Coastal Resilience Assessments
Predicting Emergent Groundwater with Sea Level Rise
A Pilot Program Proposal

Emergent Groundwater from Sea Level Rise

The USGS and others have proven the general concept that groundwater emergence is a result of sea level rise (SLR). The emergence of groundwater above the land surface is also called the following: groundwater rise, groundwater flooding and groundwater inundation. Most studies lack the complex hydrogeologic elements of sea level rise and the associated groundwater movements in the subsurface, especially in preferential pathways. This proposed pilot program is designed to evaluate the interactions of SLR in preferential pathways in coastal urban environments with the goal of designing better mitigation measures to address groundwater flooding. Although one representative community on the San Francisco Bay (with commercial and residential developments on a filled wetland with constructed levees) is presented, below, the concepts and evidence presented in this proposal can be applied elsewhere.

While emergent groundwater occurs when sea level rises, emergent groundwater appears in seemingly random locations because of the heterogeneity of the subsurface. That random siting can be explained by the existence of preferential pathways in the subsurface. Examples of subsurface preferential pathways include the following: geologically pervious horizons or faults, lava tubes, buried historic stream channels, gravel or sand backfilled utility trenches, stormwater and sewer pipes without seals and with cracks and breaks, French drains, and the gravel layers of road base, among others.

Of the many hydrogeology data gaps that exist in research on SLR, few are as consequential to urban dwellers as the role that subsurface preferential pathways in the coastal urban environment will play in future flooding. This proposed pilot program sets out to show this.

Introduction to Emergent Groundwater in the Coastal Urban Environment

The threat of SLR as coastal flooding (in the figure on the next page, marine inundation - dark blue water on the left of the figure) is more easily understood. The concept of SLR causing a rise of groundwater (in the figure on the next page, groundwater inundation - light blue 'after sea level rise') from below is not intuitive.

While sea walls or ramped levees can be constructed to prevent direct marine inundation, these engineering controls will not block emergent groundwater. Rising sea level causes a rise of the level of the shallow groundwater table, for example in coastal aquifers well inland of the coast, affecting inland ocean and bayside communities.

When sea level rise is added to the groundwater in the subsurface, excess water will come to the surface and be seen as (1) perpetually wet areas, (2) ponded areas in flats or in ditches, (3) backups in stormdrains (flooding streets), especially in conjunction with heavy rainstorms, and finally (4) sewer manhole covers pushed off their seat, (releasing raw sewage with groundwater over the ground surface). Wastewater treatment plants are already treating groundwater and tidal water which drain in to fill their pipes, causing increased treatment costs. SLR will cause higher costs for treating more groundwater/tidal water.

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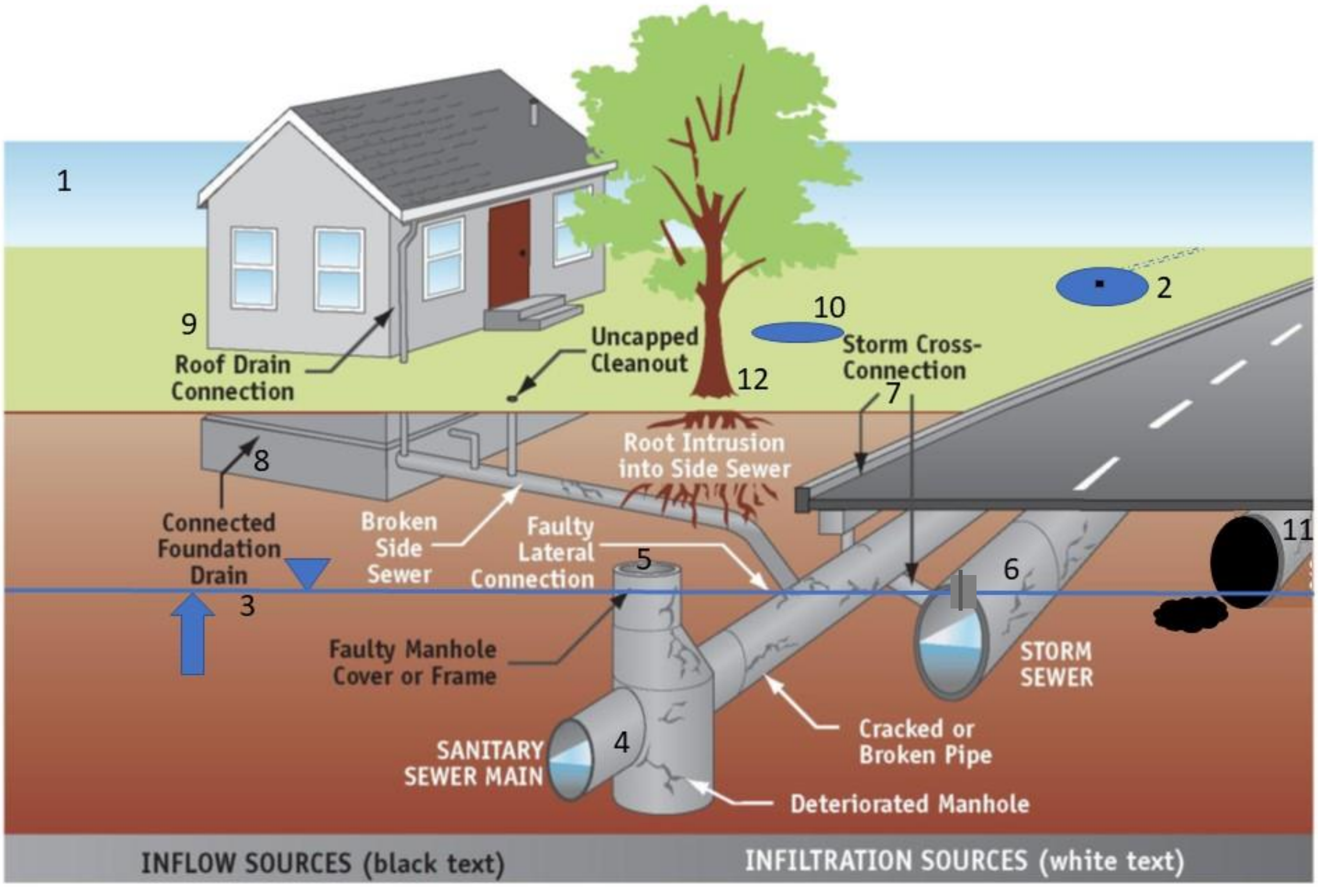

