Adaptive planning for sea level rise-threatened transportation corridors

Word count: 6,497
Number of figures and tables: 4

Corresponding author:
Fraser M Shilling
Road Ecology Center
Department of Environmental Science and Policy
University of California, Davis CA 95616
Ph: 530-752-7859
Fax: 530-752-3350
Email: fmshilling@ucdavis.edu

Justin Vandever
AECOM
2101 Webster St., Suite 1900
Oakland, CA 94612
Ph: 510-879-4505
Email: Justin.vandever@aecom.com

Kris May
AECOM
2101 Webster St., Suite 1900
Oakland, CA 94612
Ph: 510-622-6640
Email: kris.may@aecom.com

Ina Gerhard
CA Department of Transportation, District 4
111 Grand Avenue, MS 10D, Oakland, CA 94612
Ph: 510-286-5598
Email: ina.gerhard@dot.ca.gov

Robert Bregoff
CA Department of Transportation, District 4
111 Grand Avenue, MS 10D, Oakland CA 94612
Ph: 510-286-5503
Email: robert.bregoff@dot.ca.gov

ABSTRACT

We describe a generalizable planning and assessment process for transportation planning adaptive to sea level rise (SLR). State Route 37 (SR 37) is the California highway most vulnerable to temporary flooding and permanent inundation due to SLR. Like many other coastal highways in the US, SR 37 is adjacent to protected coastal systems (e.g., beaches, tidal wetlands), meaning that any activity on the highway is subject to regulatory oversight. Both SR 37 and the surrounding marshes are vulnerable to the effects of SLR. Due to a combination of congestion and threats from SLR, planning for a new highway adaptive and resilient to SLR impacts was conducted in the context of stakeholder participation and Eco-Logical, a planning process developed by FHWA to better integrate transportation and environmental planning. In order to understand which stretches of SR 37 might be most vulnerable to SLR and to what degree, a model of potential inundation was developed using a recent, high-resolution elevation assessment conducted using LiDAR. This model projects potential inundation based upon comparison of future daily and extreme tide levels with surrounding ground elevations. The vulnerability of each segment was scored according to its exposure to SLR effects, sensitivity to SLR, and adaptive capacity (ability of other roadways to absorb traffic). The risk to each segment from SLR was determined by estimating and aggregating impacts to costs of improvement, recovery time (from impacts), public safety impacts, economic impacts, impacts on transit routes, proximity to communities of concern, and impacts on recreational activities.

INTRODUCTION

Sea level has already risen by 8 inches along the California coast and by 2100 may be 36” to 66” above present levels *(1,2)*. Climate change is expected to result in accelerated rates of sea level rise *(3)* and changing seasonal wave conditions *(4)*, further exposing the shorelines to impacts *(5,6)*. Infrastructural and living systems adaptations will need to occur to avoid a wholesale change in the marshes, estuarine systems, low-lying urban areas, and exposed highway infrastructure along the US coast. Transportation system and coastal ecosystem changes occur slowly and may not adapt at the rates necessary to keep up with increased sea levels and storminess. Many coastal communities and infrastructural features face risks from storms in the form of flooding, erosion, and shoreline retreat. A longitudinal survey of coastal managers in California found sea-level rise (hereafter SLR) and related problems among the most challenging issues *(7)*.

Identifying infrastructure that is both exposed now or in the future to the ocean and vulnerable to SLR and increased storminess is a complicated and potentially expensive process for local and state transportation agencies *(8)*. The physical structures themselves are vulnerable to SLR, which is likely to result in increased costs for maintenance, repair, replacement of facilities and materials, and eventual adaptation *(9,10)*. In addition, the function of linked, regional transportation systems may be vulnerable to disruption if a SLR-vulnerable link (e.g., a coastal highway) fails (11,12).

State Route 37 (SR 37) constitutes a major regional east-west vehicular transportation corridor in the northern San Francisco Bay Area (hereafter “Bay Area”, Figure 1) and was used as a case study to understand adaptive transportation planning in the face of SLR. Like many coastal highways in the US, this corridor is under threat from SLR. In fact it is the lowest-lying highway (in terms of elevation relative to mean higher high water, MHHW) in California and was considered by Caltrans to be the best case study with which to develop an adaptive planning process to deal with SLR. The projected SLR of 1 – 1.7 m in the next 90 years *(2)* poses a potential threat to the highway. Because of its position upon a berm passing through existing marshes and marshes under restoration, SR 37 also poses a threat to the ability of nearby coastal-marsh systems to adapt to SLR. These marshes are nationally important as habitat for endangered species, so the role of the highway in their adaptation must be considered in corridor planning. Many animal and plant species are threatened or endangered as a result of loss of 85% of historical Bay Area wetlands *(13)*.

An important aspect of adaptive planning for climate change and sea level rise is the creation of SLR exposure maps, which overlay future sea level and wave runup hazard areas on existing infrastructure and natural features to assess SLR vulnerability *(14,15)*. The public seems to find these maps of sea level rise and potential impacts, including interactive maps online, the most useful way to understand climate change effects *(16,17,18,19,20)*. Because there is considerable uncertainty in how much sea levels might rise, the types and costs of impacts, and when certain elevations and impacts will occur, many modeling and mapping projects attempt to display uncertainty and variability *(18)*. At the same time, there is variation in how SLR maps are received by the public, which may be based upon scientific expertise, or trust in scientists *(18)*.

Adaptive Transportation Corridor Planning

Planning and constructing modifications to a highway corridor usually requires consideration of current and future travel modes, linked arterial roads and highway, and current and proposed motor vehicle capacity *(21)*. A critical feature of SLR effects on coastal systems is that most of the natural systems affected are protected by one or more statutes and agencies. This means that adaptive action taken to preserve transportation systems must also take into account adjacent and connected natural systems. In coastal areas of the US, saline, brackish, and freshwater marshes abut many low-elevation highways/interstates and other infrastructure.

