The difference in migration space width caused by any error in reckoning the geodetic elevation of the MHHW contour depends mainly on the topographic slope of the lands between the present-day and future tidal boundaries. Based on the DEMS for the Bay Area and Delta, a reckoning error of 2 ft could represent nearly 1,000 ft in migration space width for the most gently sloping areas. However, for most of the Estuary, a reckoning error of 2 ft represents much less than 200 ft of migration space width.

Landward Boundary

The landward boundaries are projected contours of MHHW for selected future sea levels. How fast the sea will rise to the selected levels is unknown. Furthermore, it is expected that the rate of sea level rise will generally decrease from the deeper areas the Estuary to it shoreline, and with distance upstream from the Golden Gate. The future differences in the rate of sea level rise around the Estuary are also unknown.

The landward boundary of the migration space does not correspond to the landward boundary of the associated transition zone. The transition zone extends seaward and landward of the MHHW contour. Under natural conditions, the landward extent of the transition zone depends directly on the slope of the land. For any given slope, the landward extent of the zone also varies with its physical and ecological services. It is generally wider for ecological services, such as wildlife support, than for physical services, such as shoreline protection (BEHGU 2015). This means that the migration space defined by the 5-ft rise in sea level might, for some services, be needed to conserve the transition zone associated with the 2-ft rise. For the purpose of conserving the transition zone, there is a need to visualize its full extent around the Estuary for all its essential services, and to determine what migration space is needed to conserve the services under different sea level rise scenarios.

Systematic error in the measurement of migration space begins with the uncertainty in reckoning existing sea levels, as discussed immediately above in relation to seaward boundaries. The error can be increased by the uncertainty of sea level rise projections (Reilly et al. 2001, Guttorp et al. 2014). These uncertainties can seem large (Church et al. 2013). However, it is useful to develop local scenarios of sea level rise, conduct vulnerability assessments based on the scenarios, and start to consider suitable adaptation policies (IPCC 2011). The migration space indicator is consistent with this guidance provided by the International Panel on Climate Change (IPCC).

The error in migration space measurement is also affected by omissions and inaccuracies in the digital elevation models (DEMs) used to resolve topographic relief and estuarine flooding pathways. The DEMS for the Bay Area and Delta do not incorporate such details as culverts and ditches that can significantly influence flooding extent. This can be remedied in the future by using DEMs that are based on high-resolution LiDAR and ground-truthed through local flood control agencies.

NOAA (NOAA 2010) provides guidelines for the accuracy of estuarine flood mapping due to sea level rise. Considering that a 1-ft contour map has a Root Mean Square Error (RMSE) of 0.3 ft, the 95% confidence level of the estuarine flood map would be 0.6 ft. The minimum sea level rise that can be confidently mapped is twice (1.96 x) that of the 95% confidence interval, and is therefore about one foot (1.19 ft) for a 1-ft contour map. The DEMs used in the migration space indicator therefore support the estimates of migration space for the selected sea level rises of two and five feet.

Land Cover

As reported here, the migration space indicator assumes that croplands (i.e., lands used for truck crops, vineyards, orchards, and hay) are not available to accommodate the landward migration of the transition zone. This assumption is based on the subjective decision that croplands are as valuable as the built environment and might be subject to same degree of protection from sea level rise. Two aspects of this assumption are worth noting. First, the maps of croplands was published in 2011 (NLCD 2011) and might not reflect more recent land use change. Second, there is some uncertainty about the future dedication of these lands to agriculture. Salt water intrusion due to sea level rise, the cost of building and maintaining levees, and an increased frequency of extreme flood events could eventually render these lands physically or economically unsuited for agriculture (Lund et al. 2008, Madani and Lund 2011, NRC 2012). Adding these croplands into the category of undeveloped lands could significantly increase the estimated amount of space potentially available to accommodate transition zone migration.

The migration space indicator assumes that reclaimed areas of the Estuary that have not been filled more than 2 ft or 5 ft above present-day MHHW are not part of the migration space. However, this assumes that these areas will not be filled to these elevations or higher in the future. The migration space indicator could accommodate scenarios of filling diked areas of the Estuary to create migration space by adjusting the DEMs to reflect the future fill elevations. In this way, the indicator could be used to assess the effects of intentional modifications of the shoreline, such as the creation of "horizontal levees", (Lowe et al 2013) on the amount of undeveloped migration space.