Evidence of the impacts from sea (1) level which is rising might include drainage backflow up drains (2), rising groundwater (3), leaky sewer pipes (4), manhole cover displacement (5), leaky storm drains (6), backup to catch basins (7), rising groundwater into basements, crawlspaces, garages, wicking water up concrete walls and numerous neighborhood sump pumps and discharge pipes (8), subsurface instability of buildings causing tilting (9), emergent groundwater (10), remobilized shallow contamination at an oil pipeline (11), and trees and other vegetation stressed from influx of salt water (12). All pipelines have an engineered design lifespan. Preferential pathways such as utility trenches and leaky subsurface metal pipes (sewer lines, stormwater lines, utility trenches, etc.) fail due to lack of maintenance, subsidence, pipe wall cracking, failing or separating joints, metallic precipitation, and metal corrosion, among other causes. (Figure modified after King County, Department of Natural Resources and Parks Wastewater Treatment Division, 'North Beach CSO Control Project', 2005).

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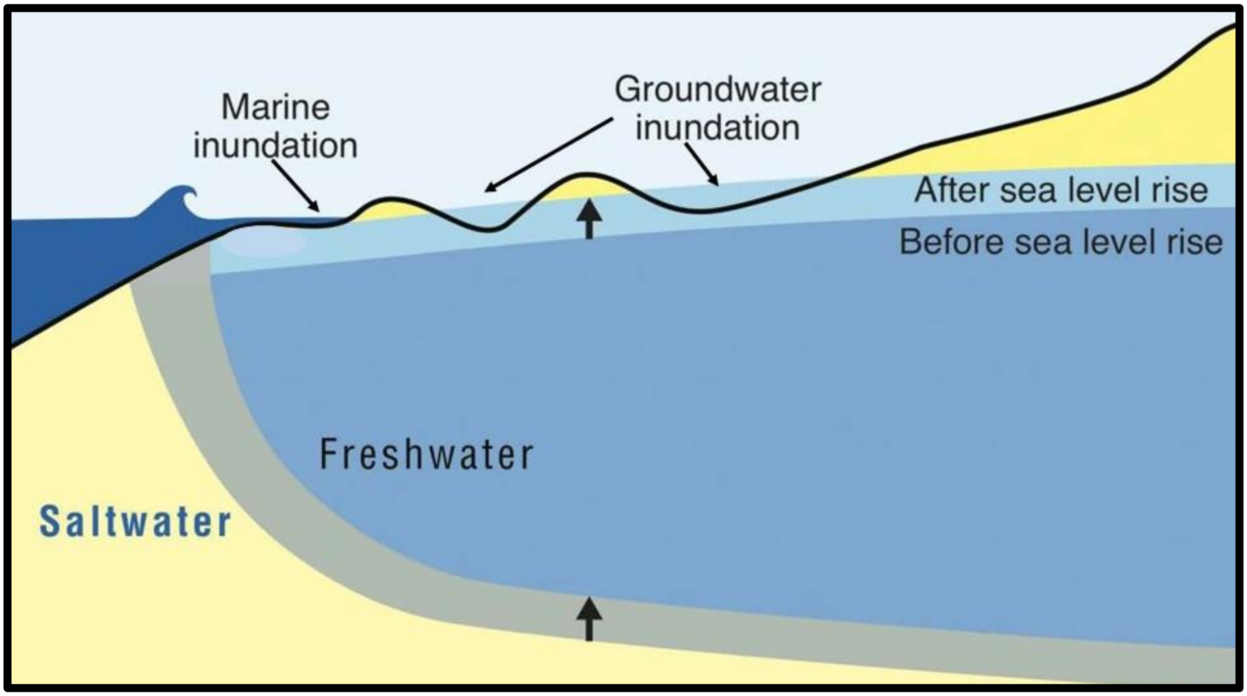


As sea level rises, less dense groundwater, pushed inland, emerges as pools of water or newly boggy areas (modified after University of Hawaii, Manoa, Coastal Geology Group).

Among coastal communities, a subset, those filled-wetland urban environments, are uniquely at risk from groundwater rise because they already are prone to subsidence (thus reducing their ground elevations) and they are traversed by historic and urban preferential pathways, which will become filled and ultimately submerged by the rising groundwater.

Current Evidence of Emergent Groundwater

Tamalpais Valley is representative of many communities in the San Francisco Bay Area (Bay) which are built on filled wetlands. Based on resident interviews conducted in mid-November 2020 and field evidence observed during that time (photos provided below), Tamalpais Valley shows the following signs of groundwater emergence:

- **Lush vegetation** even in drought, with ponded groundwater in low-lying areas;
- **Flooding inside structures** - Groundwater entering the ground floor and garage floors;
- **Multiples of clean and clear discharge pipes per property in road curbs**, each representing a downspout or sump pump. One 3" gravity pipe and several 1" diameter poly vinyl chloride (PVC) pipes discharging at the curb signal a need to move water off of the property.
- **Wicking water** patterns on vertical concrete walls and the perimeter of horizontal concrete pavers;
- **Daily sump pump discharge**;

- Daily **standing water** (during drought) alongside curbs;
- **Drainage backflow** of/from bay or creek waters up into storm drain inlets. Currently this occurs during high tides. When the high tides go out, the water drains through stormwater pipes as designed;
- **Elevated wastewater volume and high salinity** of wastewater due to leaky sewer pipes and storm pipes which act as drains for excess groundwater during high tides and extreme rain events. The local wastewater treatment plant, the Sewerage Agency of Southern Marin (SASM) in Mill Valley, California has documented these conditions during high tides and during the extreme rain events of January 2008; and,
- Increased **metal corrosion** rates of infrastructure (pipes, foundations, bridges, roadways) as their metal components come into contact with more saline waters with sea level rise.

