Appendix H

Adapting to Rising Tides and Our Coast, Our Future – A Comparison of the Approaches

Appendix H: Adapting to Rising Tides and Our Coast, Our Future – A Comparison of the Approaches

Adapting to Rising Tides and Our Coast, Our Future – A Comparison of the Approaches

INTRODUCTION

Sea level rise inundation and extreme high tide[1] (a.k.a., storm tide) flooding maps for the San Francisco Bay Area are available from multiple sources. The two most prominent sources are the Adapting to Rising Tides (ART) and Our Coast, Our Future (OCOF) projects. While the mapping products from ART and OCOF are similar, there are several underlying differences in the methods and data used to develop each product. This document highlights some of the key over-arching technical differences between the ART and OCOF analysis methods and mapping products:

- The **purpose** of the mapping products (i.e., what considerations drove their development);
- The **scenarios** mapped;
- The **terrain** used;
- The **model components** and considerations;
- The **storm definitions** (i.e., how the 100-year storm is defined); and
- A brief overview of the **inundation mapping** approach.

PURPOSE

Adapting to Rising Tides

The Adapting to Rising Tides (ART) Program, led by the San Francisco Bay Conservation and Development Commission (BCDC), provides support, guidance, tools, and information to help agencies and organizations understand, communicate, and begin to address complex climate change issues. The ART sea level rise and storm surge flooding maps use a “one map equals many futures” approach, which allows each map to represent multiple potential future combinations of sea level rise and extreme water levels. The maps show the inland areas that are at risk of inundation or flooding, and the companion products -- the shoreline delineation, shoreline type, and overtopping potential maps -- identify the pathways of inundation or flooding from the Bay. Together, the products support robust, local scale vulnerability

Our Coast, Our Future

Our Coast, Our Future (OCOF) is a collaborative, user-driven project focused on providing San Francisco Bay Area coastal resource managers and planners locally-relevant, online maps and tools to help them understand, visualize, and anticipate vulnerabilities to sea level rise, storm surge, and wave hazards.

The project included a collaborative product-development process that was designed to: meet stakeholders’ information needs; map infrastructure and ecosystem vulnerabilities at scales relevant to planning and management; develop products in accessible, user-friendly formats; and provide training and technical assistance on the

[1] Extreme tides (a.k.a., storm tides) are relatively infrequent water level events that are a result of relatively high astronomical tides coupled with a storm surge event. The absolute elevations reached during these events are due to short-term meteorological processes (such as low atmospheric pressure due to storms) and large-scale oceanographic conditions (such as King Tides or El Niño conditions).

assessments and the development of both near-term and long-term adaptation strategies.

Through a collaborative effort with local and state agencies, the ART mapping is currently available for Alameda, Contra Costa, San Francisco, and San Mateo Counties. With funding from the Bay Area Toll Authority and the Metropolitan Transportation Commission, the ART maps will be completed for all nine Bay Area counties by early 2017. Technical reports, maps, case studies, and additional information, including ART Program staff Help Desk support, are available at: www.adaptingtorisingtides.org.

use of the products and tools.

The OCOF maps are available for all nine Bay Area counties, as well as additional areas along the open Pacific coast. The maps are presented within an online viewer, and the data can also be downloaded and used offline, depending on the project need. The online viewer and additional information on the OCOF project are available at: www.ourcoastourfuture.org/

An additional online viewer that translates the flood extents in socioeconomic exposure will be available soon.

SCENARIOS

Adapting to Rising Tides

The ART maps depict the inland extent of inundation or flooding associated with ten scenarios ranging from 12 inches to 108 inches above mean higher high water (MHHW). Using the one map equals many futures approach, the ten scenarios can represent over 50 combinations of sea level rise (i.e., from 0 to 66 inches) and extreme water level (i.e., from 1- to 100-year tide) scenarios. The scenarios range from an existing conditions King Tide (i.e., MHHW + 12 inches) to a 100-year storm surge condition coupled with 66 inches of sea level rise (equivalent to MHHW + 108 inches). The ten mapped scenarios are intended to be used in tandem with a county-specific matrix (i.e., reference table) of sea level rise and extreme water level elevations that identify the equivalent scenarios that can be represented by each of the ten maps.

