ASSESSING COPELAND CREEK INTER-WATERSHED OVERBANK FLOW, A PILOT STUDY

by

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Abstract: Under normal conditions, Copeland Creek is tributary to the Russian River Watershed. During high flow events, Copeland Creek may overtop its banks at an avulsion site as it exits Sonoma Mountain. The overbank flow during such events enters the San Pablo Bay watershed, likely exacerbating flooding in Penngrove and Petaluma. This study uses HEC-RAS version 5.0.3 two-dimensional hydraulic modeling and various return interval peak flow events to understand the conditions that cause Copeland Creek to flood and where the floodwaters travel. Modeled overbank flow for 10-year peak flow events and greater are shown to travel south across Lichau Road into Roberts Creek, where it enters the San Pablo Bay watershed. Overbank flow from Copeland Creek contributes up to 1.7 feet to the river stage height of Lichau Creek near Penngrove from 10-year peak flows, up to 4.0 feet from 25-year peak flows, up to 4.5 feet from 50-year peak flows, and up to 5.2 feet from 100-year peak flows. Farther downstream, Copeland Creek overbank flow contributes to river stage height in the Petaluma River during 25-, 50-, and 100-year peak flows, adding up to 2.0 feet, 2.7 feet, and 2.9 feet respectively.

Key words: avulsion, Copeland Creek, flood, hydraulic modeling, inter-watershed, overbank flow, Sonoma County

Introduction

Flooding of the Copeland Creek headwaters causes overbank flow to switch watersheds from the Russian River to the San Pablo Bay watershed (Figure 1). State officials dating back to 1896 claimed these floodwaters contribute to flooding in the San Pablo Bay watershed, affecting the cities of Penngrove and Petaluma (Price and Nurse 1896). An atmospheric river event in January 2017 caused Copeland Creek headwaters to overflow its channel (a phenomenon called avulsion) near Lichau Road, which is believed to have contributed to flooding of mobile home parks in Penngrove and an auto mall in Petaluma (Brown 2017). Flood events near these areas in 1982 and 2006 are also believed to have been exacerbated by Copeland Creek floodwaters. While published documentation asserts that Copeland Creek overbank flow enters the San Pablo Bay watershed, little is understood about the conditions that cause Copeland Creek to overtop its bank, where floodwaters travel, and the impacts of Copeland Creek flooding on property and human life. This study will provide a detailed assessment of Copeland Creek inter-watershed overbank flow, and offer insight on the impacts experienced by residents from these floodwaters.

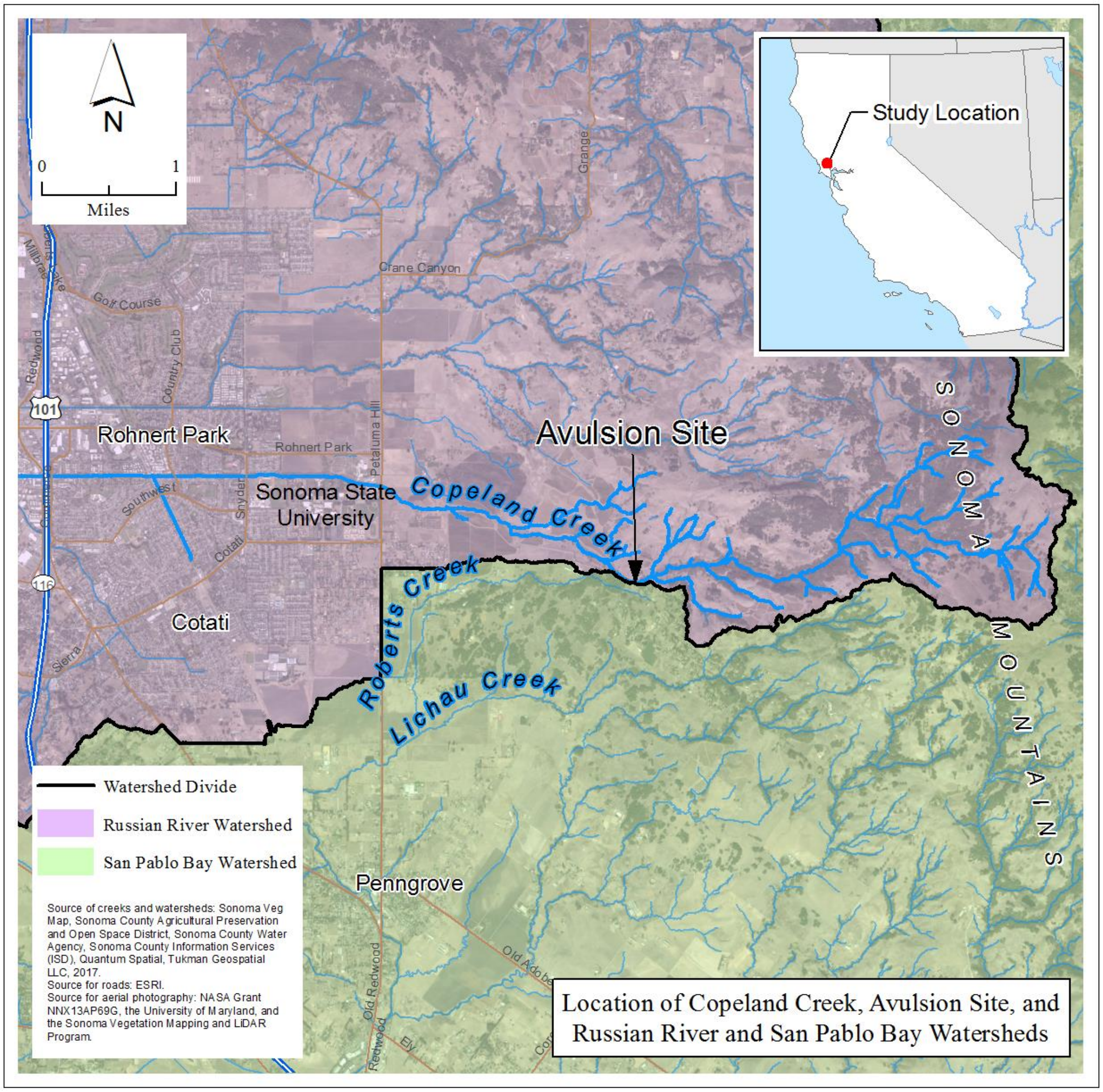


Figure 1- Location Map

According to Keller and DeVecchio (2016), floods were the most destructive form of natural disater during the twentith century in the United States, resulting in an average of 100 lives lost per year. Secondary negative effects of flooding include displacement of humans, livestock, and wildlife, and failure of water treatment facilities, including sewer and septic systems, which can contaminate floodwaters with disease-casuing microorganisms. In this human-environment context, flooding can often have costly ramifications. Understanding where and when floods occur is imperative for mitigation efforts and the reduction of property damage and loss of life.

This study first reviews published material about the geologic setting and hydrology of Copeland Creek, and climate and precipitation events in the region. Then, the methods used to better understand where Copeland Creek floodwaters travel and its impacts will be detailed. These include the use of hydraulic modeling software created by U.S. Army Corp of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) version 5.0.3 and an online survey of residents near Copeland Creek. This study models multiple return interval peak flow events to compare Copeland Creek overbank flow with the perception of long-time residents and historical documents. Thereafter, the results of the hydraulic model and resulting inundation maps will be discussed, and the results of eleven respondents to the online survey will be reviewed and analyzed. Finally, this study will discuss possible solutions to overbank flows from Copeland Creek headwaters and provide recommendations for future modeling efforts.