Local subsidence in this former wetlands area lowers the surface elevation, causing a greater impact of SLR and increasing flood risk. Filled wetlands sink because of soil compaction, microbial consumption of organic material, changes in soil moisture and, in some cases, groundwater pumping. These former wetlands covered with residential and commercial development commonly present with tilting (unlevel) structures, cracked foundations, vertical cracks in concrete and asphalt surfacing, and a need for periodic repairs in ramps connecting vertical separations in houses, sidewalks, driveways, roads and bridges, to compensate for observable and unsafe elevation changes.

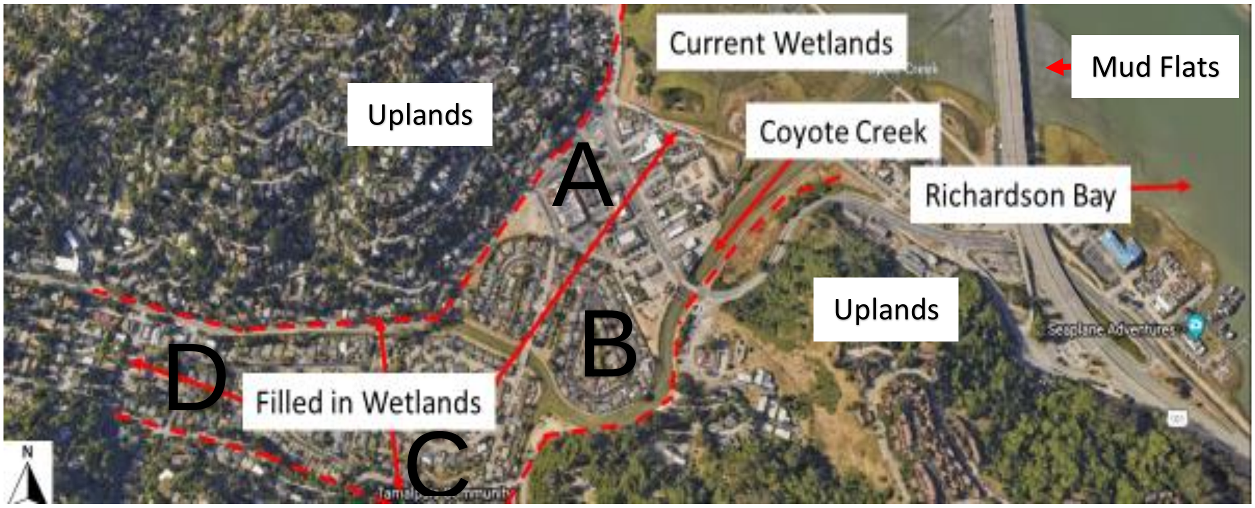
Tamalpais Valley, in the unincorporated part of Mill Valley, California, located on the San Francisco Bay between the cities of Mill Valley and Sausalito, already shows evidence of groundwater emergence and subsidence. The communities (like Tamalpais Valley) ringing the Bay share similar geology, geomorphology, hydrogeology, groundwater elevation, urban infrastructure and development history.

California

San Francisco Bay

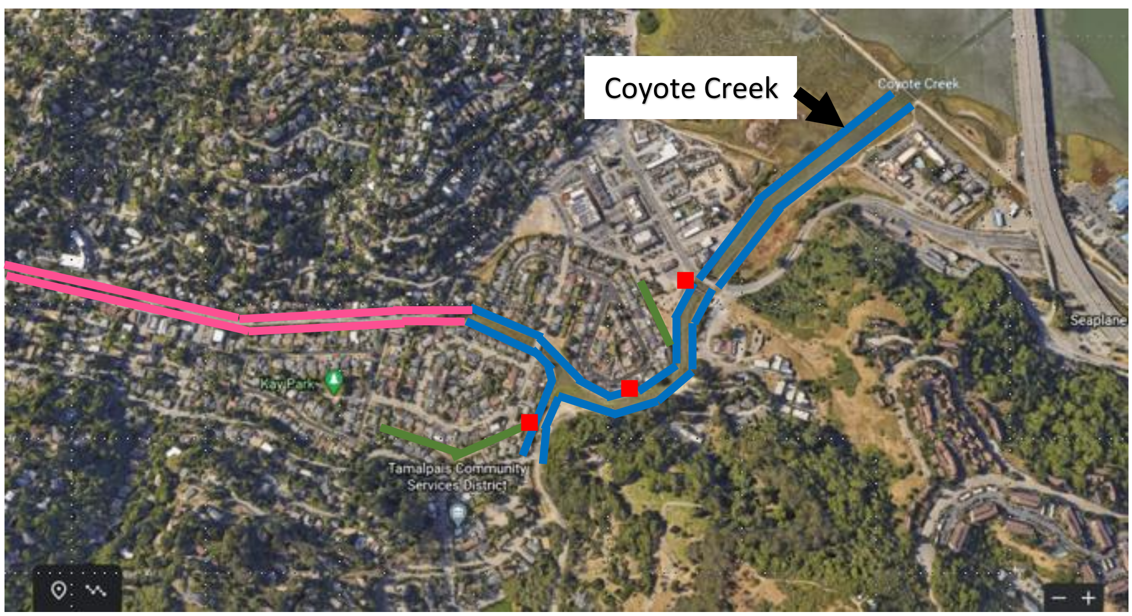
California map (left) shows Tamalpais Valley, a bayside community located on San Francisco Bay (right; SFEI). Filled historical tidal wetlands in the SFEI map are shown in green.