Our Coast Our Future

The OCOF maps depict inland extents of flooding associated with astronomic tides in combination with a range of sea level rise values and extreme coastal storms that are user-selected within the online viewer. The user can select the amount of sea level rise from 0 to 200 cm (in 25 cm increments), as well as 500 cm. These scenarios correspond approximately to 0-, 10-, 20-, 30-, 39-, 49-, 59-, 69-, 79-, and 197-inches of sea level rise. The user can pair the selected sea level rise scenario with a King or spring tide and everyday atmospheric conditions, or spring tides in conjunction with a 1-year, 20-year, or 100-year coastal storm event. This range of scenarios represents 50 possible combinations of sea level rise and extreme storm-driven water levels in San Francisco Bay.

TERRAIN

Adapting to Rising Tides

The ART maps use a 1-meter digital elevation model (DEM) developed from the 2010/2011 LiDAR collected by the USGS and NOAA as part of

Our Coast Our Future

The OCOF maps use a 2-meter bare-earth DEM developed from the 2010/2011 LiDAR collected by USGS and NOAA as the base the California Coastal Mapping Program[2]. The DEM is of sufficient resolution and detail to capture the majority of shoreline levees and flood protection assets, but structures narrower than the 1-meter LiDAR resolution may not be adequately represented in the LiDAR or the resulting DEM.

The ART approach relied on stakeholder review and feedback to verify if features such as flood walls and tide gates were accurately captured in the DEM. If areas are shown as inundated with less than 24 inches of sea level rise above MHHW, and these areas have never been inundated during a King Tide condition or storm event, the local topography is reviewed. Stakeholders submit as-built drawings or infrastructure, or higher-resolution survey data, to improve the DEM. Potential levee or shoreline improvement projects (i.e., projects that are not yet constructed) are not incorporated within the DEM. Future shoreline erosion and geomorphic change are not considered, and the base DEM does not change over time.

topographic information. The DEM is of sufficient resolution and detail to capture the majority of shoreline levees and flood protection assets, but structures narrower than the 1-meter LiDAR point spacing or the 2-meter DEM resolution may not be adequately represented in the DEM.

As part of the DEM development process, levees were hand-digitized as needed to better represent these features. However, some local features may not be adequately represented. The OCOF team maintains a “known issues” database to capture areas where the DEM may need refinement to better represent local flood protection structures or other features.

Future shoreline erosion and geomorphic change are not considered, and the base DEM does not change over time for areas inside San Francisco Bay.

MODEL COMPONENTS

Adapting to Rising Tides

The ART maps use water level output from the Federal Emergency Management Agency (FEMA) San Francisco Bay Area Coastal (SFBAC) Study[3]. The FEMA modeling relied on regional hydrodynamic and wave modeling using MIKE21 developed by DHI. The following sections describe the model simulation timeframe, general model setup, and input and boundary conditions.

Our Coast Our Future

The OCOF maps are created using the Coastal Storm Modeling System (CoSMoS) developed by the USGS. A coupled 2-way Delft3D hydrodynamic and wave model is primarily used within the CoSMoS structure to simulate flow and flooding projections within the San Francisco Bay. The following sections describe the model simulation timeframe, general model setup, and input and boundary conditions.

[2] http://www.opc.ca.gov/2010/01/mapping-californias-coastal-areas/
[3] http://www.r9map.org/Pages/San-Francisco-Coastal-Bay-Study.aspx

Model Simulation Timeframe

The FEMA MIKE21 model is calibrated and validated for existing conditions. In the Central and North Bay, the hindcast[4] period spans January 1973 through December 2003[5]. In the South Bay, the hindcast period spans January 1956 thru December 2009[6]. The models were calibrated to two storm events (January and December 1983), and validated against 11 large storm events that occurred during the model hindcast period. Although the model is well calibrated to water levels, limited wave data was available for model calibration and validation, therefore a higher uncertainty is associated with the modeled wave conditions. Model output is saved at 15-minute time steps for water levels, and 1-hour time steps for waves, over the entire 31- or 54-year hindcast period. The model is driven by observed data (e.g., water levels, winds, atmospheric pressure) and modeled data (e.g., Delta inflows, offshore waves, and tributary discharges).

Model Domain

The MIKE21 model uses a rectangular grid with 100-meter grid cell sizing for the entire model domain. The model domain spans the entire San Francisco Bay and into the Delta, with an eastern boundary just upstream of the City of Antioch. The western model boundary lies outside of the Golden Gate to capture the penetration of ocean-driven swell through the Golden Gate and into the Central Bay.