The corridor used as an example in this study is an important East-West highway connector in the Bay Area and its existing congestion is projected to increase over the next 25 years. California Department of Transportation (Caltrans) is exploring options for the future of SR 37 *(22)*. The adaptive corridor planning process developed and described here could be used in many typical transportation planning processes within coastal states. To improve consideration of regulated and protected coastal systems, and early inclusion of regulatory agencies in the adaptive planning process, explicit use was made of Eco-Logical as a procedural guide *(23)*. An extensive stakeholder process was used to build knowledge and consensus around potential adaptive structural solutions. Both regulatory and stakeholder processes resulted in agreement about joint protection of transportation infrastructure and surrounding natural systems and processes. The adaptive planning included in the corridor planning step for this state highway is one of the earliest at which transportation demand, environmental constraints, and stakeholder needs can be used to define strategies for improving transportation choices, adapting to SLR, and enhancing endangered ecosystems.

METHODS

Stakeholder & Regulatory Process

Critical to the development of the corridor assessment, adaptive approach, and foundation for agreements with regulatory agencies was the inclusion of stakeholders early in the process. Ten stakeholder meetings were held between March, 2011 and April, 2015. At successive meetings stakeholders were encouraged to share their needs and desires for corridor and landscape planning, understanding of the issues facing the transportation corridors, ecological and community well-being issues that should be considered, and values for the corridor. Participants were recruited to the stakeholder process primarily through existing social networks originating in the UC Davis Road Ecology Center, Caltrans, and partner non-governmental and local government organizations.

Because the corridor is in a coastal zone which includes many protected natural features, any adaptive projects would have to obtain permits to cover potential damage to these features. To facilitate engaging regulators as early as possible, we interviewed (individually and jointly) seven agencies that had permitting authority for transportation projects along SR 37.

Stakeholder & Community Survey

Despite advertising the stakeholder meetings through partner channels, only a small group of people and organizations (<200) who would be impacted by changes to SR 37 was involved in the planning process. Community members living in communities near (<1 mile) the corridor were randomly selected to an “n” of 20,000, and this group sent a postcard during February, 2012, asking them to complete an anonymous, web-based survey composed of 47 questions about their activities and preferences for the corridor. We recognize that others use the highway, traveling from outside the 1 mile buffer area, but this group seemed most likely to be most impacted in the greatest number of ways (e.g., use of highway, disturbance from construction, aesthetic appeal of final product). The preferences questions asked them to describe their feelings about traffic conditions, environment, rural character, and highway management. They were then asked their opinions about specific future scenarios for the highway and how well they felt these scenarios supported different possible values for the corridor context. All stakeholder process participants (149 people from 64 organizations) were also invited by email to take the survey at the same time as the community.

Sea Level Rise Modeling and Mapping

SR 37 is protected from inundation and flooding by a complex interconnected system of levees and berms that run along the shoreline of San Francisco Bay and along the five rivers and creeks that intersect the highway. These Bay and riverine flood sources provide a conduit for Bay floodwaters to inundate the highway during coastal flood events. We conducted an SLR exposure analysis to identify the extent and timing of permanent inundation or temporary flooding for each segment of SR 37 under different combinations of SLR and tide level. We evaluated the shoreline protection system vulnerabilities, taking into consideration the relative elevations of Bay floodwaters, the shoreline protection system, and the highway to determine the location and source of flooding for each segment. We shared these analyses with stakeholders as they were developed.

Data Sources

The sea level rise inundation modeling and mapping required topographic and water level data which were obtained from the following sources. Topographic LiDAR (Light Detection and Ranging) data were obtained from the U.S. Geological Survey (USGS) and National Oceanic and Atmospheric Administration (NOAA) California Shoreline Mapping Project (CSMP). Water levels were obtained from the Federal Emergency Management Agency (FEMA) San Francisco Bay Area Coastal Study.

The SLR inundation modeling and mapping was conducted using a digital elevation model (DEM) derived from the bare-earth LiDAR dataset. We solicited feedback and local data from the stakeholder group and refined the topographic DEM to better represent existing conditions and management activities within the study area (e.g., near recently constructed wetland restoration projects). In addition, water control structures such as locks and tide gates were built into the topographic DEM to better represent water management activities at some locations.

Typical daily high tides (characterized by the mean higher high water (MHHW) tidal datum) and extreme tides (characterized by the 100-yr tide level) were determined through analysis of hydrodynamic modeling data produced as part of the recently completed coastal flood study of San Francisco Bay *(24)*. The model takes into account water level variations associated with astronomical tides, storm surge, and El Niño effects.

Sea Level Rise Scenarios

We selected six mapping scenarios to represent a range of possible future conditions associated with extreme tide levels and SLR. SLR values were selected to represent current National Research Council (2012) SLR projections for the Bay Area, including a mid-range and high-range projection. Four SLR amounts were considered: the likely and the high end of the range for 2050 (+12 and +24 inches) and 2100 (+36 and +66 inches) and were evaluated with the typical daily high tide. The extreme high tide was evaluated only with the mid-range SLR amounts at 2050 and 2100 (+12 and +36 inches). By combining the daily high tide and extreme tide with each SLR amount, we produced six mapping scenarios that represent a range of possible future conditions.

Modeling and Mapping Methods

The inundation modeling and mapping were conducted following the methods developed by the NOAA Coastal Services Center *(25)*. The water surface for each mapping scenario was projected landward over the terrain to determine depth and extent of potential inundation. The mapping methodology takes into consideration hydraulic connectivity so that inundation is not predicted for low-lying areas that are disconnected from the Bay flooding source.