The setting of the Tamalpais Valley floodplain (former wetlands in question) is shown in an aerial, with some detail, in the figure, below.



Tamalpais Valley, California (with detail) on the current bay margin, with mudflats, wetlands (at bayside), filled wetlands now developed with commercial – A, and three residential subdivisions, B, C and D and uplands.

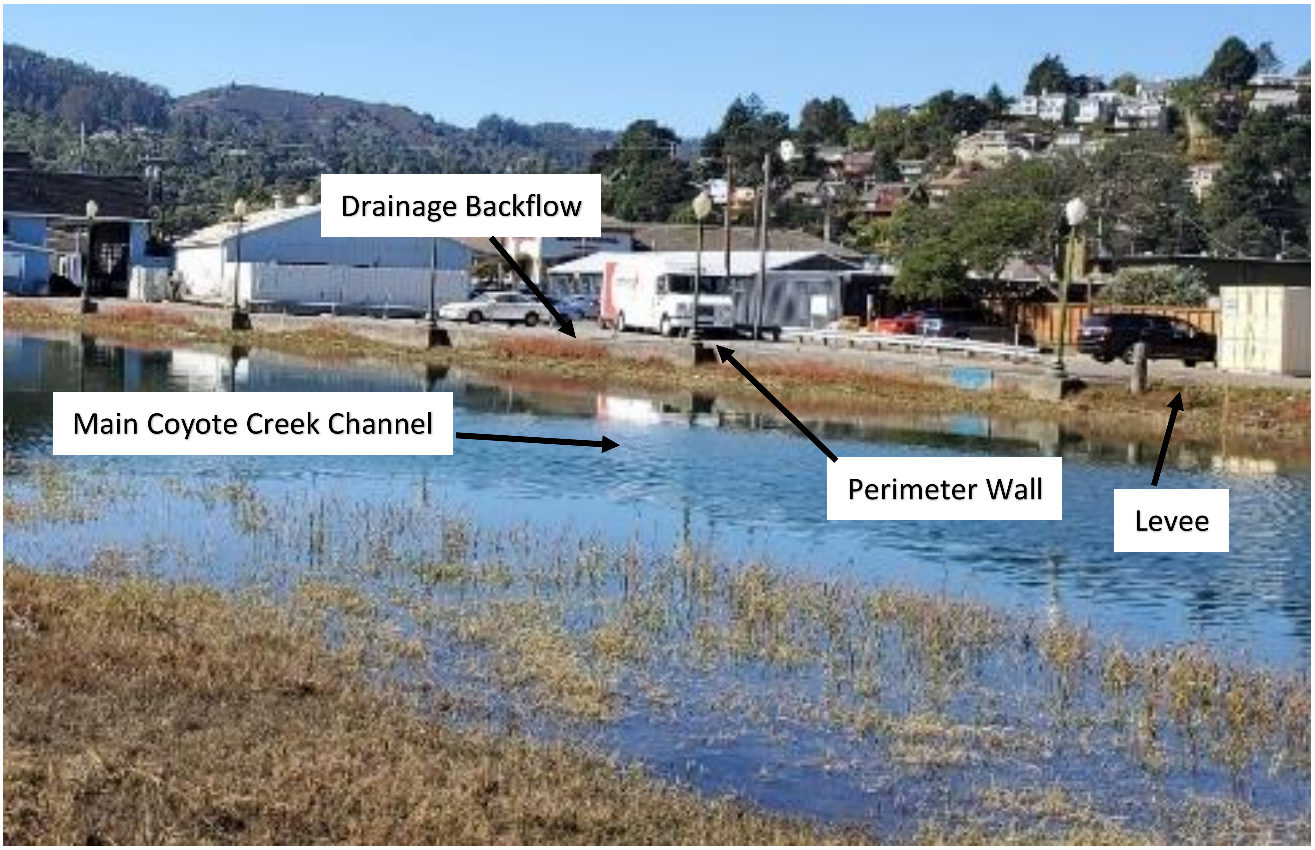
In the case of Tamalpais Valley, the original valley floor creek and its tributaries were moved (redirected) when the wetlands were filled. (Several tributaries drain into the main channel, Coyote Creek.)



Coyote Creek was first bermed with levees (blue), ditched for drainage (green) and channelized with concrete floor and walls (pink). Later, pump stations (red) were installed to move storm surface flow out of the neighborhood and over the levee into Coyote Creek.

Although springs and limited historic local groundwater wells exist in the fractured Franciscan rocks (underlying the former wetlands), no significant contiguous aquifers exist beneath the Tamalpais Valley area. Water resources are collected from the larger Mount Tamalpais watershed and the collected rain water is stored to the north in reservoirs.

Photos of Conditions at the Bay Margin in Tamalpais Valley



During an elevated tide in a drought, tidal water rises along the Coyote Creek channel levee, ponding in the parking lot (far side) through surface drains behind the levee, confirming this engineering control is not effective.

View to the east, the historic railroad bed in Richardson Bay, and now a bike path (right), designed to be above the flood waters, is shown to be just submerged during seasonally high tide – during a drought. The Richardson Bay Bridge (Highway 101) is seen in the background.

