The Shallow Groundwater Layer and Sea Level Rise: Description of Approaches

Compendium to San Francisco Bay Area Groundwater Workshop Summary | November 2019

INTRODUCTION

As sea levels rise, the shallow groundwater table[1] in coastal communities will also rise. This slow but chronic threat can flood communities from below, damaging buried infrastructure, flooding below grade structures, mobilizing pollutants, compromising foundations, and emerging aboveground as an urban flood hazard. As communities develop climate adaptation plans to address sea level rise and extreme storm events, it is important to consider this additional flood hazard. To respond to this need, two efforts have recently analyzed and mapped the existing shallow groundwater table and its response to sea level rise in San Francisco Bay coastal communities. One effort was led by Silvestrum and UC Berkeley to align with the Adapting to Rising Tides (ART) approach for sea level rise and extreme high tide mapping. The resulting mapped groundwater surface represents the water table at its highest elevation during wet winters, when emergent groundwater is first likely to occur (when the groundwater table rises above the surface of the ground and creates surface flooding). This represents a temporary or episodic condition that would occur sporadically in response to heavy precipitation. The other effort was led by the United States Geological Survey (USGS) and the University of Wyoming, which is based on the USGS Coastal Storm Modeling System (CoSMoS: www.usgs.gov/cosmos) and which aligns with the Our Coast, Our Future (OCOF) approach and products[2]. This resulting mapped groundwater surface represents the baseline (i.e., average) water table height that is overprinted by seasonal, tidal, and other transient signals. Areas with emergent groundwater are likely to experience chronic 'sunny day' surface flooding (i.e., surface flooding in the absence of heavy precipitation).

The use of both approaches together can help inform when (i.e., by what sea level rise amount) and if action is needed to address emergent groundwater flooding. The Silvestrum approach estimates the amount of sea level rise that is likely to result in emergent groundwater flooding on a temporary (e.g., hours to days) seasonal basis; whereas the OCOF approach estimates the amount of sea level rise that is likely to result in more permanent (e.g., weeks to months) or chronic emergent groundwater flooding. The difference between these two sea level rise amounts will vary throughout the Bay Area based on many factors. Some areas or assets may require actions to reduce the likelihood of temporary surface flooding, such as major transportation routes, schools, hospitals, shelters, and other life safety facilities. Other areas may tolerate temporary surface flooding for longer periods of time, such as parks and open areas, parking lots, and non-critical or floodproofed facilities, requiring action only after emergent groundwater flooding becomes chronic. This is analogous to evaluating temporary overland coastal flooding during an extreme storm surge event and permanent coastal flooding caused by sea level rise in the absence of storm surge.

1. The shallow grounder layer is an unconfined layer of water in the soil pore spaces below the ground surface. Unlike the deeper confined aquifers, the shallow groundwater layer is greatly influenced by the weather (i.e., periods of heavy rainfall and prolonged drought), as well as Bay and ocean tides and other factors.

2. A companion document compares the Adapting to Rising Tides and Our Coast, Our Future sea level rise and storm surge analysis and mapping products.

This document highlights some of the technical details and differences of these complementary efforts and products.

- The purpose of the mapping products and what considerations drove their development);
- The analysis approach;
- The resultant groundwater surface;
- The scenarios mapped;
- The terrain used;
- The model components and considerations;
- A brief overview of the inundation mapping approach.

PURPOSE

Both efforts were initiated to help fill a critical data gap in climate adaptation planning. Failure to acknowledge the threat of rising groundwater levels, particularly in low-lying coastal areas, could undermine adaptation success. Both efforts also represent current emerging science and rely on best available data. As additional research advances our understanding the shallow groundwater layer, improvements to both approaches are likely to occur.

Silvestrum and UC Berkeley

Although this mapping is not a direct product of the Adapting to Rising Tides (ART) Program, led by the San Francisco Bay Conservation and Development Commission (BCDC), the approach was developed to integrate with the ART sea level rise and extreme high tide mapping tools developed to help agencies and organizations understand, communicate, and begin to address complex climate change issues: https://explorer.adaptingtorisingtides.org.

Two separate projects have been developed. The **regional mapping**[3] was developed by UC Berkeley and Silvestrum Climate Associates and covers the low-lying areas across the nine San Francisco Bay Area counties. The regional mapping allows for a rapid assessment of areas at risk of emergent groundwater with 1 meter of sea level rise.

The **locally refined** mapping has only been created for select geographies (e.g., Alameda, east Oakland, and the Oakland International Airport). This effort includes a deeper understanding of the shallow groundwater layer and its response to sea level rise to inform adaptation strategy development.

CoSMoS-GW

Our Coast, Our Future (OCOF) is a collaborative, user-driven project focused on providing California (including the 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 and storms (including storm surge, waves and riverine influences) along the coast. The addition of the shallow groundwater layer and its response to sea level rise helps present a more comprehensive look at potential future flood hazards than only from overland flooding.