Literature Review

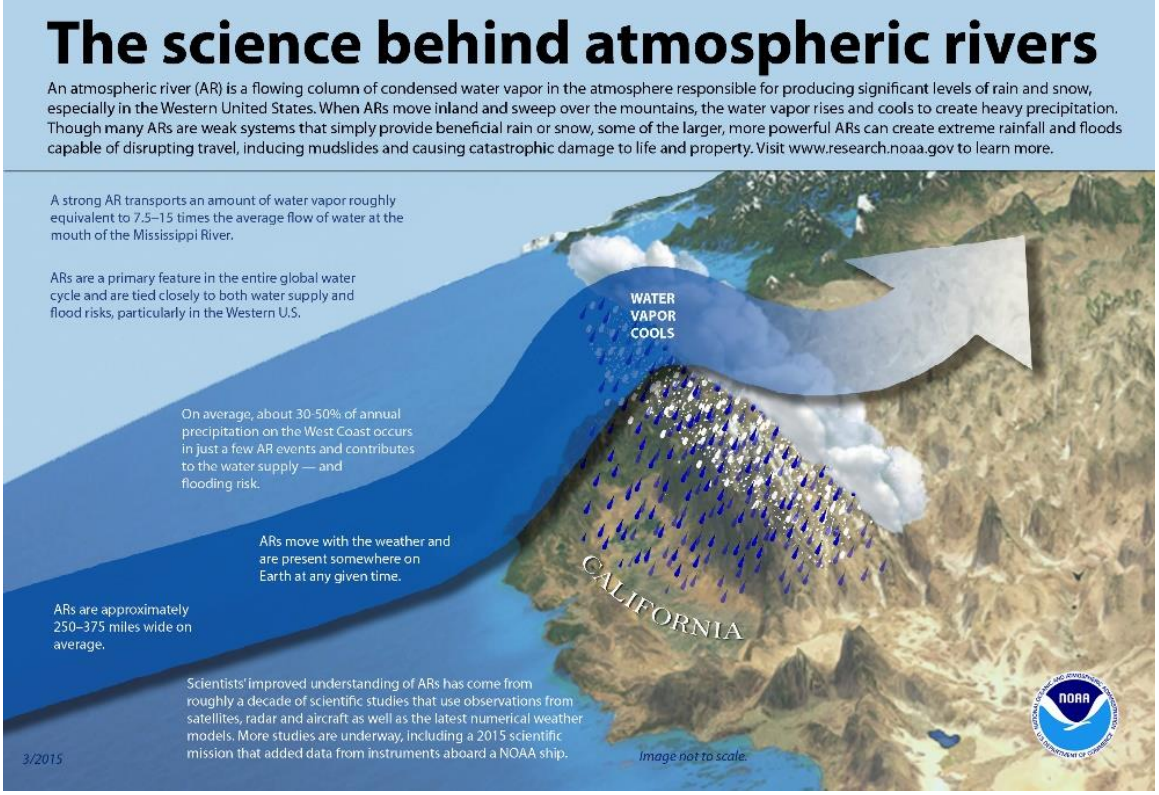
Flooding is described simply as overbank flow from a watercourse (Keller and DeVecchio 2016). Flooding is a dynamic phenomenon that typically affects low-lying areas caused by rainfall in excess of what is able to infiltrate the ground or be carried away in channels. If the amount of precipitation is high enough, or if a storm is prolonged, the ground becomes saturated and unable to absorb additional water, which causes water to run off the land surface as overland flow or into channels. When channels become overloaded, water overtops their banks and floods into the adjacent land, called a floodplain, which is a natural and important process in co-adapted riverine systems. Floods carry sediment and nutrients out of the channel and into the adjacent floodplain, where they are deposited. This natural service function replenishes soils with fertile sediment which is imparative for farming and agriculture.

Hydrology

Copeland Creek is a 9.1-mile-long channel originating on the western slope of Sonoma Mountain in Sonoma County, California (SRCD 2004). The stream travels west and runs through the city of Rohnert Park. Historically, the creek would have traveled through a series of wetland and vernal pool complexes before discharging to the Laguna de Santa Rosa. As part of urbanizing the area, many creeks, including Copeland, were channelized to drain the wetlands. Presently, the creek flows through a natural channel until Petaluma Hill Road, where it is conveyed through the straightened flood control channel to the Laguna de Santa Rosa (see Figure 1). The drainage area of Copeland

Creek encompasses 5.1 square miles of rural and urban landscapes, of which the drainage area above the avulsion site encompasses 2.9 square miles. Copeland Creek is perennial along some portions of its reach, in which it flows year-round, sourced by precipitation in the winter months and groundwater interflow and springs in the dry months (Norwick 2007). It is the largest tributary to the Laguna de Santa Rosa, which itself is the largest tributary to Mark West Creek, which in turn is the largest tributary to the Russian River.

The region is characterized by a Mediterranean climate, receiving most of its rainfall in the winter months, with hot dry summer months (GHD 2017; SRCD 2004). The mean annual precipitation for the Copeland Creek headwaters above the avulsion site is 49.8 inches (USGS n.d.). The region is prone to atmospheric rivers, which are large masses of water in the atmosphere that originate in the equatorial Pacific region and move across the western U.S. (NOAA 2015). Atmospheric rivers can produce rainfall events of five to ten inches in a matter of hours, resulting in large volumes of run off and flooding (Figure 2).


The science behind atmospheric rivers

An atmospheric river (AR) is a flowing column of condensed water vapor in the atmosphere responsible for producing significant levels of rain and snow, especially in the Western United States. When ARs move inland and sweep over the mountains, the water vapor rises and cools to create heavy precipitation. Though many ARs are weak systems that simply provide beneficial rain or snow, some of the larger, more powerful ARs can create extreme rainfall and floods capable of disrupting travel, inducing mudslides and causing catastrophic damage to life and property. Visit www.research.noaa.gov to learn more.

A strong AR transports an amount of water vapor roughly equivalent to 7.5–15 times the average flow of water at the mouth of the Mississippi River.

ARs are a primary feature in the entire global water cycle and are tied closely to both water supply and flood risks, particularly in the Western U.S.

On average, about 30-50% of annual precipitation on the West Coast occurs in just a few AR events and contributes to the water supply — and flooding risk.

ARs move with the weather and are present somewhere on Earth at any given time.

ARs are approximately 250–375 miles wide on average.

Scientists' improved understanding of ARs has come from roughly a decade of scientific studies that use observations from satellites, radar and aircraft as well as the latest numerical weather models. More studies are underway, including a 2015 scientific mission that added data from instruments aboard a NOAA ship.

3/2015

Image not to scale.

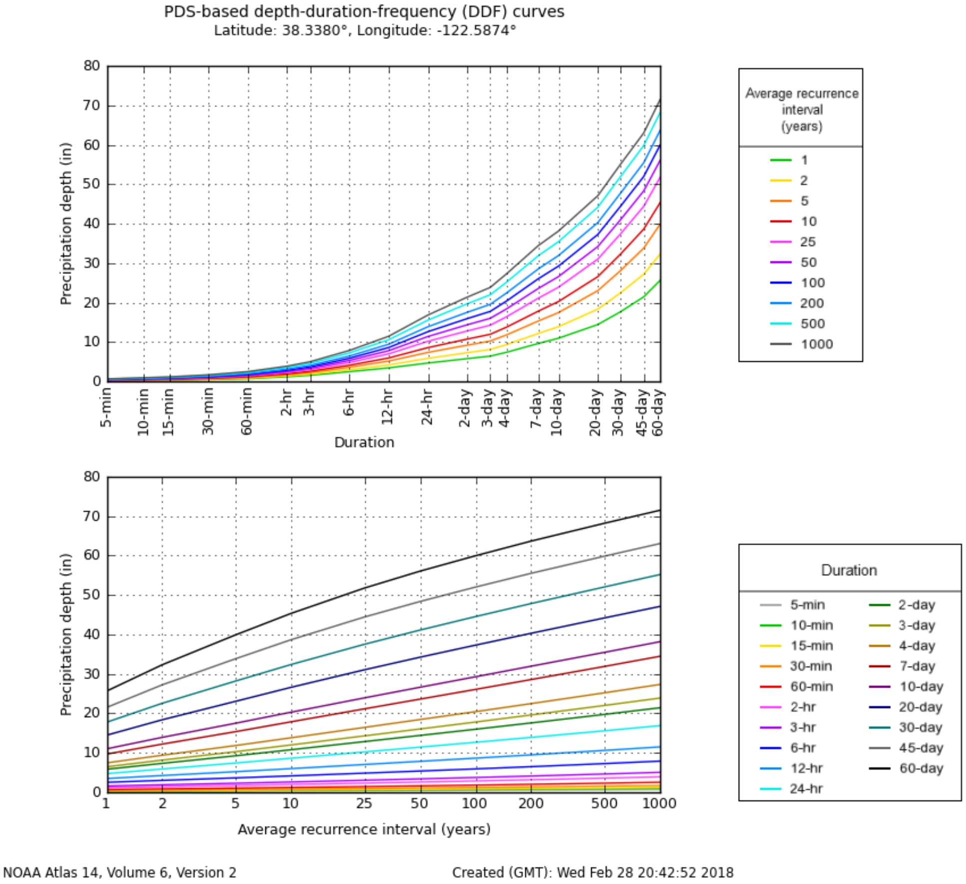
Figure 2 - What are atmospheric rivers? (Source: NOAA 2015)

The occurrence and magnitude of storm events and peak flows are described statistically as an average recurrence interval (or return period), which is the average period between years in which a given precipitation magnitude is exceeded at least once

(NOAA n.d.). It is determined based on the probability that a given amount will be met or exceeded in any given year. For example, a 1-year storm is produced or exceeded every year (1/1, or 100 percent), a 25-year storm has a 4 percent chance of occurring or being exceeded in any given year (1/25), while a 100-year storm has a 1 percent chance (1/100). Using this statistical tool in combination with measured precipitation data, one can estimate the likelihood a storm event of a given magnitude is to happen at a given location. Thus, in the headwaters of Copeland Creek, a 24-hour storm 2-year storm has a 50 percent chance to occur in any given year, in which it will precipitate 4.73" of rainfall or more (NOAA n.d.). Similarly, a 24-hour 100-year storm (1 percent chance of occurring in any given year) will precipitate 12.7" or more of rainfall. Table 1 shows the precipitation for each return interval used in this study, and Figure 3 shows this data (and more) graphically.