We also delineated the highway alignment and surrounding protective shoreline assets (such as levees, roads, and railroad berms) to determine the crest elevation along each feature. The inundation datasets were overlaid on the crest delineations to determine the depth of overtopping along each highway segment or shoreline asset. The total length of overtopping of each highway segment was tabulated for each scenario. Low spots (or “weak links”) along the shoreline were located to identify potential shoreline vulnerabilities, areas for further investigation, and sites of potential future mitigation action.

The inundation and overtopping datasets were used in the subsequent vulnerability study to assess exposure of the highway and shoreline protection assets to sea level rise inundation and flooding.

Marsh and Highway Vulnerability Assessment

We assessed vulnerability by evaluating the exposure, sensitivity, and adaptive capacity of each segment to SLR impacts. Each highway segment exhibits different physical characteristics (e.g., elevation, proximity to Bay shoreline), use attributes (e.g., commuter and truck traffic), and SLR impacts, which affected the vulnerability and risk ratings developed as part of the assessment. Exposure was evaluated by examining the depth and extent of inundation, length of overtopped highway, and vulnerability of shoreline protection features. Sensitivity was evaluated by examining indicators such as age, level of use, historical performance during storm events, seismic sensitivity, and liquefaction susceptibility. The adaptive capacity of the regional transportation system was evaluated by examining the existence and viability of alternate routes in the event of SR 37 closure due to flooding. For each component of vulnerability – exposure, sensitivity, and adaptive capacity – a low/moderate/high rating (numerical values of 1 to 3) was assigned to develop a composite vulnerability rating for each segment of the highway.

We assessed risk by evaluating the likelihood and consequence of SLR impacts to the highway to develop risk ratings for each segment. Potential consequences of inundation or flooding by SLR include costs to restore service, public safety impacts, economic impacts to goods transport and commuters, proximity to communities of concern, and impacts to recreational activities. For each component of risk – likelihood and consequence – a low/moderate/high rating (numerical values of 1 to 3) was assigned to develop a composite risk rating for each segment of the highway.

The results of the vulnerability and risk assessment will help Caltrans prioritize adaptation options along the most vulnerable and at-risk segments of SR 37.

Corridor Adaptive Planning

California has embraced corridor planning and management as part of regional transportation planning and as an intermediate scale between regions and the project level. Caltrans has begun planning for the SR 37 corridor, originally because of congestion and more recently to also adapt to potential impacts from SLR. Despite periodic congestion, on average, traffic volumes are currently below capacity for the entire length of the corridor. Without capacity enhancement, segments of the corridor are anticipated by 2035 to operate significantly above capacity. Regionally, there is broad political and institutional acceptance of the possibility of rising sea levels requiring adaptive action in the near future. Because of the breadth of stakeholders involved in SLR adaptation discussions, the SR 37 corridor planning process has intentionally included a similarly broad set of involved parties.

The approach we took was to combine the idea of transportation system modification with ecological protection and improvements to create an overall portfolio of future stewardship actions. To make this more concrete in terms of the highway, future scenarios were created that reflected the discussion among transportation agencies and with stakeholders. These scenarios provided a more grounded discussion of impacts and benefits to different constituencies, environmental impacts and permits, cost and feasibility, and potential corresponding ecological and mitigation actions`.

RESULTS

Stakeholder & Regulatory Process

The goals varied slightly between early and later phases of stakeholder participation. Initially, the goal scopes were broad and related to the use of Eco-Logical approaches to highway corridor planning and assessment. In later phases, the goals were narrowed and related to the specific need to develop a new and adaptive transportation system in response to the likely impacts from SLR, while protecting the natural processes and attributes associated with the corridor. At the initiation of the overall project (Phase 1, 2011), 49 individuals from 40 organizations were invited to participate. By the end of the second phase (11/2015), 204 people from 102 organizations and 9 unaffiliated individuals were participating in person and via a list-serve.

Agencies with permitting responsibility were key stakeholders in the process. We involved every regional (n=1), state (n=4), and federal (n=4) agency from whom Caltrans would need a permit to build a project in a coastal zone to adapt to SLR. There was a spectrum of agency responses for how early they wished to engage in the project development process. Some agencies wanted to be a part of the very initial discussions of ideas for the corridor, which is consistent with EcoLogical, while others preferred to have Caltrans decide on a proposal and come to them with a fully developed plan and description of the affected area, primarily because of funding constraints. Some agencies preferred to be somewhere in the middle of that spectrum.

Infrastructural Adaptive Strategies

During discussion within Caltrans and among stakeholders participating in this study, five high-level scenarios arose as possible futures for SR 37. These five were intended to provide alternative scenarios suitable for future transportation needs and also recognize the sensitivity of the environment in the area surrounding this transportation corridor. The scenarios were as follows: A) No Highway Expansion - Manage the corridor with maintenance and repair activities and minor operational improvements (no significant change in the footprint or capacity); B) Expanded Footprint - Height and width of the roadway/levee through the marshes would at least double and the corridor would be expanded to 4 lanes to address current and projected future traffic volumes; C) Causeway - Option 1: over existing SR 37 footprint at areas of low elevation and Option 2: across San Pablo Bay between Novato & Vallejo; D) Strategic Re-alignment - corridor would be re-aligned away from marshes & wetlands between Vallejo and Novato, with I-80 and 580 to the south, or with Highways 29 and 12/121 to the north; E) San Pablo Bay Tunnel - corridor would be routed through a tunnel at the shortest feasible distance between the Vallejo area and the Novato area.