Offshore Water Levels

The offshore open boundary was driven by water levels recorded by the

Model Simulation Timeframe

CoSMoS simulates potential future conditions during 21st century storm events. Storm events (1-year, 20-year, 100-year, and average conditions) and associated atmospheric/environmental conditions were identified and derived from one CMIP5 (Coupled Model Intercomparison Project Phase 5) Global Circulation Model (GCM): the Geophysical Fluid Dynamics Laboratory (GFDL) Earth System Model (ESM2M). For each discrete 21st century event, CoSMoS'Delft3D models were driven by projections of water levels, offshore ocean swell, winds, atmospheric pressure, and riverine discharges for the storm's conditions. Models were run for more than 1 tide cycle (17+ hours to include the higher-high tide); time-steps varied on location and resolution of the particular model (see 'Model Domain').

Model Domain

The Delft3D model uses a grid with ~100 meter grid cell sizing, with higher resolution of 10 to 20 meters in select focus areas including: Coyote Creek/Alviso, Foster City, Corte Madera, Highway 37, Petaluma River, Napa River estuary, Richardson Bay, Oakland Airport, Embarcadero (Pier 54/Mission Bay), and East Palo Alto, among others. Focus areas were identified as locations where hydrologic and shoreline complexity necessitated finer resolution, and with further input from the OCOF Advisory Committee. The model domain spans the entire San Francisco Bay and into the Delta, with an eastern boundary just upstream of the City of Antioch. The western boundary lies outside of the Golden Gate and offshore of the continental shelf to capture the penetration of ocean-driven swell through the Golden Gate and into the Central Bay.

Offshore Water Levels

Offshore and regional water levels rely on tidal constituents from the

[4] A hindcast is a simulation of historical conditions using a model driven by historical observations of certain environmental parameters such as wind or water level.
[5] Regional Coastal Hazard Modeling Study for North and Central San Francisco Bay, 2011. Prepared by DHI Water and Environment for FEMA Region IX.
[6] Regional Coastal Hazard Modeling Study for South San Francisco Bay, 2013. Prepared by DHI Water and Environment for FEMA Region IX.

National Oceanic and Atmospheric Administration (NOAA) at the San Francisco Presidio (Presidio) tide station. The observed sea level rise trend was removed from the recorded water levels to raise the historical water levels to present day (i.e., 2009 for Central and North Bay; 2011 for South Bay) mean sea level conditions.

Offshore Ocean Swell

The offshore ocean swell boundary condition relies on a 31-year hindcast of 3-hourly deep ocean wave conditions produced by Oceanweather, Inc. (OWI). OWI developed the hindcast using their Global Reanalysis of Waves (GROW) model which relies on deep water and nearshore wave measurements from the National Data Buoy Center and the Coastal Data Information Program for model calibration and validation.

Oregon State University TOPEX/Poseidon model. Modeled water levels inside San Francisco Bay are highly correlated ($r^2 > 0.97$)[7] with observed water levels for most water level stations inside San Francisco Bay.

Offshore Ocean Swell

Offshore ocean swell conditions were modeled using a combination of the global and nested Eastern North Pacific grids of the NOAA WAVEWATCH III (WWIII) model. Swell conditions were originally modeled as part of OCOF projections for the outer coast[8]. To capture the variability in global-scale projections for the 21st century, the WWIII model was driven by wind fields generated from two different climate scenarios (Representative Concentration Pathways (RCP) 4.5 and 8.5) and four CMIP5 GCMs. Ocean swell simulated with the RCP4.5 scenario and winds from NOAA's GFDL-ESM2M GCM was selected as boundary conditions to the Bay's coupled Delft3D and Simulating Waves Nearshore (SWAN) models. The RCP4.5 scenario was selected based on analysis of the WWIII results which show higher storm waves offshore of the Central California coast compared to the RCP8.5 scenario. The GFDL-ESM2M GCM was selected because the resulting wave time-series compare well with the observed wave climatology spanning 1976-2005 from the regional wave buoy network (i.e., from the National Data Buoy Center and the Coastal Data Information Program), and additionally, spatially downscaled GFDL-ESM2M wind data through the year 2100 available for the San Francisco Bay area at the time of the modeling effort (see section on winds and wind-driven waves below).