Return Period for 24-hour Storm	**Precipitation in Copeland Creek Headwaters (inches)**
1-year	4.73
2-year	5.91
10-year	8.63
25-year	10.2
50-year	11.4
100-year	12.7

Table 1 - Precipitation frequency estimates for various return periods.
(Source: NOAA Atlas 14, Volume 6, Version 2, n.d.)



NOAA Atlas 14, Volume 6, Version 2

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Figure 3 - Partial Duration Series (PDS) graphical representation of various storm events in the Copeland Creek headwater (Source: NOAA Atlas 14, Volume 6, Version 2, n.d.)

The Sonoma County Water Agency (SCWA) commissioned a study by GHD and other supporting consulting firms to develop a “Basis of Design Report” (BOD) for the construction of a stormwater detention basin on Copeland Creek just east of Petaluma Hill Road (GHD 2017). The BOD details a hydraulic model using a HEC-RAS one-dimensional model, but notes that a two-dimensional model should be conducted to better model overbank flows from Copeland Creek. This study is a response to that note and intends to further the understanding of Copeland Creek flood processes.

As part of the BOD, hydrology for Copeland Creek was modeled using U.S. Army Corp of Engineers Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) software, and peak flow statistics for a 24-hour storm event were calculated. The results for the flow just upstream of the Copeland Creek avulsion site, at the Lichau Bridge crossing (see Figure 6), are listed in Table 2 below. These peak flow rates will become the basis for modeling various return interval peak flow events in this study’s two-dimensional HEC-RAS model.

Return Period for 24-hour Storm	**Peak Discharge at Lichau Bridge (cfs)**
1-year	691.27
2-year	1,001.97
10-year	1,781.19
25-year	2,258.91
50-year	2,628.42
100-year	2,995.64

Table 2- Results from HEC-HMS stormflow model for various 24-hour storm events (Source: GHD 2017)

Geology

Review of U.S. Geological Survey (USGS) 7.5-minute quadrangles show Sonoma Mountain, where Copeland Creek headwaters begin, to be about 2,400 feet above mean sea level. Its primary constituents are the Franciscan Complex, overlain by the Sonoma Volcanics, consisting of volcanic rhyolite tuff and basaltic rocks (SRCD 2004; Norwick 2007). The Rodgers Creek Fault runs through Sonoma Mountain in a northwestly to southeasterly direction. Norwick (2007) notes the mountain is overlain with softer tuff and ground up basaltic material, which are too weak to support their own weight and create a ridge, to flow—on geologic timescales—downslope to the west and east as earth flows and landslides. This material is easily eroded, and contributes high sediments loads to Copeland Creek and downstream during storm events (SRCD 2004).

Copeland Creek is characterized by three distinct sections along its course: 1) the headwaters in the Sonoma Mountains, 2) the alluvial fan, where the creek exits the Sonoma Mountain into the piedmont region and transitions from a net erosive stream to a net depositional steam, depositing material and frequently (over geologic timescales) changes its path, and 3) the course through the valley floor and floodplain (SRCD 2004). The material that is eroded from the upper reaches is a combination of gravel, cobbles and boulders, as well as finer material such as sands and clays, and invisible chemical compounds in solution. Once this material enters a water course, it is called sediment. This sediment begins to “fall out” of the stream as the stream loses competence (the ability to carry sediment further downstream), depositing material in the streambed, and on the floodplain during high flow events. Section 2 is of particular interest, as the avulsion site is located at the apex of the alluvial fan (Figure 4). Alluvial fans have a cone-shaped morphology, forming where a creek emerges from a mountainous area onto the lower sloped piedmont or plain (Huggett 2011). Seen in cross-section, alluvial fans have a dome shape, with lower elevations at the sides and higher elevations toward the center (Figure 5). Over time, sediment piles up, or aggregates, which causes the stream to change course in order to find the path of least resistance. This continual deposition of material and changing of course of the stream over millennia has created an alluvial fan where Copeland Creek emerges from the mountains (SRCD 2004).

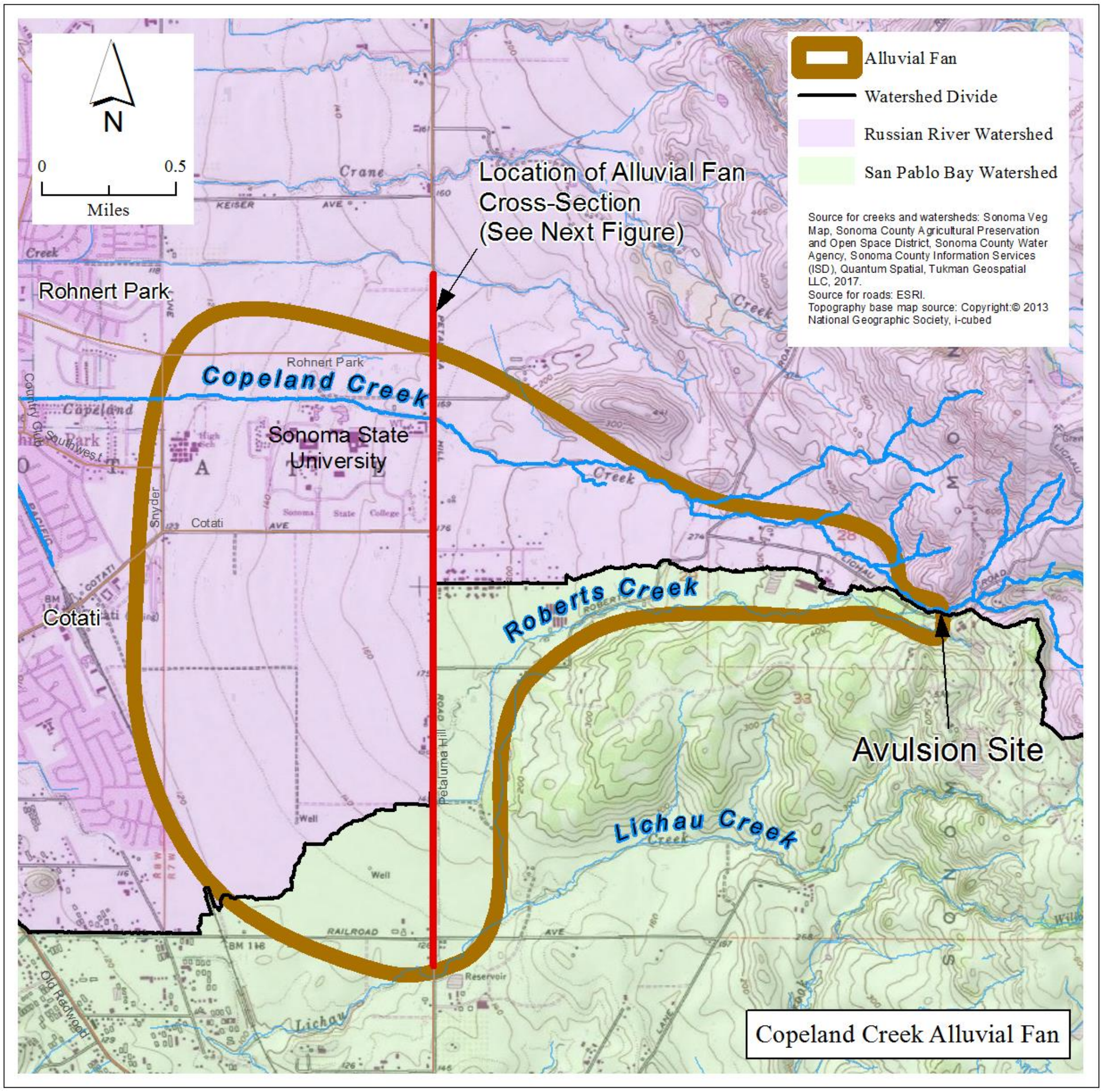


Figure 4 – Topographic map showing alluvial fan (highlighted in brown)