Survey Findings

Stakeholder process participants and community survey respondents were queried about their opinions regarding use of and futures for SR 37. Their frequency of use of the highway was slightly different (Table 1), as was their familiarity/knowledge of sea level rise. Stakeholder process participants and community members had almost identical support for minimizing transportation impacts to the environment, using a causeway to meet combined transportation and environmental needs, and transit availability. However, community members were more likely to respond that they would avoid using transit. If tolling was used to finance construction of the adaptive project, community members were more likely to prefer that no project take place, or they would use another route.

Respondents to the survey were asked about the environment, transportation, and community components of the corridor context that they valued. These values were then used to refine their selection of transportation scenarios, insofar as the scenarios supported their values. Respondents ranked each future adaptive scenario for its support of different values and these ranks were coded as follows: does not support = 0, somewhat supportive = 1, supports = 2. The weighted-average support "score" was calculated for each scenario-value combination. The different future options for corridor management were then comparable based on their contribution to these combined values. For example, placing SR 37 through a tunnel under San Pablo Bay, or on top of a causeway, or aligned with a parallel highway were all seen as supporting environmental values.

The adaptive option seen as most supportive of combined environmental, community, and transportation needs was the causeway option (also in Table 1), despite this being one of the more expensive possible constructed scenarios. The wetlands, waterways and grasslands surrounding the corridor are habitat for a wide variety of native fauna and flora, including several state and federally-protected species. The abandonment of the low-lying alignment was favored over armoring the existing footprint, which makes this an interesting case study for coastal areas in the US which are considering the same questions. It is noteworthy that environmental regulatory agencies described the causeway option as the one future scenario for the corridor that was "self-mitigating" when it came to endangered species. This is because it would elevate the roadway above its existing grade and potentially reconnect tidal flows to adjacent marshes on either side of the highway.

Sea Level Rise Modeling and Mapping

The results of the SLR inundation modeling and mapping were used to objectively predict the depth and extent of potential inundation and determine the length and depth of overtopping of the highway and protective shoreline assets for each segment. Segment A was the most potentially-impacted and a significant portion of the segment would be exposed to permanent inundation (i.e., inundation by typical daily high tides) under the 36-inch sea level rise scenario (Figure 2). Segment B is generally higher in elevation but would still be impacted by permanent inundation under the 36-inch scenario along low-lying portions of the highway in the eastern and western ends of the segment. Segment C would not be overtopped under a 36-inch scenario. Segments would also be impacted by combinations of SLR and storm surge under different return intervals, or by a 100-yr tide event even under existing conditions without sea level rise

(Figure 2). This highlights the fact that the existing highway is already vulnerable to flooding during extreme events.

The sea level rise inundation mapping and overtopping analysis revealed that the large scale inundation within Segment A and the western portion of Segment B is primarily due to overtopping of flood protection levees along the Bay shoreline and adjacent rivers and creeks. At moderate inundation and flooding scenarios (e.g., 12” SLR) , overtopping occurred only along very short isolated segments of levees. At the high inundation and flooding scenarios (e.g., ≥36” SLR), widespread overtopping occurred along significant portions of the shoreline.

Highway Vulnerability Assessment

We combined exposure, sensitivity, and adaptive capacity ratings to derive composite vulnerability ratings for each segment. Segments A and B were predicted to be most vulnerable to potential SLR impacts and Segment C less so (Table 2). The poor adaptive capacity of all segments (value of 3) had a significant influence on the vulnerability score. This is because alternate routes, in the event of failure of SR 37, are also vulnerable to SLR effects or require much longer travel distances and travel time.

We combined the likelihood and consequence ratings to derive composite risk ratings for each segment. Since likelihood of a given SLR scenario was assumed to be the same for all segments, it was not considered in determining the relative risk among segments. Segment B was predicted to be at the highest *immediate* risk, Segment A is vulnerable to future risk from potential SLR effects and Segment C at the least risk (Table 2). The potential economic impact to commuters and proximity to communities of concern had the greatest influence on the risk value for all segments. High values for economic impacts to goods transport and impacts to recreational impacts were also influential on the risk value for Segment B.

DISCUSSION

Adaptive Eco-Logical Planning

Eco-Logical embodies a multi-agency vision for smarter transportation planning *(23)*. Many of the Eco-Logical steps do not readily apply to comprehensive visioning and planning processes, such as the development of a corridor management plan to adapt to SLR. The Eco-Logical steps seem targeted toward specific projects with shorter timelines, and with a greater opportunity to develop specific crediting strategies with regulatory partners. A corridor management plan involves the development of a long-term vision that is not legally binding, but that also leads to project development and mitigation requirements. The current regulatory and funding structure for project mitigation is a difficult fit for a longer-term visioning process. It would be appropriate to adapt steps in Eco-logical to advance corridor-scale planning, especially for coastal highways affected by SLR.

Views about regulatory participation differed among agencies. Some regulators were interested in participating in the early visioning, but others preferred to wait until specific impacted ecosystem components were identified before becoming involved. This is due to both the prevailing culture of the agencies as well as the resources to support staff in long-term planning. Because corridor planning does not attach to a single proposed project, some regulatory partners were attending meetings on their own time, unfunded. It would be helpful in setting up future efforts to consider how to prioritize larger planning processes for regulatory liaisons so that their early participation can support more efficient, project-specific engagement later. Non-regulatory stakeholders felt that regulatory agency participation in early discussions and planning for the corridor was critical to eventual successes on the corridor. This was because of the obvious benefits of getting regulatory input early in choosing among potential competing ideas for future scenarios for the corridor. There was little patience or understanding among stakeholders for why this approach, which is a core element of Eco-Logical, was not already the case.