[7] r^2 (r-squared) is a statistical measure of the goodness-of-fit of model data to observed data. A higher r^2 value (closest to 1), usually indicates a better fit.
[8] Barnard, P. L., O. van Maarten, L.H. Erikson, J. Eshleman, C. Hapke, P. Ruggiero, P. Adams, and A. Foxgrover (2014), Development of the Coastal Storm Modeling System (CoSMoS) for predicting the impact of storms on high-energy, active-margin coasts, Nat. Hazards, 74(2), 1095-1125, doi:/10.1007/s11069-014-1236-y.
[6] Abatzoglou J. T. and Brown T.J. 2011. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology.

River Discharge

The open Delta riverine boundary condition is represented by discharge from the Sacramento River (just upstream of the City of Antioch). Delta inflows are based on daily mean streamflow throughout the model hindcast period. Daily mean streamflow was generated using the California's Interagency Ecological Program (IEP) Dayflow daily discharge model. Smaller freshwater tributary inflows are input at a constant rate, represented by mean annual discharge.

River Discharge

River discharge rates for principal tributaries in the Bay (Napa, Sonoma, Petaluma, San Francisquito, Guadalupe, Coyote, Old Mill, and Corte Madera, and the Delta) were included in the CoSMoS framework. Using 21st century precipitation patterns depicted in the GCM (GFDL-ESM2M) and similar patterns from the GFDL-ESM2M-derived Delta discharge from the CASCaDE project (Computational Assessments of Scenarios of Change for the Delta Ecosystem), appropriate Delta discharges were identified for CoSMoS storm events. Historical relationships between the tributaries and the Delta were then used to calculate river discharge rates for each 21st century coastal storm event.

Winds and Wind-Driven Waves

Wind-driven waves are not considered in the ART mapping because increases in wave heights do not scale linearly with increases in mean sea level due to sea level rise. The ART mapping process only incorporates processes that can scale linearly with sea level rise (e.g., MHHW). However, wind-driven wave information is available from the FEMA SFBAC study. The wind fields for the SFBAC study were developed from hourly observations of wind speed and direction from the San Francisco International Airport, the Oakland International Airport, and the Travis Airforce Base. The wind fields were used as forcing for MIKE21 simulations to appropriately simulate waves and surge. Wind-driven waves were modeled using the MIKE21 SW (Spectral Wave) model.

Winds and Wind-Driven Waves

Wind fields were derived from a downscaled version of the GFDL ESM2M GCM. The downscaled wind projections come from the University of Idaho Multivariate Adaptive Constructed Analogs[9] (MACA) statistically-downscaled GCM data. The MACA method downscales GCM output to 1/24 degree (~4 km) spatial resolution at a daily time step. The temporal resolution of the wind fields were increased to 3-hour time steps to support the wind-wave modeling within Delft3D using the coupled SWAN (i.e., wave) model. Wind fields for identified storm events were used as forcing for Delft3D simulations to appropriately simulate waves and surge. Data from the single GCM was used due to time constraints and to maintain consistency with other single GCM-derived storm conditions (i.e. river discharge and swell).

STORM DEFINITION

Adapting to Rising Tides

The ART maps use a response-based[10] statistical approach to define local extreme tide recurrence intervals (e.g., 1-year, 10-year, 100-year,

Our Coast Our Future

The OCOF maps rely on an event-based approach, which includes defining discrete storm events (i.e., 1-year, 20-year, and 100-year)

[9] Abatzoglou J. T. and Brown T.J. 2011. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology.
[10] Response-based analysis refers to a coastal analysis technique in which long time series of environmental parameters, such as astronomical tides, atmospheric pressure, and winds, are combined and simulated to derive an estimate of storm water level conditions at the shoreline. This is in contrast to an event-based analysis technique in which a short time period considered to be representative of a desired storm magnitude (such as a 100-year event) is simulated. The

etc.) based on historical conditions at 900 points along the Bay shoreline[11]. This approach assumes that no single storm "event" will simultaneously produce the 100-year (or other recurrence internal) flood extent along the entire Bay shoreline. Instead, multiple storm events with varying storm directions and intensities are analyzed to produce a composite map that represents the 100-year flood hazard[12] (the extent and depth of inland inundation that has a 1-percent-annual-chance of occurring at any given location along the shoreline). This approach is consistent with the FEMA guidelines for analyzing and mapping coastal hazards along the Pacific coast[13]. The 100-year extreme high tide levels are consistent with the values used for the FEMA SFBAC study; however, these values do not include the addition of waves or wave runup at the shoreline.