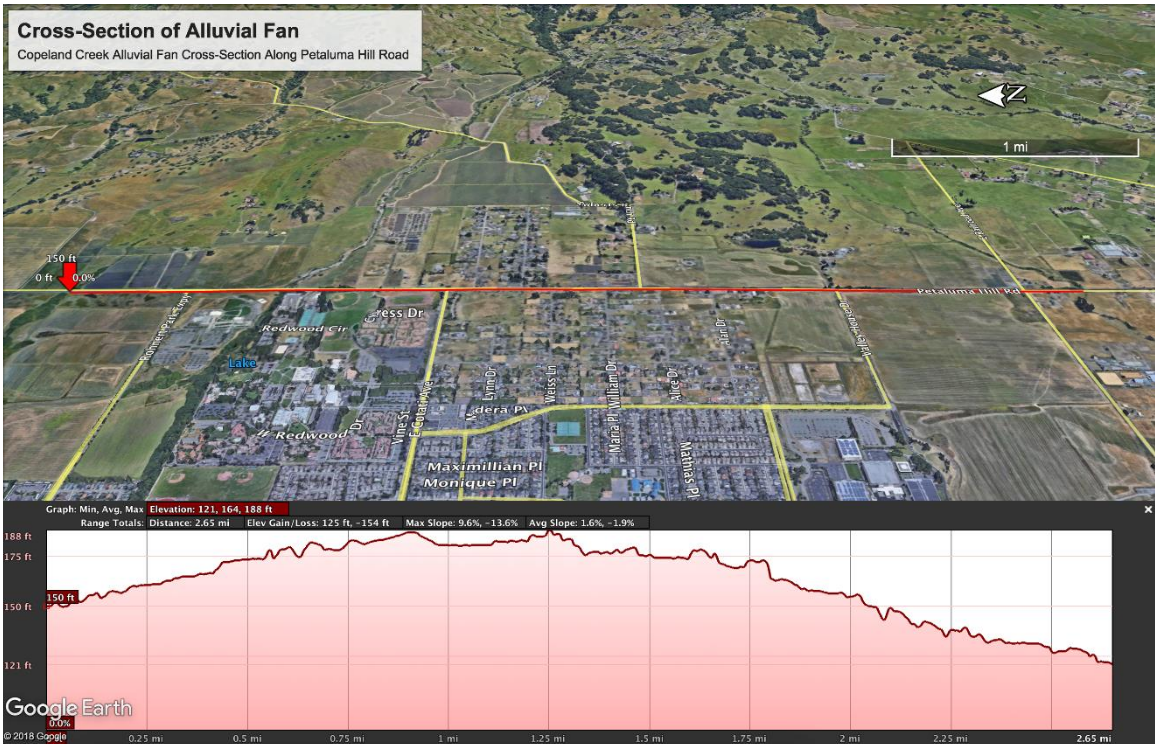


Figure 5 - Cross-section along Petaluma Hill Road of Copeland Creek alluvial fan

Due to the large sizes of the entrained material from the headwaters of Copeland Creek, mostly large cobbles and small boulders, the streambed has become armored in the alluvial fan reach, which acts to protect the streambed (SRCD 2004). When high flows events occur, the creek is unable to incise the streambed, and instead scours and overtops the banks, widening them and flooding downstream areas. Dawson and Sloop (2010) note that Bowers (1867), Cardwell (1958), and Cook (2010) suggested that this process also caused Copeland Creek to switch watersheds, sometimes draining into the Russian River Watershed, and other times draining into the San Pablo Bay watershed. This is illustrated in Bowers' 1866 "Map of Sonoma County" (Figure 6), where Copeland Creek is shown bifurcating at or near the avulsion site, flowing both west, as part of the Russian River watershed, and south, as part of the San Pablo Bay watershed. Interestingly, Cardwell (1958) mentions that according to "unconfirmed local reports," Copeland Creek formerly was tributary to the San Pablo Bay watershed, but during early development was channeled to the Laguna de Santa Rosa to "improve local drainage conditions" (Dawson and Sloop 2010).

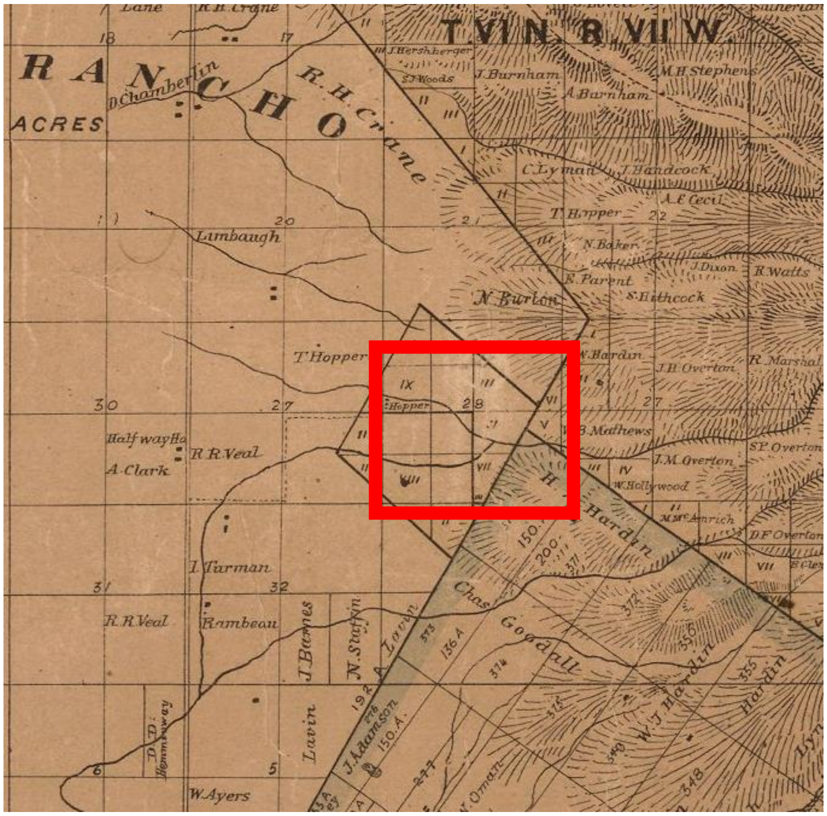


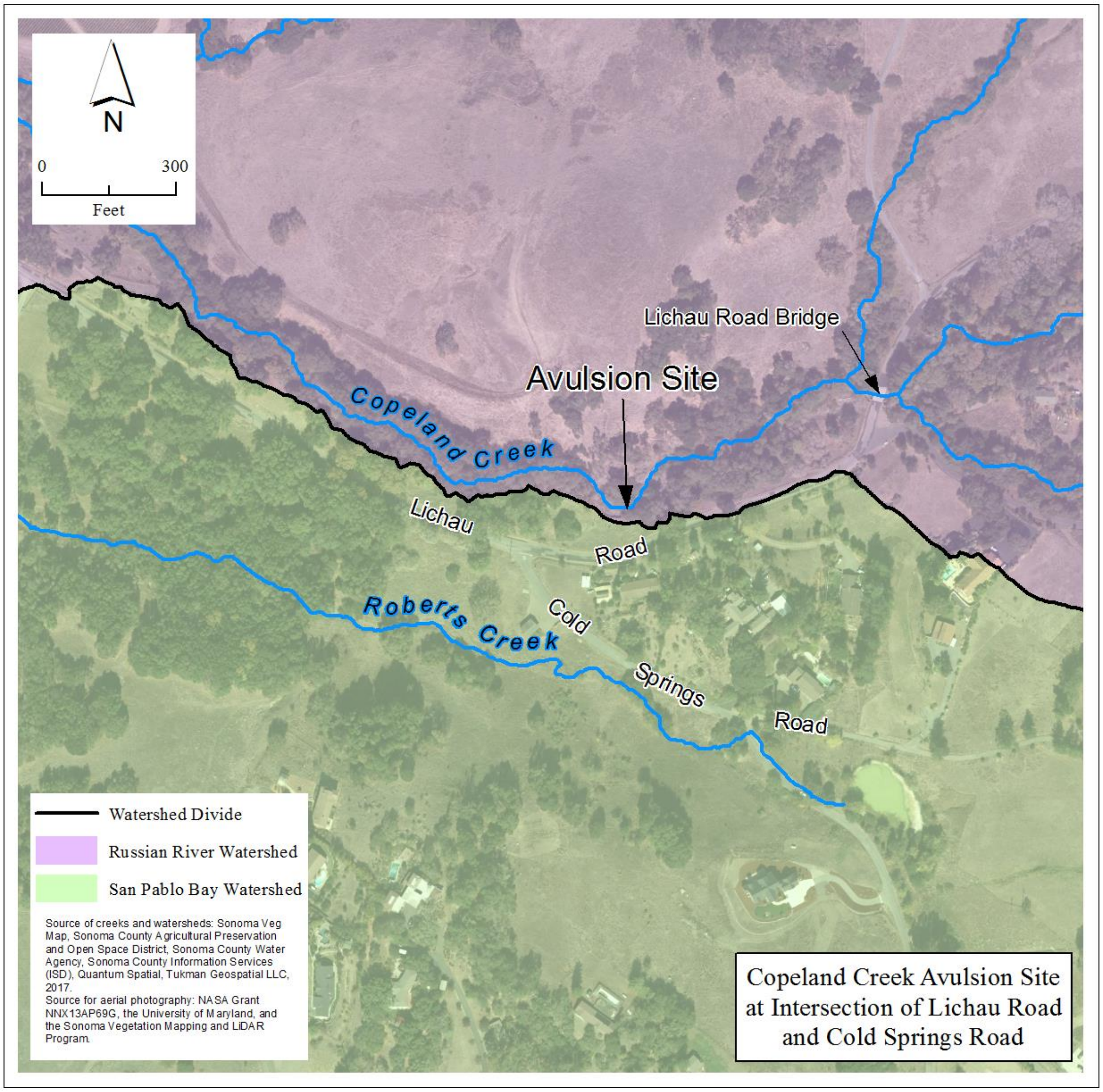
Figure 6 - Excerpt from Bowers (1866) showing Copeland Creek splitting into two drainages, one flowing west (Russian River watershed) and the other flowing south (San Pablo Bay watershed)

The Copeland Creek avulsion site

Flooding becomes a natural hazard when it interfaces with human settlements, where it can cause extensive property damage and loss of life, and can become a natural disaster. Alcántara-Ayala (2014) describes natural disasters as:

> “a suddenly [*sic*] disequilibrium of the balance between the forces released by the natural system and the counteracting forces of the social system. The severity of such disequilibrium depends on the relation between the magnitude of the natural event and the tolerance of human settlements to such an event.”