Stakeholder Participation in Adaptive Planning

Most transportation planning includes processes for outside stakeholder input, primarily through well-defined comment periods on detailed project descriptions and environmental assessments. This input tends to be late in the project development process and may not impact fundamental principles of the project, or how the project links to other parts of the integrated transportation system. Another view for external input from stakeholders is as “citizen planners” capable and willing to enter into the overall process of designing sustainable transportation systems *(26)*. SR 37 plays a critical linkage role in the transportation network around the North San Francisco Bay and raising it onto a causeway would probably be quite expensive. Because of this, Caltrans has effectively included a very broad set of stakeholders in very early SR 37 corridor planning as “citizen planners”. This process has largely driven the narrowing of choices for adapting the infrastructure to SLR and ensuring that it has a positive effect on surrounding lands.

Barriers and Opportunities in Adaptive Planning for Vulnerable Coastal Highways

We found that SLR of 36” could cause long-term inundation of long stretches of SR 37. Similar, but possibly shorter-term flooding/inundation could occur with a 5-year storm combined with 12” SLR, a 10-year storm and 6” SLR, or current conditions and a 25-year storm. Moderate SLR (24”) could result in temporary (high-tide) overtopping of levees protecting part of the route, without a storm event. These locations of potential overtopping could be identified with high-resolution field measurements of levee elevation. Therefore, significant reduction to the highway vulnerability could be made through focused improvements to small segments of the levee system, which would also require significant stakeholder agreement because of mixed ownerships. Significant corridor-scale improvements would still be required to adapt to higher SLR scenarios and/or large storm events.

Building or enhancing coastal transportation infrastructure that is resilient in the face of SLR and increased storminess will be expensive and be in competition with existing funding priorities. Until recently, SLR impact on low-lying highways like SR 37 was not included as a priority in Bay Area regional transportation planning. Although marsh restoration has recently included consideration of SLR, it is rare for coastal infrastructure planning to combine consideration of impacts of SLR on both marshes and highways. Currently and in the future, there could be two opposing threats to coastal marsh ecosystems: insufficient tidal flooding (due to restriction of flows), or excessive flooding (due to subsidence, erosion and sea level rise). Artificial coastal infrastructure, including roads or berms, has an impact on hydrological regime in certain coastal ecosystem by causing inadequate provision of tidal flows *(27)*. Constrained flows hinder ecosystem functions by disrupting the natural interactions among vegetation, soil and hydrology. In many coastal states, there has been a rapid and recent realization that both grey (roadways) and green (marshes) infrastructure are at risk from SLR and that co-adaptive planning was essential to reduce impacts to both. As one way of addressing this type of planning, a Joint Powers Authority is being organized by Congestion Management Agencies with responsibility for the SR 37 corridor to carry out further planning and environmental assessment.

Recommendations for Improved Adaptive Planning for SLR

1) The data available for predictive modeling of SLR impacts on coastal systems are extensive and high-resolution. However, there are well-recognized issues with LiDAR data not necessarily reflecting the true elevation of the ground due to interference from overlying vegetation (when present). For systems and detailed planning where protective structures (e.g., berms and levees) are key to understanding the likelihood of inundation at certain sea levels, LiDAR-derived elevations should be verified in the field (e.g., using RTK-GPS).
2) Transportation planning seldom includes extensive community outreach and in-reach (i.e., community influence on process). Because of the usually-high costs associated with SLR-related adaptive planning and retrofitting, it would benefit both communities and transportation organizations to continuously include stakeholder communities, from planning to the final system replacement/construction.
3) Transportation organizations are accustomed to planning processes for complex projects taking many years and even decades. Most stakeholders are not. Despite the risk of poor decision-making and damage to adjacent coastal systems, new legislation may be needed to authorize new funds to support more rapid planning and construction of adaptive structures, which may themselves be innovations.
4) We found overwhelming and continuous interest on the part of stakeholder organizations and individuals in the rapid and adaptive planning process we developed. However, it was not clear that responsible agencies were ready or authorized to make the new types of decisions required to respond to the novel threats posed by climate change-forced changes in shorelines and coastal infrastructure. To develop sustainable and resilient transportation and other infrastructure, department and agency leaders may need to explicitly change the support system for line-officers to make seemingly-risky decisions.

ACKNOWLEDGEMENTS

We would like to acknowledge the critical efforts of Katie Benouar and Kome Ajise (Caltrans, Headquarters) throughout the inception and conducting of this project. We would also like to thank Abby Monroe, Mary Campbell, Nathaniel Roth, Kevin Ward, and David Waetjen (UC Davis) and Sarah Kassem, Mark Lightner, Amruta Sudhalkar, and Joy Villafranca (AECOM). This work was partially supported by the Federal Highway Administration in cooperation with the American Association of State Highway and Transportation Officials. It was conducted in the second Strategic Highway Research Program, which is administered by the Transportation Research Board of the National Academies, agreement SHRP C-21(C) with UC Regents under DOT-7555-002. Remaining support was provided by Caltrans under contract 74A0728 with the UC Regents.

REFERENCES

1) Nicholls, R.J. and A. Cazenave. Sea-level Rise and its Impact on Coastal Zones. Science 328, 2010, pp.1517.

(2) National Research Council (NRC). *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Prepared by the Committee on Sea Level Rise in California, Oregon, and Washington and the National Research Council Board on Earth Sciences and Resources and Ocean Studies Board Division on Earth and Life Studies. 2012.

(3) Cayan, D.R., E.P. Maurer, M.D. Dettinger, M. Tyree, and K. Hayhoe. Climate Change Scenarios for the California Region. *Climatic Change*, Vol. 87, (Suppl 1), 2008, pp. S21-S42.