based on detailed analysis of the storm climatology from the downscaled GFDL ECM2M GCM output over the 21st century. The analysis considers storm direction and orientation, as well as the geometry and orientation of the Bay shoreline, to define a storm event that has a 1-percent-annual-chance (or other recurrence interval) of occurring in any given year. As the complex topography of the Bay affects exposure to storms and wind direction, and in turn resulting storm waves and related flooding, multiple events for major storms (20-year and 100-year) were identified and simulated. Storm events were identified for predominant wave and wind directions in each region of the Bay. Thus, the resultant hazard projections are a composite of all contributing storm simulations for the event. Orientation differences between storm events may yield flood extents that are larger for less-intense storms (i.e. 20-year vs. 100-year) in some locations.

FLOOD MAPPING

Adapting to Rising Tides

The ART inundation mapping uses an approach developed by the NOAA Coastal Services Center[14]. San Francisco Bay water levels are projected landward on a 1-meter DEM to assess the inland extent and depth of flooding, and low-lying areas that are protected from flooding by levees or other topographic features are removed from the direct flood zone and highlighted in green. The extent and depth of flooding is controlled by the difference between the water and ground surface elevations.

The flood mapping uses a base water level of existing MHHW, which is spatially variable along the San Francisco Bay shoreline. Discrete

Our Coast Our Future

For each storm event (1-year, 20-year, 100-year), a coupled (hydrodynamic-wave) Delft3D model with inclusive storm conditions (e.g., discharge, wind, atmospheric pressure) is run over more than 1 tide cycle (17+ hours to include higher-high tide). Resulting water levels are projected onto a 2-meter DEM to create OCOF flooding maps and corresponding depth of flooding. This approach and inclusion of overland high-resolution grids captures the physics of overland flow; therefore the inland extent of flooding accounts for the volume of Bay water available during the simulated event that may overtop the shoreline and flood low-lying areas during a discrete storm event. Each storm simulation is repeated for the range of sea level rise scenarios

---

response-based analysis is considered to be more robust than an event-based analysis, especially in the Bay where extreme tide levels can be realized through many different combinations of astronomical tides and storm surge conditions.

[11] San Francisco Bay Tidal Datums and Extreme Tides Study, 2016. Produced by AECOM for FEMA.

[12] Extreme Storms in San Francisco Bay – Past to Present. 2016. Produced by AECOM for FEMA.

[13] Guidelines for Coastal Flood Hazard Analysis and Mapping for the Pacific Coast of the United States. 2005. FEMA.

[14] Marcy, D., B. William, K. Dragonoz, B. Hadley, C. Haynes, N. Herold, J. McCombs, M. Pendleton, S. Ryan, K. Schmid, M. Sutherland, and K. Waters. 2011. "New Mapping Tool and Techniques or Visualizing Sea Level Rise and Coastal Flooding Impacts." In: *Proceedings of the 2011 Solutions to Coastal Disasters Conference*. June 2011.

amounts of sea level rise are added to MHHW to create the ten mapped scenarios. This approach does not account for the complex physics of overland flow, dissipation, levee wave overtopping, storm duration, or the potential for shoreline erosion and levee failure that can occur during storm events. To account for these processes, a more sophisticated modeling effort would be required. However, given the uncertainties associated with climate change and sea level rise, as well as potential future land use changes, development, and geomorphic changes that will occur throughout the 21st century, a more sophisticated approach may not necessarily provide more accurate results.

The ART maps include an analysis of the type and elevation of the shoreline that produces an overtopping potential map that illustrates not only where overtopping may occur, but how deep the water may be, on average, over the shoreline. Overtopping potential maps help identify locations that pose the largest risk to shoreline communities and infrastructure. This is a powerful tool that is unique to the ART maps. Coupled with the inundation and storm surge maps, the overtopping potential maps help users quickly and efficiently identify the shoreline locations and flowpaths that could lead to inland flooding so that additional investigation (e.g., field verification or more sophisticated modeling) can be targeted at these locations.

considered and the resulting depth and extent of flooding is mapped.

Acknowledgements

Prepared by: Kris May, Michael Mak, Justin Vandever (AECOM), Patrick Barnard, Andy O'Neill, Li Erikson (USGS), Wendy Goodfriend (BCDC)

This document was created in part with funding from the California State Coastal Conservancy