Historically, Copeland Creek has jumped its bank at Lichau Road during high precipitation events, flooding adjacent and downslope houses, farms, and ranches. Additionally, it is believed that flood waters crossing Lichau Road enter Roberts Creek just 350 feet to the south (Figure 7). This is particularly significant because Roberts Creek is a tributary to Lichau Creek, which flows into the Petaluma River; meaning that when Copeland Creek floods at Lichau Road, it jumps to a different watershed (San Pablo Bay) entirely. During an atmospheric river event in 2017, Copeland Creek jumped its bank at the avulsion site, flooding Lichau Road. Lichau Road is the only throughway for a neighborhood upslope of the avulsion site, so the avulsion of Copeland Creek left residents stranded in their homes or unable to get home. These flood waters then caused damage to houses downslope, where it was reported that some houses and properties were flooded by half a foot of water (Colby Accacian, Online Survey, November 29, 2017). The influx of water from Copeland Creek entering Roberts Creek tributary to the Petaluma River is believed to cause flooding in Penngrove and Petaluma at a mobile home park and the Petaluma Auto Mall (Brown 2017). The 2017 flood event at Lichau road has led to community organization to address the issue (County of Sonoma Public Affairs 2017).



Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

Copeland Creek Avulsion Site
at Intersection of Lichau Road
and Cold Springs Road

Figure 7 - Copeland Creek Avulsion Site

Methods

An online survey of residents identified by the SCWA as living near Copeland Creek was conducted to identify the impacts Copeland Creek flooding has on the community. In addition, a two-dimensional (2D) hydraulic model using HEC-RAS version 5.0.3 was developed to understand the conditions that cause Copeland Creek to flood its banks and where overbank flow travels. The modeled results are mapped to show flood inundation extent and depth for each peak flow scenario.

Online survey

To assess the impact of Copeland Creek overbank flow and flooding, an online survey of nearby residents was conducted using Google Forms. Using an e-mail database from the SCWA, a hyperlink to the survey was sent to seventy-four members of the community living adjacent to or near Copeland Creek, and mainly constituted residents from Penngrove, but included some residents from Rohnert Park and Petaluma. Residents were asked where they observed flooding from Copeland Creek during the January 8, 2017 storm event, the approximate depth of flood, a description of the flooding, associated property damage costs (if any), and the number of days they were affected by the incident. They were then allowed to answer the same questions with regard to any other flood events they had observed or experienced in the past. Lastly, respondents were asked to provide a rank of affectedness from flooding caused by Copeland Creek on a scale from 1 to 5, with 1 being no impact and 5 being severe impact. In addition to identifying societal impacts from Copeland Creek flooding, the online survey aided the calibration of the two-dimensional hydraulic model, discussed next.

Two-dimensional hydraulic model

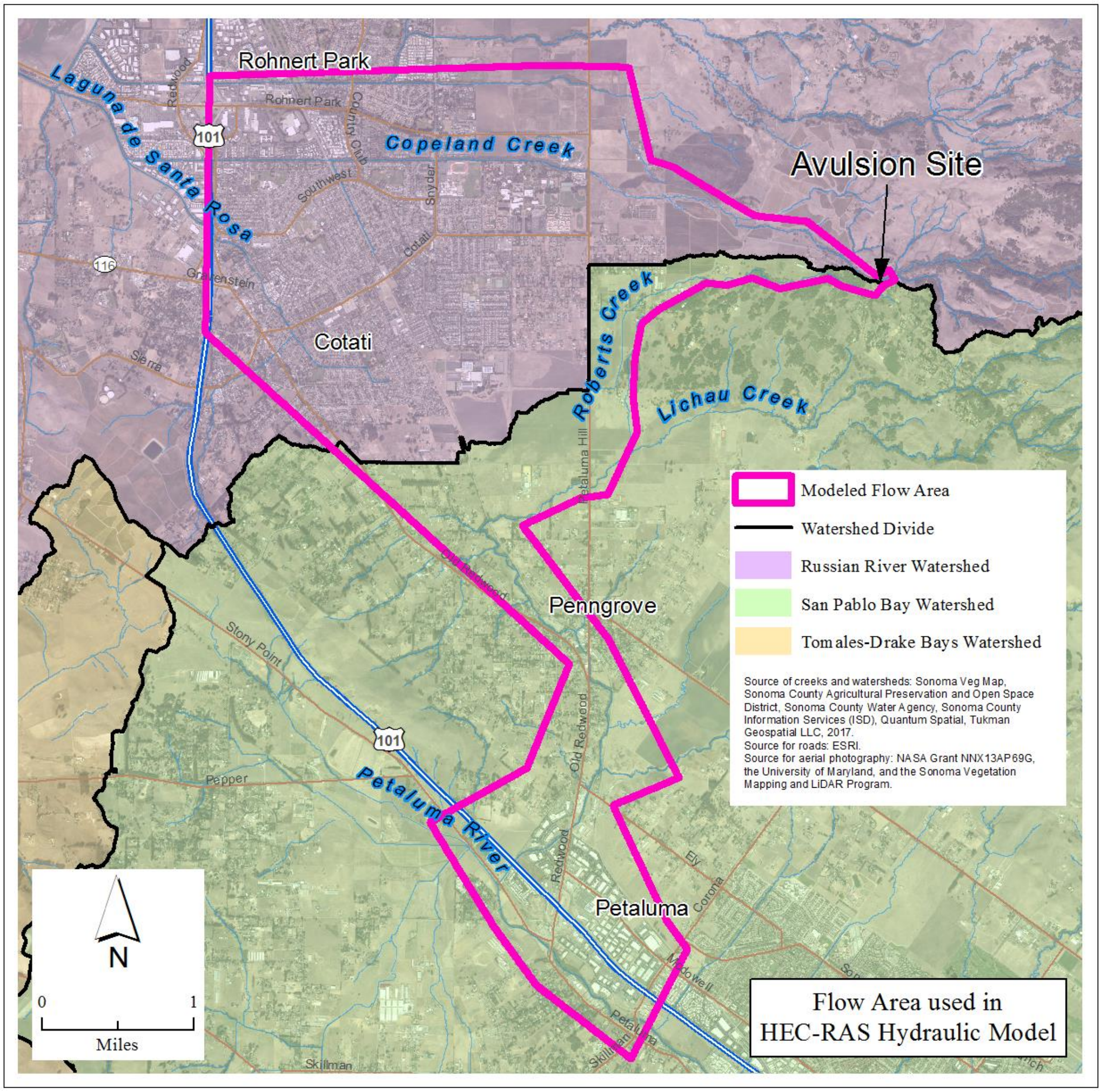
A two-dimensional hydraulic model was created using HEC-RAS version 5.0.3 hydraulic modeling software. The model used 1-, 2-, 10-, 25-, 50-, and 100-year return interval peak flows to ascertain when Copeland Creek overbank flooding occurs, and where overbank flow travels. A two-dimensional model differs from the classic one-dimensional model in that flows are not relegated to occur perpendicular to a cross-section; rather, in a two-dimensional model, flows can travel in any direction, which makes it better suited for modeling inundation from overbank flows. A two-dimensional model uses a computational flow area to define the domain that is to be modeled. Individual cells are then computed based on cell size for the domain, and each cell is used by the model to solve the 2D Diffusion Wave set of equations which describe the movement of surface water flow. Model inputs consist of elevation data, surface roughness coefficients (Manning's *n*), identification of flow area to be computed, and boundary conditions. Responses from the online survey were reviewed and analyzed to check the accuracy of the model, and to understand impacts from Copeland Creek overbank flow. Each of these will be discussed, in turn, below.

Elevation data The primary data source of a two-dimensional model is a digital elevation model (DEM). This study utilizes data from the Sonoma County LiDAR and Vegetation Mapping Consortium (Sonoma Veg Map) and NASA, who contracted a Light Detection and Ranging (LiDAR) flight by Watershed Sciences, Inc. for purposes of vegetation mapping, planning, and resource management (Sonoma Veg Map 2016). Elevation data was collected by aircraft over the course of two months in 2013. The LiDAR point cloud data has a vertical accuracy at 95 percent confidence of 0.17 feet. The point cloud data was then converted to a gridded digital elevation model (DEM), with a resolution of each grid cell being three feet by three feet, which represents an average elevation for that area. LiDAR maps the surface of the earth, however, bridges and culverts are not “seen” in this dataset, so any water flow would be obstructed by road crossings, for example. To mitigate this, the data was then further processed to create hydrologically connected dataset, which “burns in” culverts and road crossings with true elevations to allow for continuous surface water flow. According to Sonoma Veg Map (n.d.) this hydro-enforced DEM is a suitable for modeling surface water flows.