(4) Bromirski, P.D., D.R. Cayan, J. Helly, and P. Wittman. Wave Power Variability and Trends Across the North Pacific. *Journal of Geophysical Research: Oceans*, Vol. 118, 2013, pp.1–20

(5) Heberger, M., H. Cooley, P. Herrera, P.H. Gleick, and E. Moore. Potential Impacts of Increased Coastal Flooding in California Due to Sea Level Rise. *Climatic Change,* Vol. 109, (Suppl 1), 2011, pp. S229–S249.

(6) King, P.G., A.R. McGregor, and J.D. Whittet. *The Economic Costs of Sea-Level Rise to California Beach Communities*. Report to the California Department of Boating and Waterways, 2011.

(7) Finzi Hart, J. A., P. M. Grifman, S. C. Moser, A. Abeles, M. R. Myers, S. C. Schlosser, and J. A. Ekstrom. *Rising to the Challenge: Results of the 2011 Coastal California Adaptation Needs Assessment*. USCSG-TR-01-2012. University of Southern California Sea Grant Program .2012.

(8) Rowan, E., C. Snow, A Choate, B. Rodehorst, S. Asam, R. Hyman, R. Kafalenos, and A. Gye. Indicator Approach for Assessing Climate Change Vulnerability in Transportation Infrastructure. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2459,* Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 18–28. DOI: 10.3141/2459-03

(9) Mallick, R.B., M.J. Radzicki, J.S. Daniel, and J.M. Jacobs. Use of System Dynamics to Understand Long-Term Impact of Climate Change on Pavement Performance and Maintenance Cost. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2455*, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 1-9. DOI: 10.3141/2455-01

(10) Lu, G-C., Z-R Peng, and R. Du. Economic Analysis of Impacts of Sea Level Rise and Adaptation Strategies in Transportation. In *Transportation Research Record: Journal of the Transportation Research Board,No. 2273*, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 54–61.

11) Testa, A.C., M.N. Furtado, and A. Aipour. Resilience of Coastal Transportation Networks Faced with Extreme Climatic Events. In *Transportation Research Record: Journal of the Transportation Research Board,*
No. 2532, Transportation Research Board, Washington, D.C., 2015, pp. 29–36. DOI: 10.3141/2532-04

12) Chen, X-Z., Q-C. Lu, Z-R Peng, and J.E. Ash. Analysis of Transportation Network Vulnerability Under Flooding Disasters. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2532,* Transportation Research Board, Washington, D.C., 2015, pp. 37–44. DOI: 10.3141/2532-05

13) Marshall, J.T. and K.G. Dedrick. Endemic Song Sparrow and Yellowthroats of San Francisco Bay. Pp316-327 in N.K. Johnson & J. Jehl (eds.), *A Century of Avifaunal Change in Western North America. Studies in Avian Biology* 15. 1994.

(14) AECOM, Arcadis, Geografika, and 3D Visions. *Adapting to Rising Tides Transportation Vulnerability and Risk Assessment Pilot Project*. Prepared for Metropolitan Transportation Commission, Caltrans, Bay Conservation and Development Commission, and U.S. Department of Transportation Federal Highway Administration. November 2011.

(15) San Francisco Bay Conservation and Development Commission (BCDC). *Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on its Shoreline*. 2011.

(16) Schnotz, W. Commentary: Towards an Integrated View of Learning from Text and Visual Displays. *Educational Psychology Review,* Vol. 14, No. 1, 2002, pp. 101–120. Doi: 10.1023/A:1013136727916.

(17) Retchless, D. P. Communicating Climate Change: Spatial Analog Versus Color-banded Isoline Maps with and without Accompanying Text. *Cartography and Geographic Information Science,* Vol. 41, No. 1, 2014a, pp. 55–74. doi:10.108 0/15230406.2013.826479.

(18) Retchless, D.R. Sea Level Rise Maps: How Individual Differences Complicate the Cartographic Communication of an Uncertain Climate Change Hazard. *Cartographic Perspectives,* Vol. 77, 2014b, pp. 17-32. DOI: 10.14714/CP77.1235.

(19) Monmonier, M. Web Cartography and the Dissemination of Cartographic Information about Coastal Inundation and Sea Level Rise. In *International Perspectives on Maps and the Internet*, Lecture Notes in Geoinformation and Cartography, edited by P. M. P. Peterson, 49–71. Berlin/Heidelberg: Springer Berlin Heidelberg, 2008.

(20) Kostelnick, J. C., D. McDermott, R. J. Rowley, and N. Bunnyfield. A Cartographic Framework for Visualizing Risk. *Cartographica,* Vol. 48, No. 3, 2013, pp. 200–224. doi:10.3138/carto.48.3.1531.

(21) Asare, S.K. and B.L. Smith. Evaluation Framework for Rigorous Exploration of Potential Benefits of Integrated Corridor Management. *Transportation Research Record: Journal of the*

Transportation Research Board, No. 2470, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp.113–121. DOI: 10.3141/2470-12.

(22) Caltrans. *Transportation Concept Report: State Route 37*. 2015 (http://hwy37.ucdavis.edu/files/upload/resource/TCR%2037-FINAL-SIGNED.pdf)

(23) Brown, J. *Eco-logical: An Ecosystem Approach to Developing Infrastructure Projects*. A Report for the US Department of Transportation Federal Highways Administration. FHWA-HEP-06-011. 2006.

(24) DHI *Regional Coastal Hazard Modeling Study for North and Central Bay*. Prepared for: Federal Emergency Management Agency. 2011.