The migration space indicator involves no analyses or decisions about which areas of the Estuary most need the transition zone restored or conserved. The indicator as presently configured assumes that all existing transition zone areas should be conserved and that all suitable migration space should be dedicated to the transition zone of the future. This first generation of the migration space indicator can serve to begin prioritizing the opportunities that are identified.

Landscape Response

The data for future estuarine flooding do not consider how natural processes, such as erosion and marsh migration, will be affected by future sea level rise. The effects of changes in estuarine depth on tidal velocities are also not considered. Ongoing changes in the depth profile of the Estuary, including especially increases in the extent of shallow water, are likely to cause the rate of sea level rise to vary along the shoreline. Sea level is unlikely to rise at the same rate throughout The Estuary (Holleman 2013). Large scale levee breaches in Suisun Bay and the Delta could increase the rates of sea level rise in those sub-regions (DWR 2002, Jack R. Benjamin & Associates 2005), although they would likely be lesser than the rates further downstream toward the Golden Gate. Failing to address these processes is a significant limitation of the estimates of migration space. Overcoming this limitation will be difficult because it requires new understanding of the likely interactions between sea level rise and its landscape effects Important efforts to achieve this understanding though simulation modeling have begun (e.g., Morris et al 2002, Stralberg et al. 2011, Kirwan and Megonigal 2013), and are likely to continue. When the models are suitably developed, they should inform transition zone conservation and restoration efforts.

Benchmark and Scoring

The migration space benchmark is 50% of the total migration space in each sub-region being undeveloped, and 75% of that undeveloped space being protected. The scoring break between fair and poor scores is 40% and 50%, respectively. This benchmark and the threshold scores are arbitrary. They are not based on any ecological or economic analysis. An alternative benchmark could easily be incorporated into the indicator at any time. Ideally, the benchmark should reflect collaborative decisions by the responsible agencies about how much transition zone is needed, where it is needed, and why. Such decisions should reflect the new transition zone typology from the Baylands Goals Science Update (Goals Project 2015), the ecosystem services of the types, the costs and likely success of any necessary land use conversion or realignment, and the contribution of each future area of transition zone to the overall health of the Estuary. The scoring thresholds should be based on empirical relationships between the scores and levels of selected ecosystem service.

Peer Review

Comments on a draft of this technical report were solicited from Donna Ball of Save the Bay, Susan De La Cruz and Karen Thorne of the US Geological Survey, Matt Gerhart of the State Coastal Conservancy, Brenda Goeden of the Bay Conservation and Development Commission, Kirk Klausmeyer of The nature Conservancy, Andy Gunther of the Center for Ecosystem Management and Restoration, Hildie Spautz of the CA Department of Fish and Wildlife, Luisa Valiela of US Environmental Protection Agency, and Sam Veloz of Point Blue.

Results

The results of applying the migration space indicators for the San Francisco Estuary are summarized in the text below and the following figure (see Figure 4).

Total Migration Space

Total migration space includes all lands, developed or not, within the area delimited by the present-day MHHW contour and the likely landward extent of MHHW for either a 2-ft or 5-ft rise in sea level (Figure 4A). There is no relationship between total migration space and land cover. The amount of migration space is directly related to the tidal elevation and topographic slope of lands immediately joining the existing MHHW contour and draining toward the Estuary. In the Bay Area, the total amount of migration space increases from Suisun Bay through North Bay and Central Bay to South Bay. The relatively large amount of migration space in South Bay, relative to other Bay Area sub-regions, is due to the extensive lowlands of Santa Clara Valley adjoining the Estuary that have subsided below sea level due to groundwater extraction (Polland and Ireland 1988). The migration space of the other Bay Area sub-regions does not involve subsidence and is much more constrained by more steeply sloping lands. The three sub-regions of the Delta have nearly as much or more migration space than South Bay, due to the extensive low gradient lowlands of the Central Valley. For the Delta, the total migration space deceases from North Delta through Central Delta to South Delta. These patterns are not obvious at small scale (i.e., when either the Estuary or any one of its sub-regions is viewed in its entirety) because the migration space is seldom more than a few hundred feet wide, although it can exceed a thousand feet in some locations. The migration space corresponding to a rise in sea level of two feet is uniformly about half the size of the space corresponding to a sea level rise of five feet. This is indicative of the fairly uniform topographic slope of both the 2-ft and 5-ft migration spaces.