Surface roughness The roughness of Earth’s surface is a primary consideration in the equations that model surface water flows. Surface roughness coefficients are the mathematical representation of various land cover types, described as “Manning’s *n*.” This study utilizes the National Land Cover Database (NLCD) for 2011 to identify land cover at a spatial resolution of ~98 feet, meaning each 98’ x 98’ grid cell is ascribed one land cover type value, such as “deciduous forest,” “grassland,” or “developed” (Homer et. al. 2015). Manning’s *n* coefficients were then assigned for each land cover type from data from the National Resources Conservation Service (NRCS 2016).

Flow area and computational mesh The flow area is a polygonal boundary which identifies the area that will be modeled in HEC-RAS. The flow area for this analysis begins at Copeland Creek just downstream of Lichau Bridge, and contains portions of east Rohnert Park, Penngrove, and Petaluma (Figure 8). Model computation runtime is a factor of flow area, computational mesh cell size, and computational time step. The computational flow area was defined to cover the areas that were thought to possibly receive Copeland Creek overbank flow, and generally follows high topography where floodwaters are not believed to reach. The flow area was delineated such that it would capture Copeland Creek overbank flow to the furthest downstream extent possible while also considering model run time – as the flow area increases, so too does model run time.

As stated previously, the goal of this study is to identify the conditions that causes Copeland Creek to avulse and identify the flow path of the overbank flow.

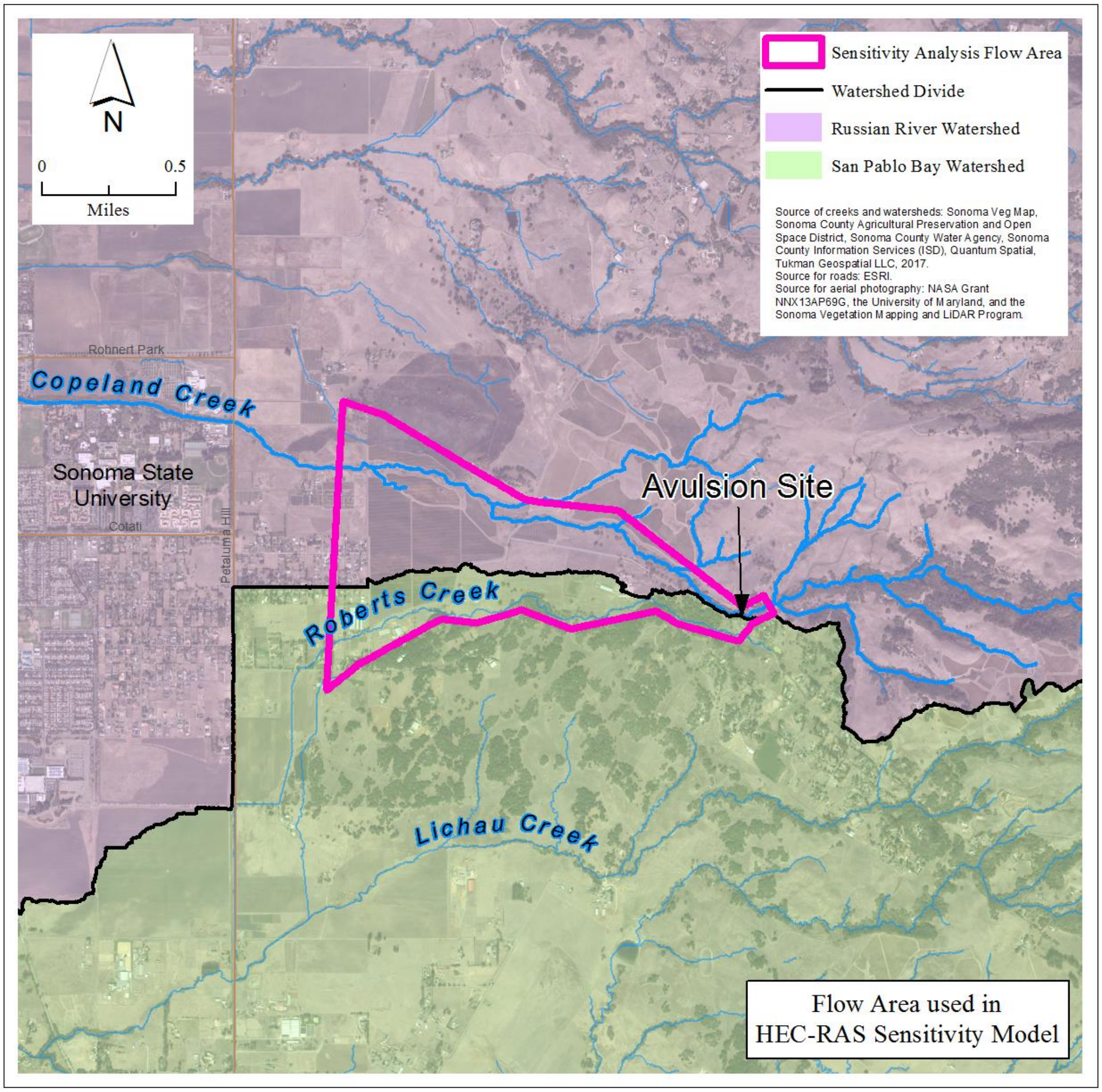


Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

Flow Area used in HEC-RAS Hydraulic Model

Figure 8 – Flow area used in HEC-RAS hydraulic model, which defines the spatial extent of the model

A sensitivity analysis was performed to determine the computational mesh cell size. The sensitivity analysis modeled Copeland Creek flows at Lichau Bridge utilizing a 25-year storm event (described later), encompassing the area downstream to just east of Petaluma Hill Road (Figure 9). The sensitivity model was run for 100-foot cell size, 50-foot cell size, 20-foot cell size, and 5-foot cell size. After review of the output and considering computational time, 20-foot cell size was determined to be the best balance of detail and model runtime, resulting in a total of over 778,000 computational mesh cells within the flow area.



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Source for roads: ESRI.
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Figure 9 - Test flow area used for sensitivity analysis

Each face of a computational mesh cell is analogous to a cross-section, utilized by HEC-RAS to determine terrain elevation and water surface elevation. Accurate stream bank elevations are critical in ensuring Copeland Creek streamflow is correctly modeled when (and if) flows over-top stream banks. If a computational mesh cell straddles a stream bank, it may not capture the highest elevation of the bank. This may allow the creek to “leak” when river stage height exceeds the stream bank height as captured by the misaligned computational mesh cell. To ensure stream bank elevations were correctly captured in the computational mesh, breaklines were manually added along stream banks (and some road ways), along Copeland Creek, Roberts Creek, Lichau Creek, and Petaluma River (Figure 10). This resulted in cell faces that align with the breaklines, ensuring stream bank elevations are more accurately captured in the model.

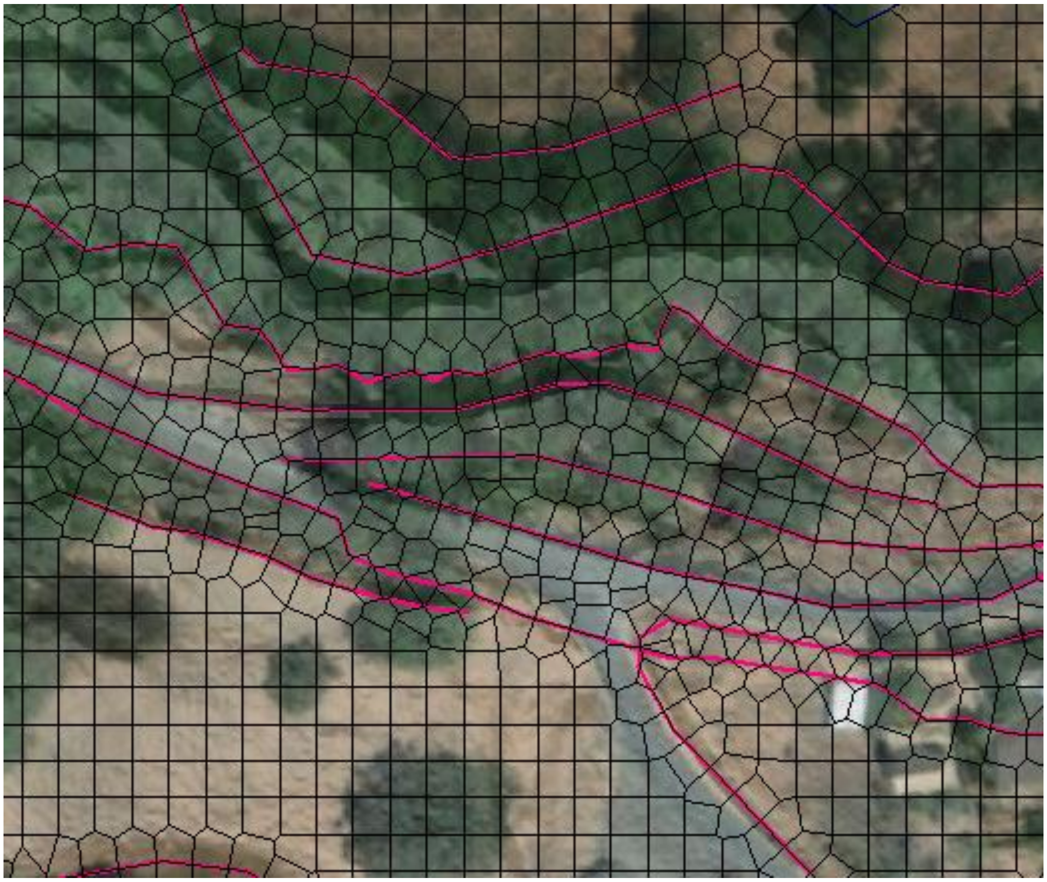


Figure 10 - Subset of breaklines (pink lines) added to reorient cell faces to capture stream banks