The groundwater analysis and mapping were developed for the entire California coast, including the nine Bay Area counties around San Francisco Bay. The Bay Area groundwater mapping will be integrated in the OCOF viewer: www.ourcoastourfuture.org

[3]. Plane, E., K. Hill, and C. L. May. 2019. A Rapid Assessment Method to Identify Potential Groundwater Flooding Hotspots as Driven by Sea Levels Rise in Coastal Cities. Water 2228:8–10. DOI:10.3390/w11112228

APPROACH

Silvestrum and UC Berkeley

Empirical: Based on observation data and a Geographic Information System (GIS) surface interpolation

The groundwater mapping relies on depth to water measurements collected at monitoring wells throughout the San Francisco Bay area. The monitoring well observation data is available from the California Water Resources Control Board (SWRCB) GeoTracker Groundwater Ambient Monitoring and Assessment Program.

The **regional mapping** is based on the highest measurement on record (i.e., the shallowest depth to water measurement) for over 10,000 shallow groundwater monitoring wells, filtered to consider the most recent measurements (i.e., the year 2000 to the present) and to remove measurements representative of deeper aquifers and artesian wells. The height of the rise at each well is not considered.

The **locally refined mapping** also relies on the highest measurement on record (i.e., the shallowest depth to water measurement). However, the data is sub-filtered for depth to water observations collected during wet winters (i.e., wells without measurements collected during a wet winter were discarded). The depth to water measurements at each well consider the height of the riser. Some well risers are located at grade, and others may be located 2 feet or more above grade (particularly in vegetated open space areas). Geotechnical soil boring data collected in wet winters after the year 2000 were used to fill data gaps in nearshore areas with limited well observation data.

CoSMoS-GW

Numerical Model: mathematical representation that describes the physics of groundwater flow using equations

The groundwater mapping is based on steady-state groundwater flow modeled in three dimensions using the U.S. Geological Survey (USGS) MODFLOW[4] program . Water tables for present-day to +5 meters are simulated separately over 12 increments, allowing water tables to equilibrate to each sea-level scenario based on two tidal datums, mean sea level (MSL) and mean higher high waters (MHHW). Seasonal and tidal fluctuations are not considered, nor are any human activities (e.g., pumping, drains, augmentation).

A series of overlapping groundwater flow models, ten within the Bay Area, allow high-resolution (10 m by 10 m) predictions that are merged for continuous groundwater results. Model inputs include LiDAR topography-bathymetry data, gridded effective average groundwater recharge rates from 2000-2013, ocean salinity, and tidal datum elevations for setting present-day and higher sea levels. Unknown 3D hydrogeology is included in the models by varying the hydraulic conductivity three orders of magnitude (0.1-10 m/day) while setting the lower impermeable boundary as a flat layer at -50 m NAVD88.

Modeled present-day water table elevations (i.e., hydraulic heads) are validated against SWRCB GeoTracker, USGS, and California Department of Water Resources well observations, totaling approximately 3000 locations.

[4.] MODFLOW is the USGS's modular hydrologic model. MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions: https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs.

SCENARIOS

Silvestrum and UC Berkeley

The **regional mapping** considers 1 meter of sea level rise and assumes the water table will respond at the same rate as sea level rise (i.e. linearly).

For the **locally refined mapping**, the existing shallow groundwater surface was increased linearly to account for sea level rise using seven of the ten sea level rise scenarios mapped as part of the Adapting to Rising Tides program: 12", 24", 36", 48", 52", 66", 83", and 108" of sea level rise. This conservative 1:1 correlation between sea level rise and water table rise is only applicable in nearshore areas where sea level and tidal fluctuations can influence the water table. The rate of rise in the groundwater surface will ultimately depend on many factors, including tidal range, salinity, aquifer geology, soil characteristics, coastline change, shore slope, and surface permeability. The rate of rise is unlikely to be exactly linear, especially near tributaries, streams, and rivers. The high-end sea level rise scenarios (i.e., 83" and 108") were selected for consistency with the State of California Sea Level Rise Guidance[5].

CoSMoS-GW

The groundwater models consider two tidal datums, local mean sea level (LMSL) and mean higher high water (MHHW), to set the steady-state elevation of marine/bay waters at present-day. Water tables on land are pinned at these surface water elevations along the coast, and the physical hydrogeologic conditions are then used to compute inland water tables. The two tidal datums are raised in the sea level scenarios by 0.25-2 m in 0.25 m increments (9.8"-77.7"), and also include sea levels of 2.5 m, 3.0 m, and 5.0 m higher than today's tidal datums (98.4"-196.9"). Depending on the sea-level trajectory of the future, these scenarios will occur earlier or later in time. The steady-state models do not include predictions of when or if these scenarios will occur.

MAPPING

Silvestrum and UC Berkeley

The groundwater surface was created with the multi-quadratic radial basis function interpolation technique in ArcGIS using the well water level elevations, geotechnical soil borings (for locally refined mapping only), and FEMA tidal datum points. All data points were referenced to the NAVD88 vertical topographic datum for the interpolation. Depth to water maps were created by subtracting the groundwater surface from the DEM.