(25) Marcy, D., B. William, K. Draganoz, B. Hadley, C. Haynes, N. Herold, J. McCombs, M. Pendleton, S. Ryan, K. Schmid, M. Sutherland, and K. Waters. New Mapping Tool and Techniques for Visualizing Sea Level Rise and Coastal Flooding Impacts. *Proceedings of the 2011 Solutions to Coastal Disasters Conference*. Anchorage, AK. 2011.

(26) Sagaris, L. Citizen Participation for Sustainable Transport: The Case of “Living City” in Santiago, Chile (1997-2012). *Journal of Transport Geograph*y Vol. 41, 2014, pp. 74-83.

(27) Boumans, R. M., D. M. Burdick, and M. Dionne. Modeling Habitat Change in Salt Marshes After Tidal Restoration. *Restoration Ecology* Vol. 10, No. 3, 2002, pp.543-555.

Table Legends

Table 1. Comparison between responses to the separate community (723 respondents) and stakeholder process (67 respondents) surveys for a select set of issues/questions. Values are % of the total responses for each group.

Table 2. Composite vulnerability values and ratings and risk values and ratings for each segment of SR 37.

Table 1

Issue	Community Survey	Stakeholder Process Survey
Drive the route every 1-3 days	24%	13%
Somewhat or very familiar with SLR	61%	77%
SLR not a result of climate change	10%	0%
Minimal transportation impacts to environment somewhat or very important	72%	76%
Transit is somewhat or very important	60% (yes)	61% (yes)
Would use transit if available	40% (no)	18% (no)
Transit preference along route	65% (train)	84% (train)
Prefer “no action” to paying tolls (absolutely and maybe)	44%	15%
Would choose alternate route if toll used to finance (absolutely and maybe)	43%	21%
Scenario most supportive (rank #1) of combined transportation and wetland protection	46% (causeway)	45% (causeway)

Table 2

Highway segment	A	B	C
Exposure	2.8	2.2	1.7
Sensitivity	2.3	2.2	1.7
Adaptive Capacity	3.0	3.0	3.0
Composite Vulnerability Value	2.7	2.5	2.1
Composite Vulnerability Rating	High	High	Moderate
Composite Risk Value	2.4	2.7	2.0
Composite Risk Rating	Moderate	High	Moderate

Note: Exposure, sensitivity, and composite vulnerability and risk ratings were assigned as follows: 1.0-1.4 (low), 1.5-2.4 (moderate), and 2.5-3.0 (high). Adaptive capacity ratings were assigned as follows: 1.0-1.4 (good), 1.5-2.4 (moderate), and 2.5-3.0 (poor).

Figures

Figure 1. SR 37 position in the San Francisco Bay Area and SR 37 segments (A,B,C) used in Caltrans' corridor planning. Cities associated with SR 37 planning are labeled.

Figure 2. Potential land inundation and highway overtopping for the daily high tide (MHHW) with 36 inches of sea level rise (SLR), or 12 inches SLR + 5-yr storm surge, or 6 inch SLR + 10-yr storm surge, or 0 inches SLR + 25-yr storm surge