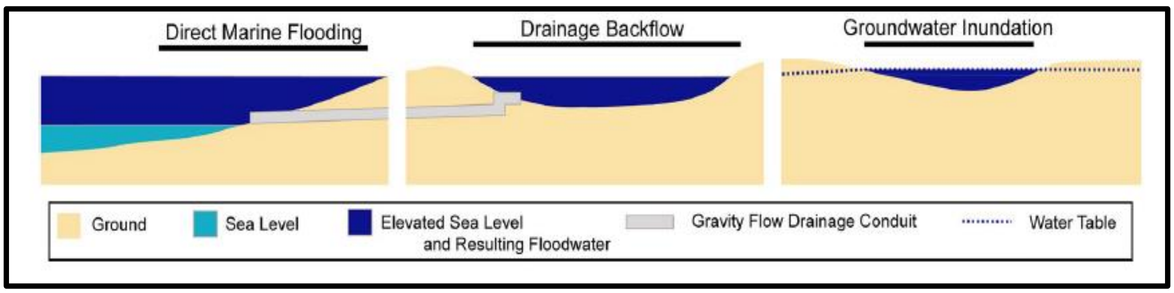
Just inland of the Bay, photos document tidal backflow up drains.

View north at a coastal border parking lot surface drain (center). The stormdrain grate is under a puddle from the beginning of tidal drainage backflow (left, Mount Tamalpais in the background and the Bay directly to the right). Low tide has just occurred and the tide is beginning to come in.

Below (photo to left) is a view North of the same grate when the tide is out, at the lowest point, and the stormdrain grate is ‘dry’.

View west (photo to right) in the same parking lot, during the height of the November King Tide. During this measurement, this drain grate is covered with 10-inches of backfilled tidal water. This is the highest measurement at this grate during this King Tide event. In the hour before this photo was taken, the water elevation increased from a height of 7-inches to a total of 10-inches.

These observations can be explained with the following diagram, where the dark blue represents the elevated sea level, elevations which represent future SLR:



This diagram (above) shows how direct marine - bay water from Richardson Bay (left) enters the coastal hotel parking lot (center) through the (grey) surface stormwater drainage pipe as a backflow during high tide. The rising groundwater at a location inland (from the currently flooding parking lot) in the figure frame (right) shows groundwater inundating the surface (from University of Hawaii, Manoa, Coastal Geology Group). Photo examples of such emergent groundwater are provided below.

At properties bordering and behind the levees on Coyote Creek, emergent groundwater leaves evidence in the form of ‘wicking’ on concrete surfaces. While the contact of the water and the concrete may be inches lower, the wicking of the water can travel up the concrete an inch to several inches.

At high tide, groundwater is observed wicking up the concrete from the joint between concrete slabs (left). Groundwater is wicking up the perimeter flood barrier's concrete wall from below (right).

Even under drought conditions, in the photo (below) groundwater is seen in a sump which is set at about 2 feet below ground surface, some 4 feet below the top of the levee (pump is sitting in a couple of inches of water). This sump is fed by a French drain parallel to (and between) the levee and the house. Trickling water was heard the day the photograph was taken. The owner reports the sump pump runs daily.

Excess Water is Moved by Sump Pumps Off Residential Properties

Despite drought conditions, this residential sump discharge pipe is clear of obstructions and wet. The standing water in the gutter is water from sump discharge. This water is shallow groundwater.

During drought, additional rise in groundwater elevation is caused by a combination of tidal rise or excess irrigation. Most houses in the low-lying neighborhoods have one or more sump pumps as evidenced by multiple small-diameter discharge lines either in the curb or discharging to the sidewalk.

Field work inspection identified 244 discharge pipes for 218 residential properties.

Multiple sump pump discharge lines (small pipes in the curb, above).

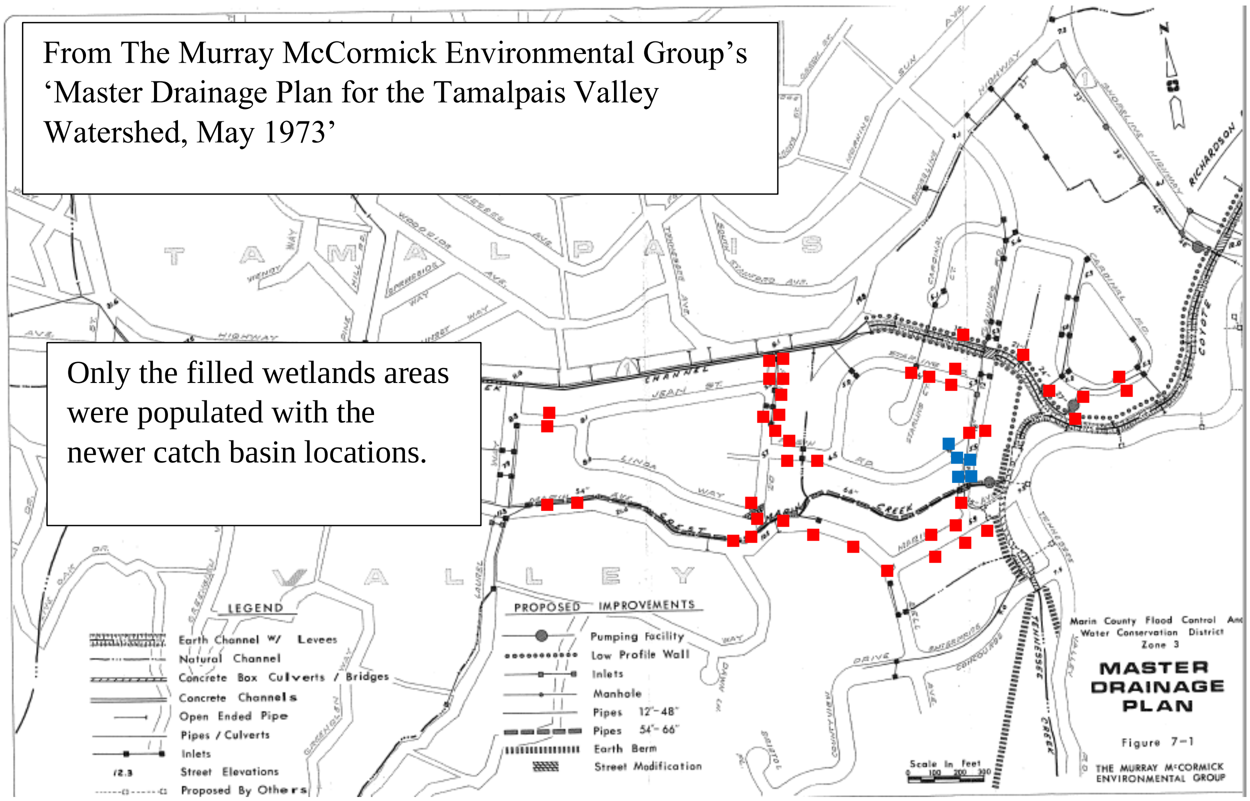
Note clear discharge and discharge pipe at full capacity in small-diameter PVC lines.