[5] https://www.slc.ca.gov/sea-level-rise/state-of-california-sea-level-rise-guidance-2018-update/

CoSMoS-GW

The groundwater surface, represented as an elevation of the water table (i.e., hydraulic head), is a direct output of the MODFLOW numerical model. The overlapping modeled head data are merged using the outputs farthest from each model boundary, resulting in a continuous and smooth water table prediction for the whole CA coast. The heads are then cropped to county boundaries, water table depths calculated (i.e., topography minus hydraulic head), and shapefiles are created of water tables binned by depth categories (Emergent: 0 m depth; Very shallow: 0-1 m depth; Shallow: 1-2 m depth; Moderate: 2-5 m depth; Deep: > 5 m depth).

RESULTANT GROUNDWATER SURFACE

Silvestrum and UC Berkeley

The shallow groundwater surface is hydrologically connected to the Bay and can rise and fall with the tides in nearshore areas. The surface is at highest elevation (i.e., closest to the ground surface) either during or shortly after large precipitation events, and then slowly falls to its lowest elevation (i.e., deeper below the ground surface) during the summer months when rainfall is scarce. The difference between the wet winter and dry summer groundwater surface can be 5 feet or more based on monitoring well observations.

The mapped groundwater surface represents the water table at its highest elevation during wet winters. This represents a scenario when emergent groundwater is first likely to occur (when the groundwater table rises above the surface of the ground and create surface flooding). This scenario represents an temporary or episodic condition that would occur sporadically in response to heavy precipitation.

CoSMoS-GW

The modeled steady state (i.e., equilibrium) groundwater surface represents the long-term average elevation of the groundwater table during the average highest tide, that is the typical daily extreme.

This represents a water table height that is the baseline that is overprinted by seasonal, tidal, and other transient signals such as storms. Areas of emergent groundwater (when the groundwater table rises to or above the surface of the ground and create surface flooding) are likely to experience chronic 'sunny day' surface flooding (i.e., surface flooding in the absence of heavy precipitation).

SAN FRANCISCO BAY BOUNDARY CONDITION

Silvestrum and UC Berkeley

To connect the shallow groundwater surface with the Bay, tidal data from the Federal Emergency Management Agency's (FEMA) San Francisco Bay Extreme Tide and Tidal Datum Study was used. This study provides tidal datum information at over 900 points along the complex Bay shoreline. In areas with limited monitoring well information directly near the shoreline, this data helps approximate the natural slope of the shallow groundwater surface towards the Bay. The tides within the Bay rise and fall twice per day in a semi-diurnal cycle, and the shallow groundwater surface was estimated to connect to the Bay approximately 1-foot above mean tide level because freshwater usually lies above the mean tide.

CoSMoS-GW

The groundwater models use two tidal datums, local mean sea level (LMSL) and mean higher high water (MHHW), to set the steady-state elevation of marine/bay waters at present-day. Both tidal datums were set for the outer CA coast using the National Oceanic and Atmospheric Administration (NOAA) VDatum tool[6]. In the Bay, observational data from 1968-2015 at 51 sites guided the definition of the datums[7]. Density corrections for the water depths are not applied to the model boundary condition to ensure that the bay water levels are exactly continuous with the modeled water table.

[6] https://vdatum.noaa.gov/

[7] Schraga, T. S., and J. E. Cloern (2017), Water quality measurements in San Francisco Bay by the U.S. Geological Survey, 1969-2015, Sci. Data, 4, 1–14, doi:10.1038/sdata.2017.98.

TERRAIN

Silvestrum and UC Berkeley

The groundwater mapping uses a 1-meter bare-earth digital elevation model (DEM) developed from the 2010/2011 LiDAR collected by the USGS and National Oceanographic and Atmospheric Administration (NOAA) as part of the California Coastal Mapping Program[8]. The DEM used for the groundwater mapping is the same DEM used for the ART sea level rise and extreme high tide mapping.

Future shoreline erosion and geomorphic change are not considered, and the base DEM does not change over time. Development and re-grading of the ground surface that has occurred since 2010/2011 is not included in the DEM.

CoSMoS-GW

The OCOF maps use a 2-meter bare-earth DEM developed from the 2010/2011 LiDAR collected by USGS and NOAA as the base topographic information. The DEM used for the groundwater mapping is the same DEM used for the OCOF sea level rise and storm surge mapping.

Future shoreline erosion and geomorphic change are not considered, and the base DEM does not change over time for areas inside San Francisco Bay. Development and re-grading of the ground surface that has occurred since 2010/2011 is not included in the DEM.

SUMMARY OF APPROACHES

Silvestrum and UC Berkeley

- Predicts the annual high, wet weather groundwater conditions
- Data-driven, based on 10,000+ well observation locations
- Assumes linear response to sea level rise
- SF Bay Area coverage

CoSMoS-GW

- Predicts daily groundwater conditions
- Model-driven, validated by observations
- Assumes homogenous sub-surface geology
- CA statewide coverage, including the SF Bay Area

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8. http://www.opc.ca.gov/2010/01/mapping-californias-coastal-areas/