A separate analysis of total migration space not reported here compared the historical (pre-settlement) migration space to the modeled future spaces. The total migration space has decreased since historical times. This is due to the purposeful filling of diked estuarine areas to elevations above the selected future sea levels. The filling has effectively moved the MHHW contour seaward and thereby increased the amount of migration space. Most of the fill has been developed and therefore has not increased the space for the future transition zone.

Undeveloped Migration Space

In the Bay Area, for a 2-ft rise in sea level, the amount of undeveloped migration space is greatest in South Bay. There is perhaps twice as much in North Bay than in Central Bay or Suisun, but the amounts are very small everywhere outside South Bay. For a 5-ft rise in sea level, the amount of undeveloped space is still greatest in South Bay, but it is approximately equal in North Bay and Suisun, and least in Central Bay. The percent increase in space between a 2-ft rise in sea level and a 5-ft rise is least for South Bay and greatest for Suisun.

In the Delta, for a 2-ft rise in sea level, there are comparable amounts of undeveloped space in North and Central Delta, and substantially less in South Delta. For a 5-ft rise, the amount of undeveloped space decreases markedly from North Delta through Central Delta to South Delta. The percent increase in space between a 2-ft rise in sea level and a 5-ft rise is by far greatest for North Delta.

These patterns reflect complex spatial relationships between topography and land use. For the Bay Area, the sub-region with the most undeveloped migration space is South Bay. Although this sub-region is densely urbanized, it also relatively flat and low-lying, with relatively numerous areas of protected open space along the shoreline. There are larger undeveloped areas in North Bay and Suisun, but they are in general much steeper. Central Bay has the least amount of total migration space and undeveloped migration space because the lands adjoining the shore are relatively steep, densely developed, and have less undeveloped area. For the Delta, where the topography of lands adjoining the Estuary is more uniformly flat and low-lying (western extent of the Central Delta notwithstanding), differences in migration space among the sub-regions largely reflect differences in land use and the distribution of people. Population density and land development along the shoreline of the Delta increase from North Delta through Central Delta to South Delta.

Undeveloped and Protected Migration Space

Much less than half of the undeveloped migration space is protected from development (Figure 4C). Nearly twice as much of the undeveloped migration space has been protected in South Bay and North Bay than in the other sub-regions, with the exception of the North Delta. This is mainly due to shoreline parks and other public open space in urbanized environments. The relatively large areas of protected migration space in North Bay, North Delta, and Central Delta are due in large part to state and federal wildlife refuges that adjoin the historical MHHW contour. A noteworthy finding is that very little of the undeveloped migration space in Suisun and South Delta is protected. While there is probably a need to explore opportunities in every region to conserve and restore the transition zone, the need might be greatest in these sub-regions of the Estuary.

Recommended Next Steps

Further development of the migration space indicator should be guided by regional experts in land use, sea level rise and its geomorphic effects, and GIS. There is a need to assure that the indicator always utilizes the best available data. There is a critical need to develop the Vdatum tool for the Delta. There is also a need to estimate the full extent of the transition zone around the Estuary for all its essential services, and to determine what migration space is needed to conserve the services under different sea level rise scenarios. Capabilities for online mapping and visualization should be developed to support analyses of alternative scenarios for transition zone conservation and restoration. These scenarios will need to be guided by scientifically sound criteria for identifying and prioritizing restoration and conservation opportunities.

