Development of a Hydrogeologic Model, and Statistical Analysis/Bayesian Network Tool to Predict, Locate, and Mitigate Against Emergent Groundwater from Sea Level Rise

BACKGROUND

Of the many hydrogeology data gaps that exist in research on sea level rise (SLR), few are as consequential as the role of buried preferential pathways (in the coastal urban environment) in groundwater rise and subsequent surface flooding. The general concept of emergent groundwater as a function of SLR has been identified by the USGS and others[1,2,3,4]. The emergence of groundwater above the land surface is also called emergent groundwater, groundwater rise, groundwater flooding and groundwater inundation. Vertical fluctuation of groundwater in coastal urban environments is the result of complex interactions of water from various sources (exceptionally high tides, rainwater, and surface drainage) migrating through laterally contiguous preferential flow pathways such as leaky urban sewer pipeline infrastructure and storm drains, buried paleostream channels, porous road base, and permeable utility trenches. Known outcomes of emergent groundwater include flooding of buried infrastructure, roads and foundations[2] as well as emergence of raw sewage from manholes, surface cracks and through drains in buildings creating a health hazard. The consequences of emergent groundwater are financial, environmental, engineering and ecological damage in the U.S. and globally. Currently missing is a model to predict the impacts of SLR in groundwater rise and flooding through urban preferential pathways.

Currently, exceptionally high tides (colloquially known as “king tides”) simulate a future SLR. These tides are caused by lunar influences and seasonal factors. During these tides in the San Francisco Bay Area (SFBA), groundwater flooding occurs inland from the shoreline. In 2019, high tides in San Francisco Bay ranged from 1.11 m to 2.15 m above mean sea level (AMSL) with an average of 1.60 m AMSL (705 NOAA measurements [5]). Comparing groundwater levels in preferential pathways (and adjacent trench fill) to sea level (the upper end of the tidal range during exceptionally high tides) should show the future of emergent groundwater related to a higher average sea level and risks to infrastructure. Proposed water elevation data collection locations include: (1) SFBA tide gauges, (2) water gauges in stilling wells attached to bridge piers for surface drainages (creeks, ditches, and channels), (3) groundwater in wells inland of the shore, including in utility trench backfill and inside leaky pipes, near flood control pumps, and in background areas; (4) rain gauges to measure precipitation.

RESEARCH QUESTION

Can the location and volume of emergent groundwater be predicted from analysis of coastal hydrogeologic urban preferential pathway data? To answer the question, water level variables (tidal elevations, groundwater levels, springs, drainage channels and creeks, flood control pumping wells, and precipitation) will be correlated with groundwater elevations within and outside of preferential pathways within the coastal urban drainage basin (inside sewer lines and storm drain pipes, buried paleochannels, porous road base, utility trenches, and French drains).

GOAL

The goal of this research is to develop a preferential pathway identification methodology (Methodology) and a predictive emergent groundwater hydrogeologic model based on water inputs and water elevation data (Model). Correlations between key water level variables and groundwater levels inside and outside preferential pathways in the case study area will be evaluated using a statistical model/Bayesian network (Tool). Mitigation strategies to address emergent groundwater related to SLR (Mitigation) will be evaluated using cost-benefit analysis.

METHODOLOGY

SLR, subsidence, and flooding in the SFBA will threaten between 125 to 429 square km^2 by the year 2100[6]. Along the 650 km of the SFBA shoreline, 30 distinct Operational Landscape Units (OLU) have been identified which share common physical characteristics[7]. Tamalpais Valley (southern Marin County, California), is in the SFBA Richardson OLU and is representative of communities built on filled wetlands, with similar geology, geomorphology, hydrogeology, groundwater elevation, urban infrastructure, and development history. The study area (0.77 km^2) is defined by the FEMA area 100-year flood boundary (Zones AE and AH). Lying on top of generally impermeable Jurassic Franciscan basement rocks, the wetland sediments are predominantly clay-rich, but also contain buried sand-rich paleostream channels. Prior to residential development, a railroad causeway from 1850 and later a highway causeway greatly restricted tidal flow, causing sedimentation. Developers filled and covered the wetlands prior to the 1940s, raising the surface above mean sea level; land subsidence of 1.3 m has already occurred over the past 80 years throughout the 200-home subdivision.

Drainage features and subsurface preferential pathways will be mapped using historic maps, aerial photographs, and interviews and materials from USGS, FEMA, NOAA, U.S. Army Corps of Engineers, First Street Foundation, San Francisco Estuary Institute (SFEI), Marin County Flood Control, and others. The geospatial content should include buried stream channels, current and abandoned storm and sewer lines, roads, utility trench backfill, water lines, storm drains, surface drains, springs, water wells, French drains, road base, sloughs, ditches, creeks and concrete lined drainage channels and will be compiled on the Marin Map GIS platform.

Surface water elevation measurements (bay, creeks, drainage channels) will be collected. To assess groundwater levels, up to 50 wells (5-cm diameter PVC) will be installed; water level data and field parameters will be collected seasonally over 4 years. Control (background) water level data will be collected for comparison (not within 5 m of a preferential pathway) to assess *in situ* groundwater levels and compared to groundwater elevations in preferential pathways. Data will be used to calculate groundwater gradients and water flow directions over time in relation to preferential pathways. Data from data loggers, measuring absolute pressure and water level, will be compensated using a barometric logger to remove barometric fluctuations. Water parameters (dissolved oxygen, oxidation-reduction potential, conductivity, pH, temperature, ammonium, nitrate, and turbidity) will be measured in the field with a calibrated multimeter. Water elevations and water parameters will allow for water source differentiation, and identification of water flow direction over time in response to water level variables (tidal elevation, precipitation, and surface drainage, flood control pumping). These data will be used to develop/calibrate and validate an empirical/process-based model to predict locations of emergent groundwater. The Model would (1) demonstrate the correlation of higher sea levels with rising inland emergent groundwater and flooding through preferential pathways, (2) predict future locations of emergent groundwater, and (3) provide data to identify, evaluate, and support mitigation strategies. The data used in the statistical analysis (Tool) will include the input data and output probabilities calculated using a Bayesian network. The Bayesian approach toward uncertainty management has the potential for nationwide use when calibrated with local data.[8] Thus, managers in other coastal cities can use it to devise unique responses to SLR and groundwater flooding. The cost benefit analysis of mitigation options (Mitigation) will be developed from the data with input from SFEI and their Climate Resilience Challenge Groundwater/SLR Study partners.

Groundwater emerging through preferential pathways is not addressed by current engineering measures to address SLR overland flooding nor is it found in SLR vulnerability assessment documents. However, a developed Methodology, Model, Tool, and Mitigation program calibrated with local data can be applied nationwide to evaluate the risks and costs of groundwater flooding through preferential pathways in urban coastal settings from SLR. Results will be presented in articles, seminars, and public meetings with a direct benefit to urban planners.

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