Other Evidence of Emerging Groundwater During Periods of Drought

A low area in an easement where lush vegetation (during drought) indicates shallow groundwater staying at the surface. The subsurface connectivity between this groundwater and the nearby Coyote Creek is currently unknown. A close-up of the ponded water in the lush vegetation, below.

In the photo above, over several days during exceptionally high tides in mid-November 2020, the water appeared, but not at times matching the highest tides. At the time of the highest tides, the water was absent, suggesting more complex subsurface hydrogeologic interactions with the nearby Coyote Creek about 300 feet away.

Evidence of Catch Basins Installed Since 1973



Existing 1973 catch basins are colored in black, proposed catch basins (in 1973) in blue and current Area A-D catch basins added in red. All current catch basins are one of these three colors.

A total of 83 catch basins in 190 acres servicing 218 houses shows the historic response to flooding.

With groundwater rise and a combination of extremely high tides and heavy rains, storm drains will back up into the streets. Storm drain pipes entering the Creek with flapper valves on the discharge end, drainage channels and ditches all require regular maintenance to work properly and prevent flooding.

Leaky sanitary sewer pipes and storm water pipes lose capacity as groundwater rises and infiltrates the pipes. In summary, street flooding is likely to occur due to an extreme rain event coupled with SLR, high tides and operational failures of clearing debris and maintaining the stormwater collection and drainage system.

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Need for a Predictive Model to Anticipate Emergent Groundwater

The USGS and others have studied SLR-caused emergent groundwater in coastal areas. However, the literature does not include examples of emergent groundwater in filled wetland-housing developments which are subsiding and are traversed with preferential pathways of urban infrastructure. Communities built on filled wetlands, proximal to coasts, will need predictive guidance based on current groundwater data to plan for SLR caused by emergent groundwater.

Current networks of groundwater monitoring wells intercepting tidal rise were generally installed to monitor groundwater contamination, and not installed to monitor SLR. Existing groundwater monitoring wells are not distributed evenly around the Bay margin. With no ongoing contamination studies in Tamalpais Valley, there is not a single well currently reporting data about groundwater elevation (on the State of California Water Resources Control Board's Geotracker website).

Data needs to be collected in the urban filled wetlands environment to predict emergent groundwater, which we have anticipated will occur with SLR. A network of piezometers (groundwater intercept) are needed. A predictive model will direct planning goals for preventing or accommodating the flooding.

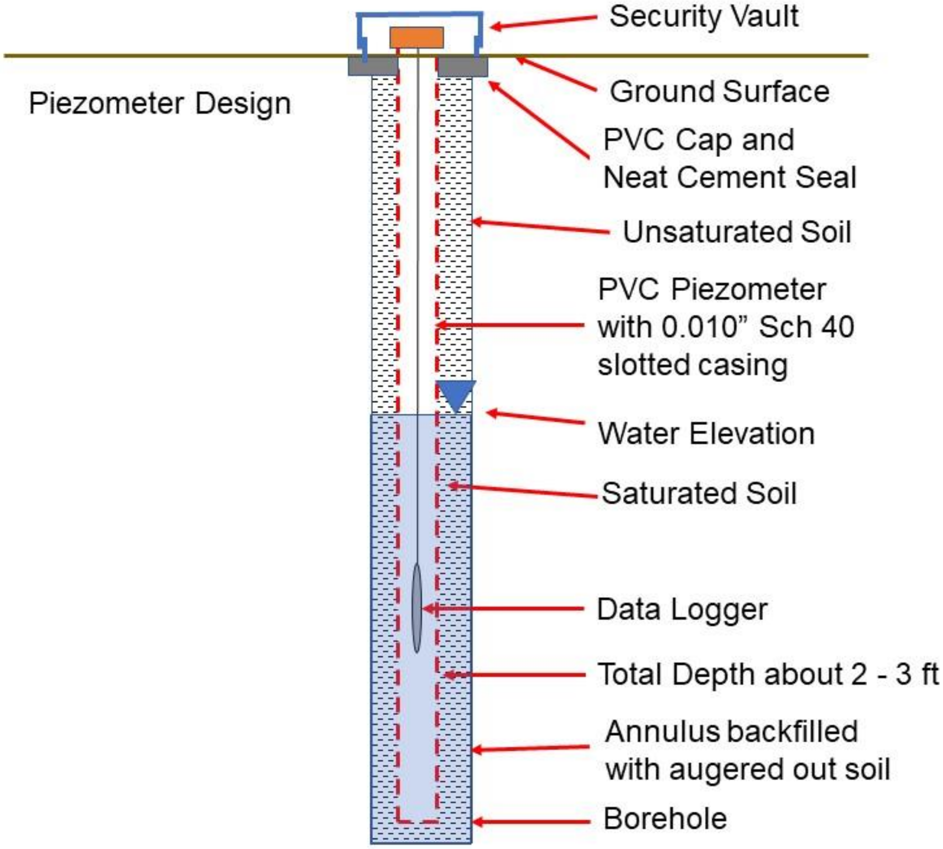
By collecting data of the current conditions (current groundwater elevation and flow direction), forming hypotheses (of the extent of seawater intrusion and the most likely future locations of emergent groundwater), and then testing those hypotheses (measuring groundwater parameters in those locations) predictive guidance can be developed. Iterative hypotheses and hypothesis testing should lead to strategies and models for predicting future emergent groundwater locations.