Figure 1

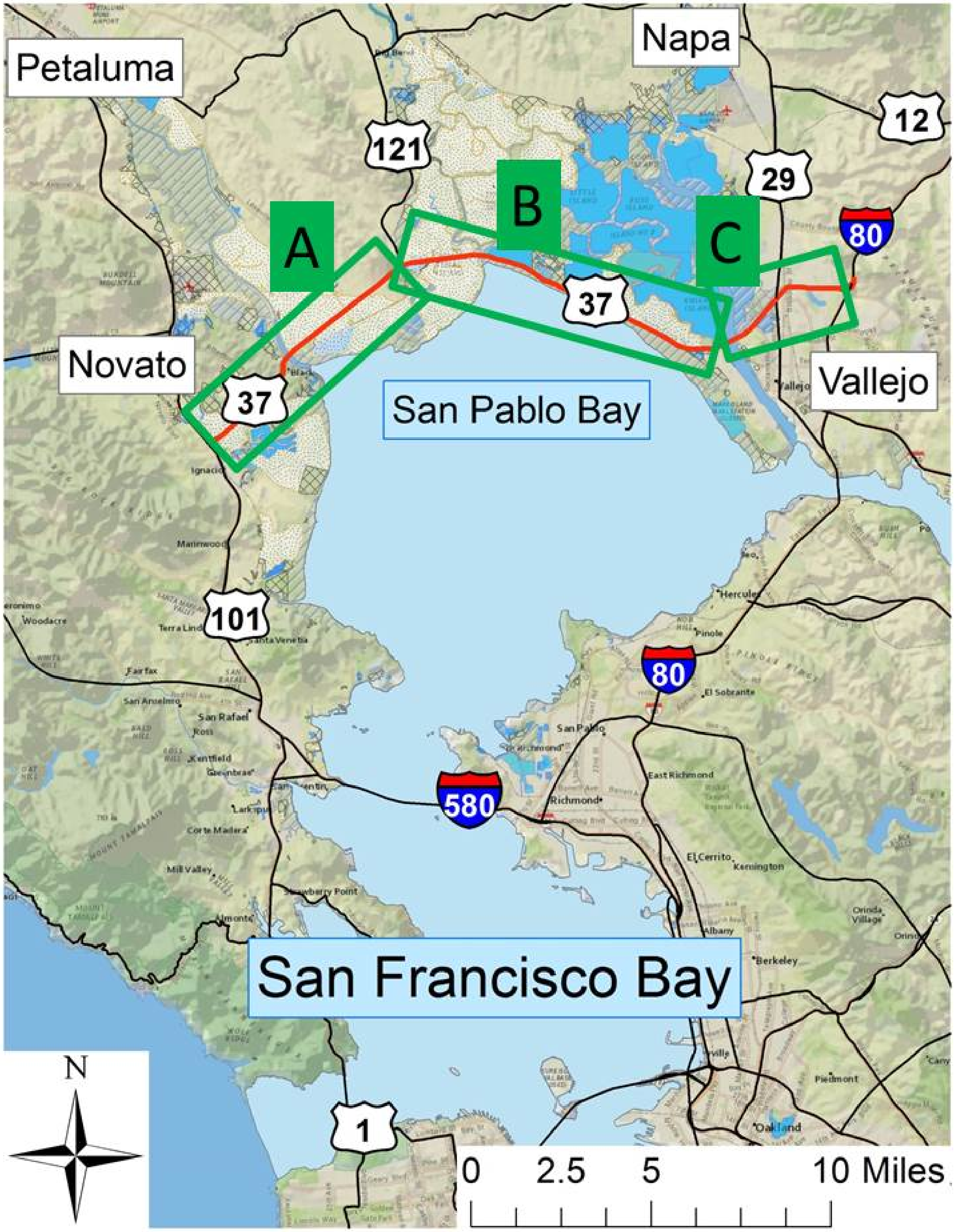
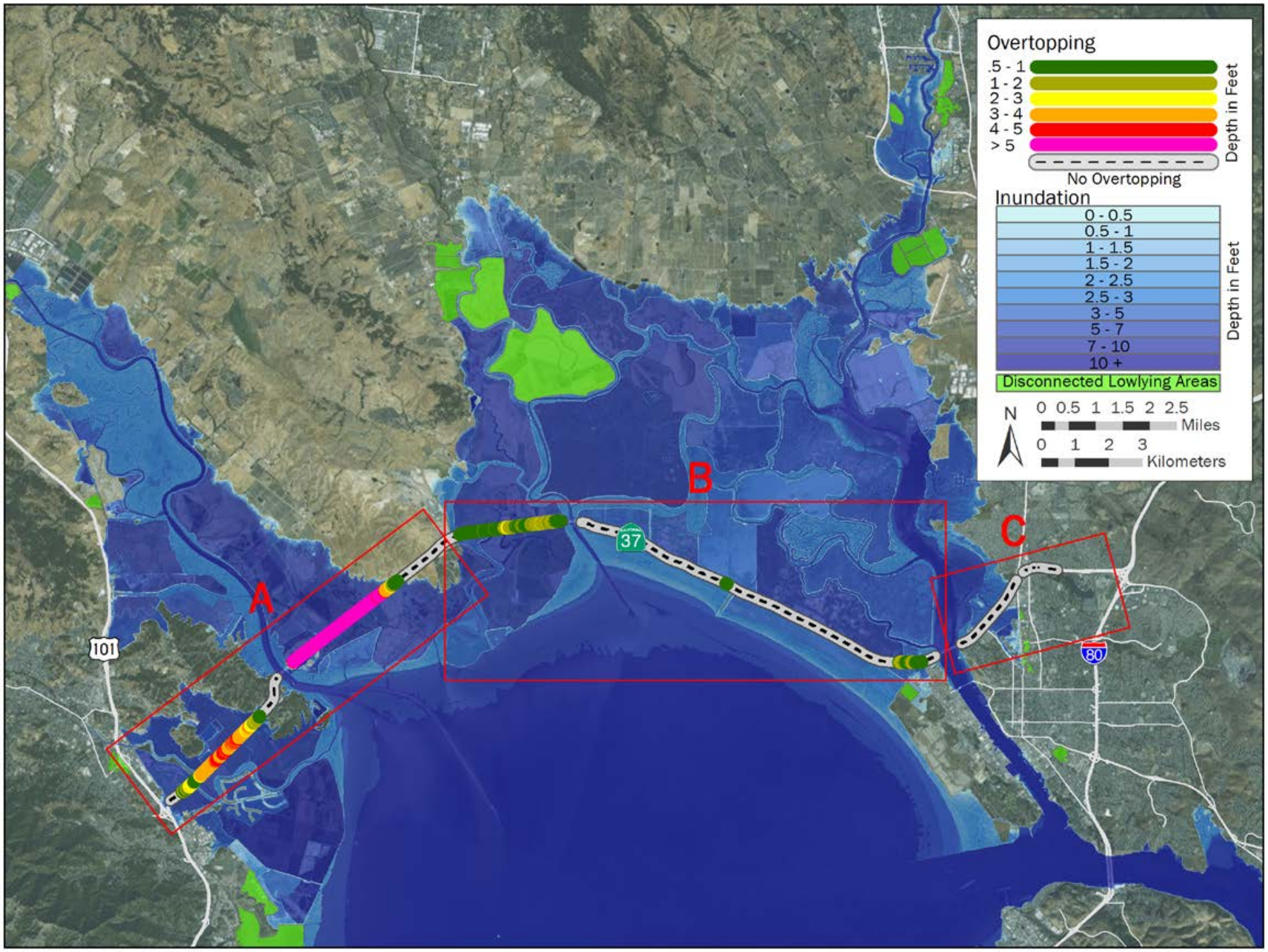

Petaluma
Napa
121
12
29
A
B
C
80
37
Novato
37
Vallejo
San Pablo Bay
101
80
580
San Francisco Bay
N
1
0
2.5
5
10 Miles

Figure 2


Overtopping
.5 - 1
1 - 2
2 - 3
3 - 4
4 - 5
> 5
Depth in Feet
No Overtopping
Inundation
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 5
5 - 7
7 - 10
10 +
Depth in Feet
Disconnected Lowlying Areas
N
0 0.5 1 1.5 2 2.5
Miles
0 1 2 3
Kilometers
A
B
C
37
101
80