Boundary conditions and streamflow data Boundary conditions identify the locations of inflow into Copeland Creek (upstream boundary condition) and outflow out of the domain (downstream boundary condition). The upstream condition was identified as the location on Copeland Creek just downstream of Lichau Road Bridge but upstream of the avulsion site. This boundary condition is the independent variable in each model run, and is the “inlet” in which each of the return interval peak flow hydrographs—explained in detail next—enter the model.

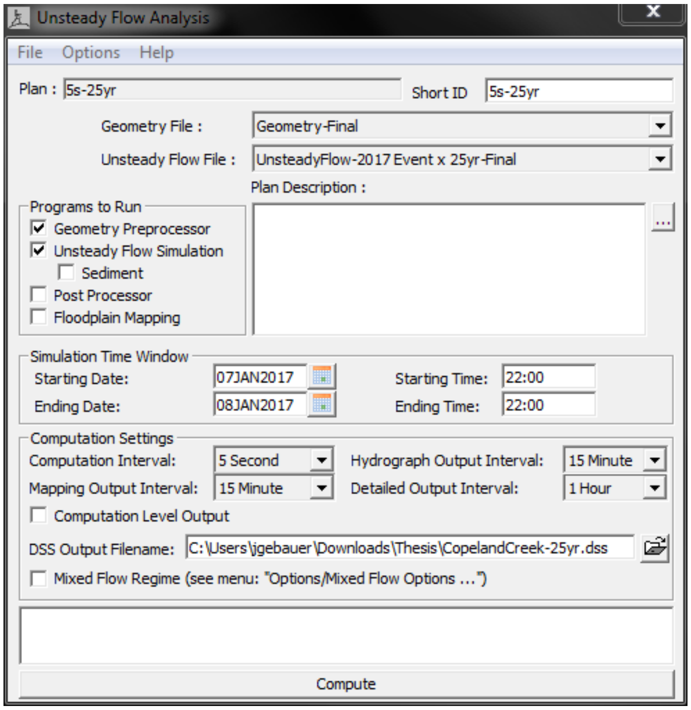
As previously shown in Table 1, peak flows for 2-year, 10-year, 25-year, 50-year, and 100-year return periods were modeled with HEC-HMS at this location (GHD 2017). The upstream boundary condition in this model uses a flow hydrograph to route streamflow through Copeland Creek. Unfortunately, the HEC-HMS flow hydrographs for each peak flow modeled by GHD were not available. To construct the flow hydrograph, 15-minute streamflow data was downloaded at the USGS Gage #11465660, Copeland Creek at Rohnert Park, CA. This streamgage is located approximately 4.2 miles downstream (west) of the avulsion site. Fifteen-minute flow data for the January 8, 2017 storm event was selected as the basis for the upstream boundary condition flow hydrograph. Fifteen-minute flow data from midnight January 7 to 10:15 am January 9 was adjusted by the ratio of the peak flow registered at the Copeland Creek streamgage to that of the peak flow for a given return interval modeled by GHD. Specifically, the peak flow from January 7 to January 9 was recorded at the Copeland Creek streamgage as 649 cfs, and occurred at 7:45 am on January 8. As such, 7:45 am was set to be the peak flow for each return interval flow hydrograph, and all 15-minute recorded data at the Copeland Creek streamgage was adjusted by multiplying by the ratio of the return interval peak flow to 649 cfs (Table 2). In other words, the Copeland Creek streamgage was used as a dimensionless unit hydrograph, providing the timing of flows at the upstream boundary condition.

Date and Time	**USGS Station #11465660 Discharge (cfs)**	**1 Year Peak Flow Modeled Discharge (cfs)**	**2 Year Peak Flow Modeled Discharge (cfs)**	**10 Year Peak Flow Modeled Discharge (cfs)**	**25 Year Peak Flow Modeled Discharge (cfs)**	**50 Year Peak Flow Modeled Discharge (cfs)**	**100 Year Peak Flow Modeled Discharge (cfs)**
01/08/2017 07:00 PST	614	653.99	947.93	1685.13	2137.09	2486.67	2834.09
01/08/2017 07:15 PST	635	676.36	980.36	1742.77	2210.18	2571.72	2931.02
01/08/2017 07:30 PST	639	680.62	986.53	1753.74	2224.10	2587.92	2949.48
01/08/2017 07:45 PST	649	691.27	1001.97	1781.19	2258.91	2628.42	2995.64
01/08/2017 08:00 PST	646	688.07	997.34	1772.96	2248.47	2616.27	2981.79
01/08/2017 08:15 PST	631	672.10	974.18	1731.79	2196.26	2555.52	2912.56
01/08/2017 08:30 PST	606	645.47	935.58	1663.18	2109.24	2454.27	2797.16

Table 2 - Subset of Copeland Creek flows recorded at USGS streamgage in Rohnert Park, and modeled peak flow discharge. The yellow cell is the peak flow recorded at the USGS streamgage for the January 8, 2017 storm event, and the green highlighted cells are the HEC-HMS modeled peak flows (GHD 2017)

Downstream boundary conditions located along Highway 101, Copeland Creek at Highway 101, the Petaluma River and the adjacent floodplain used the “normal depth” scenario and were based on the average slope of the landscape or channel across the edge of the flow area. If no downstream boundary condition is identified, the model treats the edge of the flow area as an impediment to flow. The “normal depth” downstream condition informs the model that the location identified is not an impediment to flow, and that any flows should be modeled to traverse across the boundary based on the slope ascribed.

Model parameters After the terrain model was built from the LiDAR hydro-enforced DEM, the flow area identified, and computational mesh constructed with breaklines, and boundary condition locations identified and configured, all model inputs were complete and the final model computational parameters were assigned (Figure 11). Computation interval, also known as the computational time step, was selected based on a sensitivity analysis, utilizing the same method and flow area as described for the computational mesh sensitivity analysis (Figure 9). According to Mary Grace Pawson, Rohnert Park City Engineer, the January 8, 2017 event was a 25-year peak flow event (personal communication, Upper Copeland Creek Watershed Tour, December 2, 2017). Therefore, the 25-year peak flow hydrograph was selected for the sensitivity analysis, as it provided a direct method for discriminating the sensitivity analysis results using respondent survey data.



Plan : 5s-25yr
Short ID 5s-25yr
Geometry File : Geometry-Final
Unsteady Flow File : UnsteadyFlow-2017 Event x 25yr-Final
Plan Description :

Programs to Run
☑ Geometry Preprocessor
☑ Unsteady Flow Simulation
  ☐ Sediment
☐ Post Processor
☐ Floodplain Mapping

Simulation Time Window
Starting Date: 07JAN2017
Starting Time: 22:00
Ending Date: 08JAN2017
Ending Time: 22:00

Computation Settings
Computation Interval: 5 Second
Hydrograph Output Interval: 15 Minute
Mapping Output Interval: 15 Minute
Detailed Output Interval: 1 Hour
☐ Computation Level Output
DSS Output Filename: C:\Users\jgebauer\Downloads\Thesis\CopelandCreek-25yr.dss
☐ Mixed Flow Regime (see menu: "Options/Mixed Flow Options ...")

Figure 11 - Example of model parameters prior to model simulation

The model was run for computational time steps of 1-minute, 30-seconds, 10-seconds (collectively "large time steps"), 5-seconds, and 1-second ("small time steps"). Results for large time steps were shown to be inaccurate; for example, floodwater depths in the floodplain south of Copeland Creek (between Copeland Creek and Roberts Creek) were shown to range from 15 feet for the 10-second time step to over 35 feet for the 1-minute time step (Figure 12). These depths are more than an order of magnitude higher than the depths reported from the online survey (discussed later) during the 25-year peak flow flood event on January 8, 2017. Moreover, the inconsistency in the resulting extents of inundation and water depths between each of the larger time steps suggest that none of these time steps are able to accurately model the test scenario. Conversely, the small time steps resulted in a convergence of modeled results, with only very slight differences between them related to inundation extent, but identical inundation depths where the two results were coincident (Figure 12). The flood extent differences were deemed minimal and insignificant, and therefore a 5-second time step was selected for the full model run. Selecting a 1-second or sub-second time step would result in significantly longer computation time, with little increase in model accuracy.