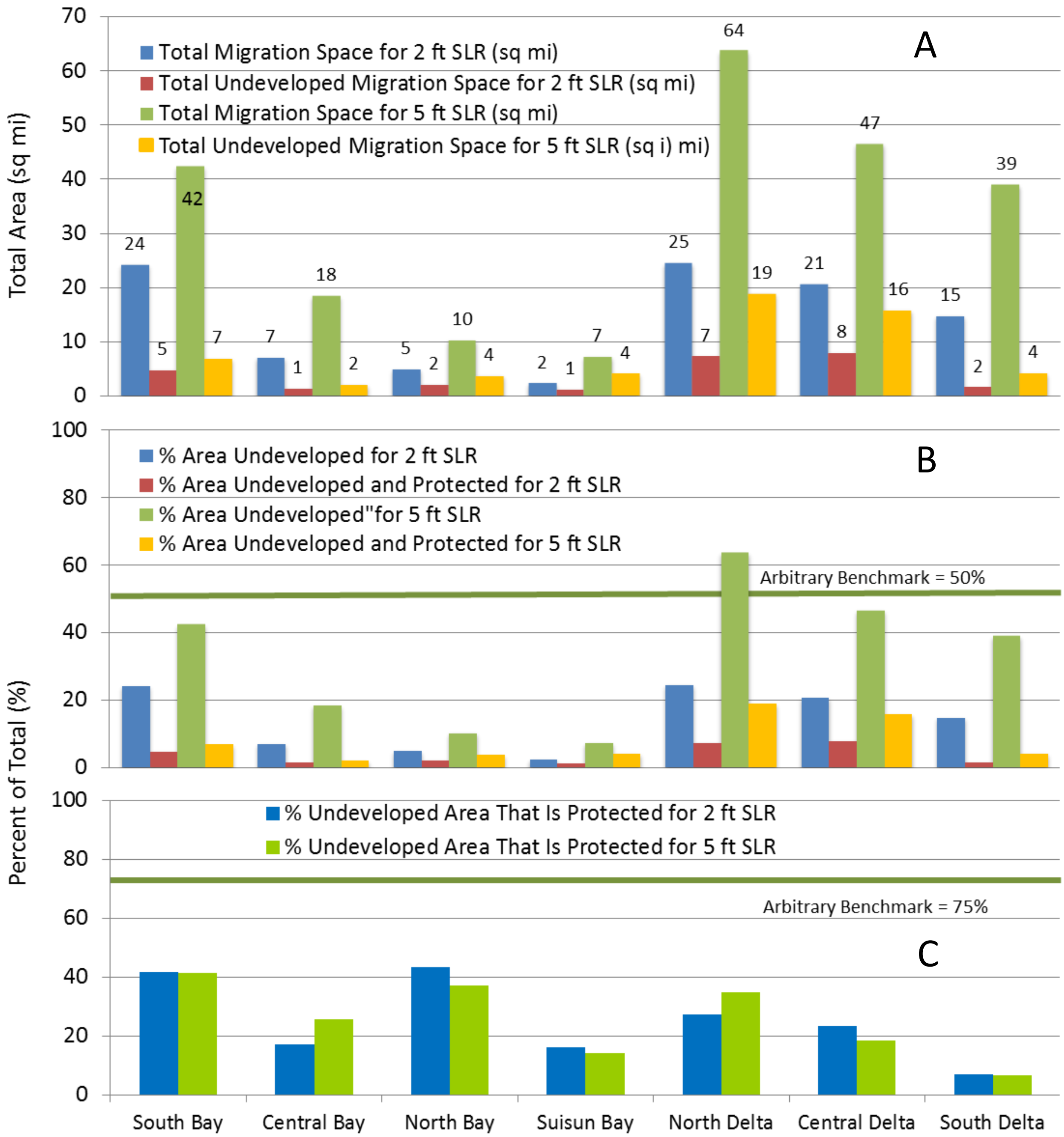

Figure 2. Sub-regional distribution of developed and undeveloped migration space for sea level rise (SLR) of 2-ft and 5-ft, showing (A) total migration space (sq mi); (B) percentage of total migration space undeveloped and protected, showing an arbitrary target value of 50%; and (C) the migration space indicator (i.e., the percentage of the total undeveloped migration space that is protected), showing an arbitrary benchmark ~~target~~ of 75%.

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