Data Collection – Data Loggers in Piezometers

Data on groundwater elevation location and changes can be acquired by measuring shallow groundwater levels using a network of water elevation depth data loggers (measure groundwater elevation over time) in sampling locations (piezometers). The piezometer with a data logger installed in it is shown in the figure below.

Installing a network of piezometers to collect data in flooding-susceptible locations will provide an insight as to current subsurface conditions. Each data logger (in a piezometer) records water elevations continuously over time (diagram below shows two piezometers staged to evaluate baseline tidal influence – not placed in known preferential pathways.)

Current groundwater conditions range because the tides range in elevation daily. Data from the highest tides will provide the worst-case scenario. During the highest tides of the year (colloquially called "King Tides"), conditions simulate the future we can expect with SLR.

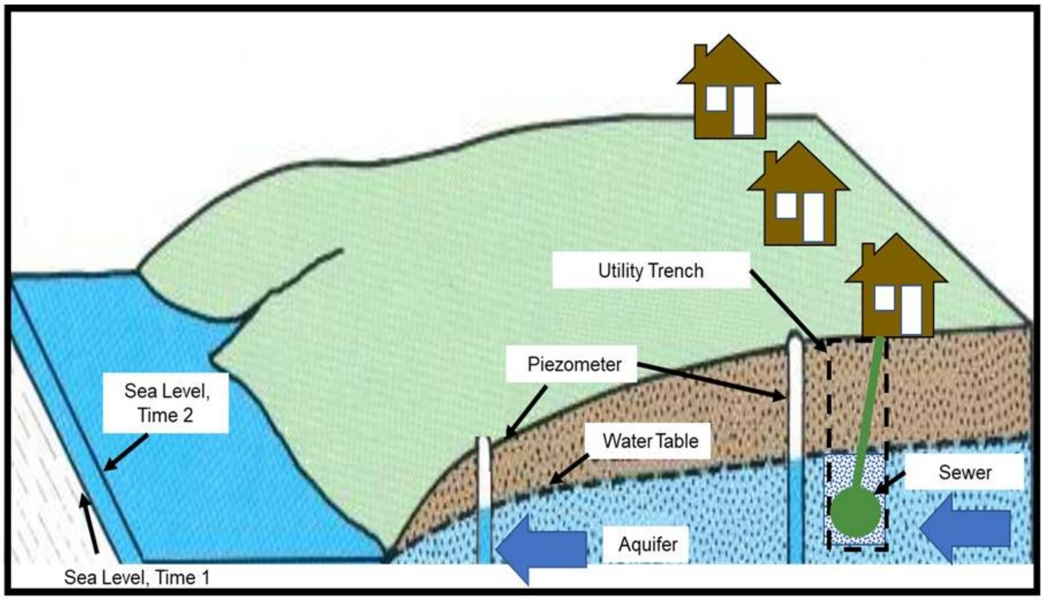


Interviews with Residents/Sampling Sumps

Groundwater flooding occurs at random times and locations, within a several day period during "King Tides" and triggered by heavy rains. Documenting the locations of emergent groundwater will help in the decision process of where to install piezometers to measure fluctuating groundwater elevations.

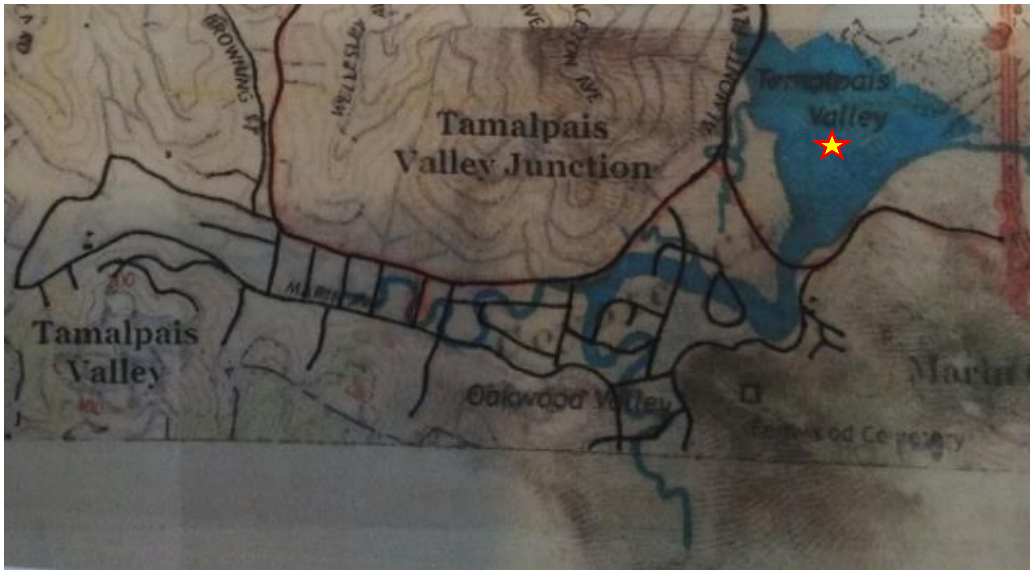
At existing sumps or French drains, groundwater elevation and water level fluctuation can be documented; conductivity can be measured on these existing features to obtain a baseline of the degree to which salt water is already intruding into the coastline.

Community involvement will be needed in identifying critical emergent groundwater locations. Surveys of the neighbors in the most at-risk locations will be an irreplaceable part of figuring out where to place the piezometers.

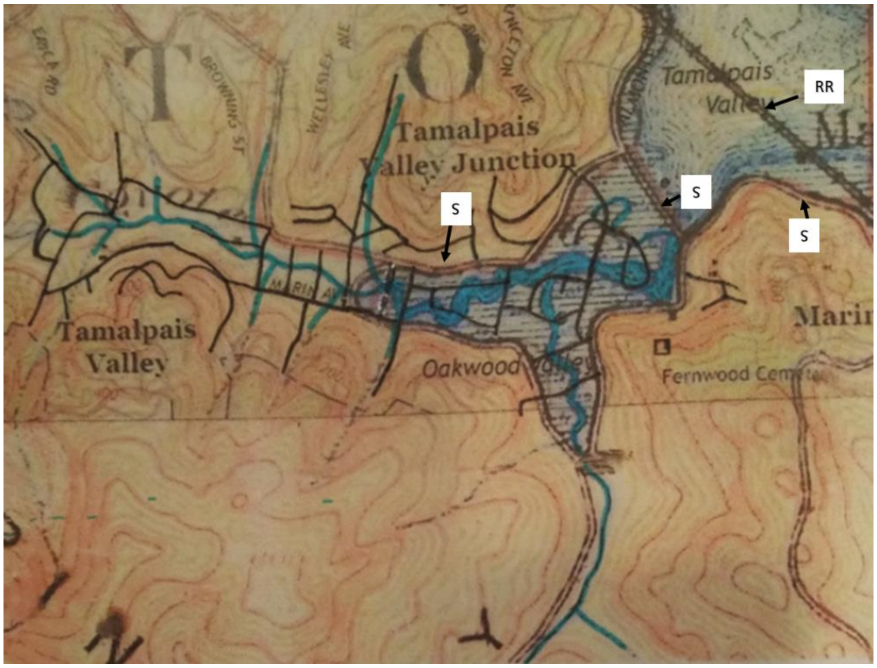


Historic Meanders and Public Works Data

Buried stream channels (meanders on historic maps), utility trenches and leaky sewer pipes, examples of preferential pathways (or conduits), are anticipated to cause preferential movement of groundwater. Obtaining the historic and infrastructure information will be required to build an overlaid map to predict where emergent groundwater may occur, and where the piezometers measuring preferential pathway groundwater should be located. As an example, draft overlays from 1859 and 1911 show various locations of previous creek meanders, channels and open water. And the Marin County Public Works storm water pipelines (maps) and Tamalpais Community Services District (TCSD) sanitary sewer pipeline (maps) will be needed to overlay to make a complete preferential pathway summary map. Historic maps (with color added) from 1859 (above) and 1911 (below) overlain with approximate current street locations are provided below.



Historic maps are overlain with current street locations (in black). In the 1859 map the Tamalpais Valley surface water body (yellow star, upper right) no longer exists as open water. In the 1911 map (below) both Shoreline Highway (S) (State Route 1) and the railroad (RR) causeway, now a bike path, have been labeled.



Data to Collect

The recommended groundwater measuring tool proposed is the Solinst 3001 Levelogger 5 LTC. The Levelogger has the following capacities to record groundwater and tidal elevations and parameters, such as conductivity, temperature, pH and dissolved oxygen:

- measures groundwater elevation every 10 minutes
- is accurate to within 0.007 ft.
- records water temperature and
- records conductivity in the range of 0 to 80,000 Siemens per centimeter, S/cm, (so sources of fresh water and sea water can be differentiated)
- detailed water elevation data which are compensated for barometric pressure.

The field data will be used to develop the following information from the network:

- Direction of groundwater flow (water elevation contour maps);
- Source of water of the sampling points based on conductivity (salt water versus fresh water content);

- Groundwater elevation change versus tidal elevation change (permeability and subsurface connectivity);
- Groundwater elevation change in preferential pathways versus tidal elevation change, and
- Relative permeability of preferential pathways compared to background areas.

Predictive Models

The data will be used to interpolate the water table level at any study area location. The resulting model will help homeowners, policy makers, planners and engineers in evaluating and prioritizing areas of groundwater emergence risk and to identify whether and where additional French drains and groundwater pumping should be considered as a viable interim mitigation strategy.

Summary

Tamalpais Valley and similar coastal communities need the data of a network of piezometers to prepare an emergent groundwater program to provide a groundwater elevation baseline and to identify significant groundwater preferential pathways and high-risk areas for flooding. A pilot program in Tamalpais Valley would include an estimated 50 and 100 small-diameter (1-inch diameter) groundwater piezometers and stilling wells (in bodies of water like a creek or ditch) to measure comparative groundwater and creek/drainage ditch/wetland water elevation and water parameters over time. Comparing the data will provide a detailed understanding of the subsurface vertical and lateral movement of groundwater/seawater. This program is needed because 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. This proposed program would address many of the scientific data gaps in the sea level rise literature. The final program objective is production of a template and methodology for other similar areas to use.

Contacts: Please contact Clearwater Group:

James A. Jacobs, P.G., C.H.G.
Principal Hydrogeologist

Olivia T.P. Jacobs, C.E.M.
President, Principal Project Manager

Clearwater Group
229 Tewksbury Ave.
Pt. Richmond, CA 94801
Tel: 510-307-9943
Website: www.clearwatergroup.com

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Photos nationwide of leaky sewer lines (above), manhole lid (249 lbs) pushed up by excess water pressure in stormdrain line (below):