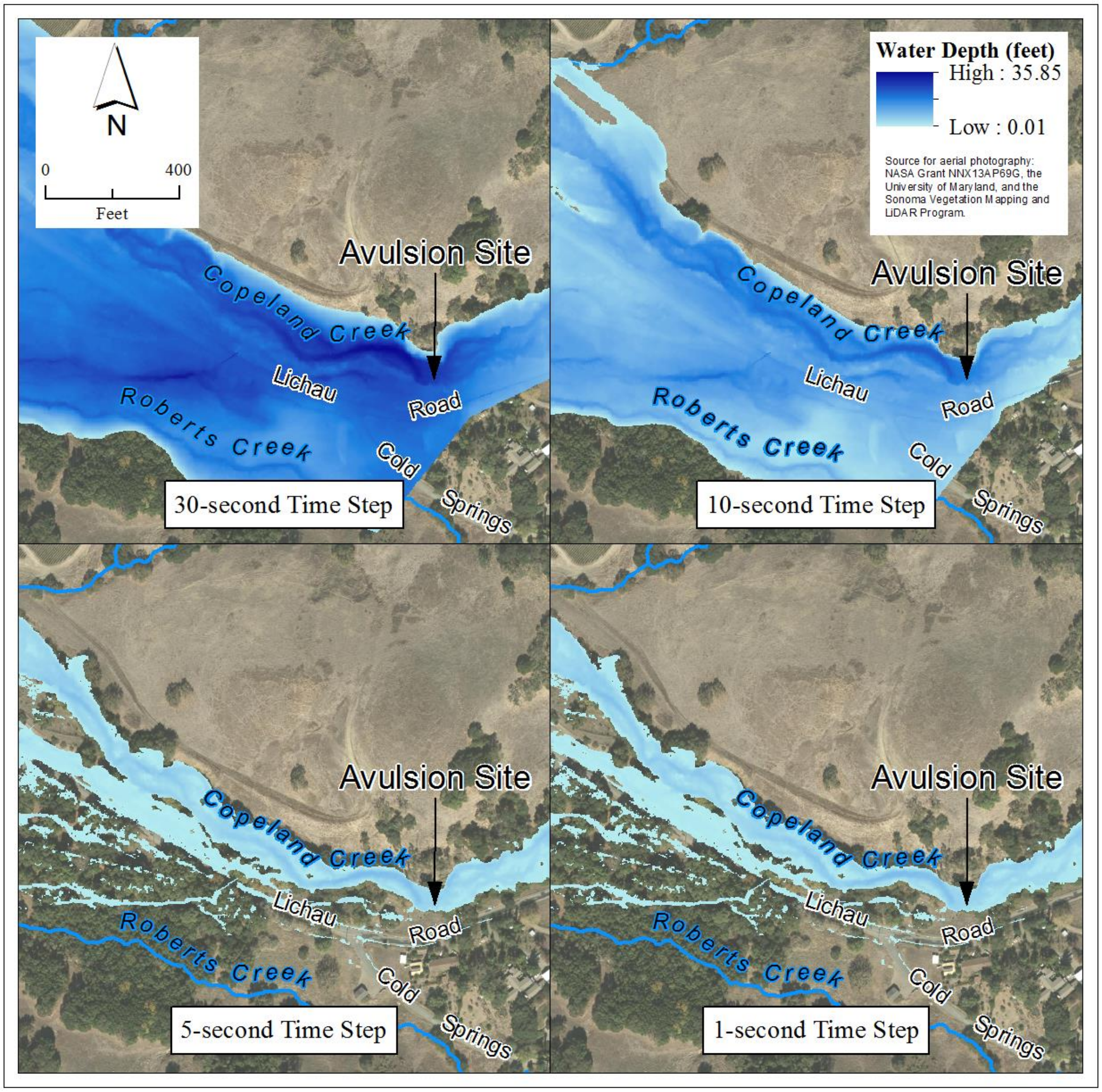


Figure 12 - Sensitivity analysis results of water depths for 30-second (top left), 10-second (top right), 5-second (bottom left), and 1-second (bottom right) computational time steps

The model was run for a 24-hour period, from 10:00 pm January 7 to 10:00 pm January 8. This time period was selected because it encompasses the peak flows from the 2017 flow hydrograph at the USGS Copeland Creek streamgage. Additionally, the HEC-HMS modeled peak flows (GHD 2017) represent peak flow in a 24-hour period. As previously described, the gaged flow data was used simply for the flow curve to approximate flow timing over a 24-hour period. The model was run once for each peak flow event, for a total of six model runs. Model run times ranged from just over three hours for the 1-year peak flow run, to over fifteen and a half hours for the 100-year peak flow run. Total model run time for all six model runs was just over sixty-two and a half hours on a Windows 7 64-bit computer with an Intel Xeon E5-1660 CPU and 64GB of RAM.

Results

Online survey

The online survey resulted in eleven responses, equating to a response rate of about 15 percent. All respondents answered questions relating to the January 8, 2017 event. Nine of the eleven responses about this flood event reported flooding on Lichau Road between Roberts Road and the Lichau Road bridge crossing, and of those, six were specific to the area at the intersection of Lichau Road and Cold Springs Road, which is located just south of the avulsion site. Reported floodwater depths at this location ranged from 0.5 feet to 2 feet. As stated in the previous section, the survey responses for January 8, 2017 flood event near the avulsion site were used as a discriminating tool in the calibration of the model. Ten of the eleven respondents noted they were affected by the January 8, 2017 flooding of Copeland Creek for at least one day, with one respondent stating they were affected for three days, and another respondent stating they were affected for four days.

One respondent reported flooding from the January 8, 2017 event of 3 to 4 feet deep near Old Redwood Highway and East Railroad Avenue (Figure 13). The respondent provided pictures of the flooding (Figure 14), which clearly shows heavy inundation of a property, and stated the flood resulted in the incurrence of $32,000 in property damages. No other respondents reported property damages from any Copeland Creek flood events.

Figure 13 - Location of avulsion site and flooding near Old Redwood Highway and East Railroad Avenue

Figure 14 - Flooding near Old Redwood Highway and East Railroad Ave, January 8, 2017 (Source: Paul Efron)

Six respondents provided information for eight other flood events, listed in chronological order in Table 3. All eleven respondents answered a question which asked how impactful they felt flood events from Copeland Creek were to them, on a scale from 1 to 5, with 1 being no impact and 5 being severe impact. Nine of the eleven respondents (81 percent) said that they felt flooding from Copeland Creek had moderate to high impacts (Figure 15). No respondents stated that Copeland Creek flooding had no impact on them.

Date of Observed Flooding	Location of Flooding	Approximate Depth
1/10/1986	Lichau Road & Cold Springs Road	2 feet
1/1/2003	Lichau Road & Cold Springs Road	1/2 foot
12/31/2005	Lichau Road & Cold Springs Road	1.5 feet
5/1/2006	Lichau Bridge	1/4 foot
12/1/2015	3662 Lichau Rd	1.5 feet
1/20/2016	[Lichau Road &] Cold Springs Road	1/4 foot
1/19/2017	Chester Drive	2 feet
1/8/2018	Chester Drive	1-3 feet

Table 3 - Flood events other than January 8, 2017 flood noted by respondents

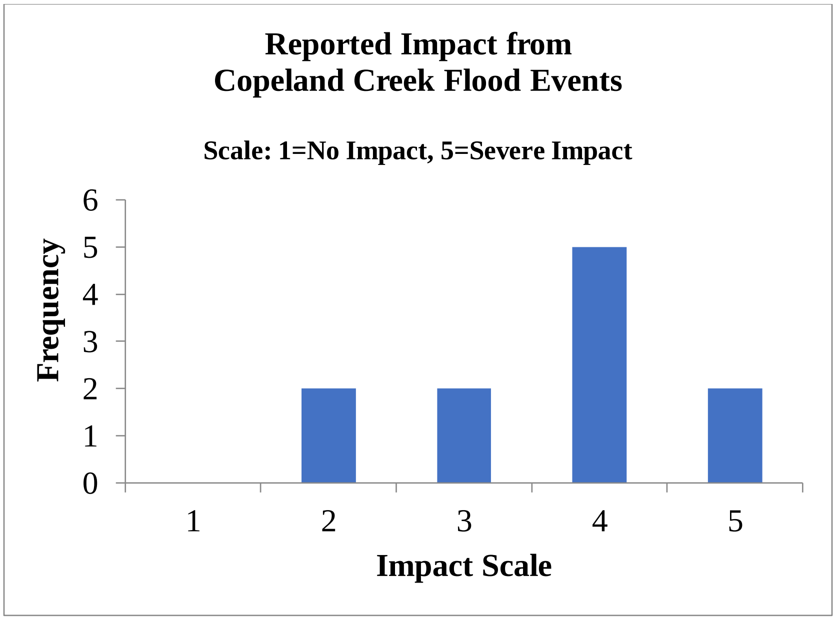
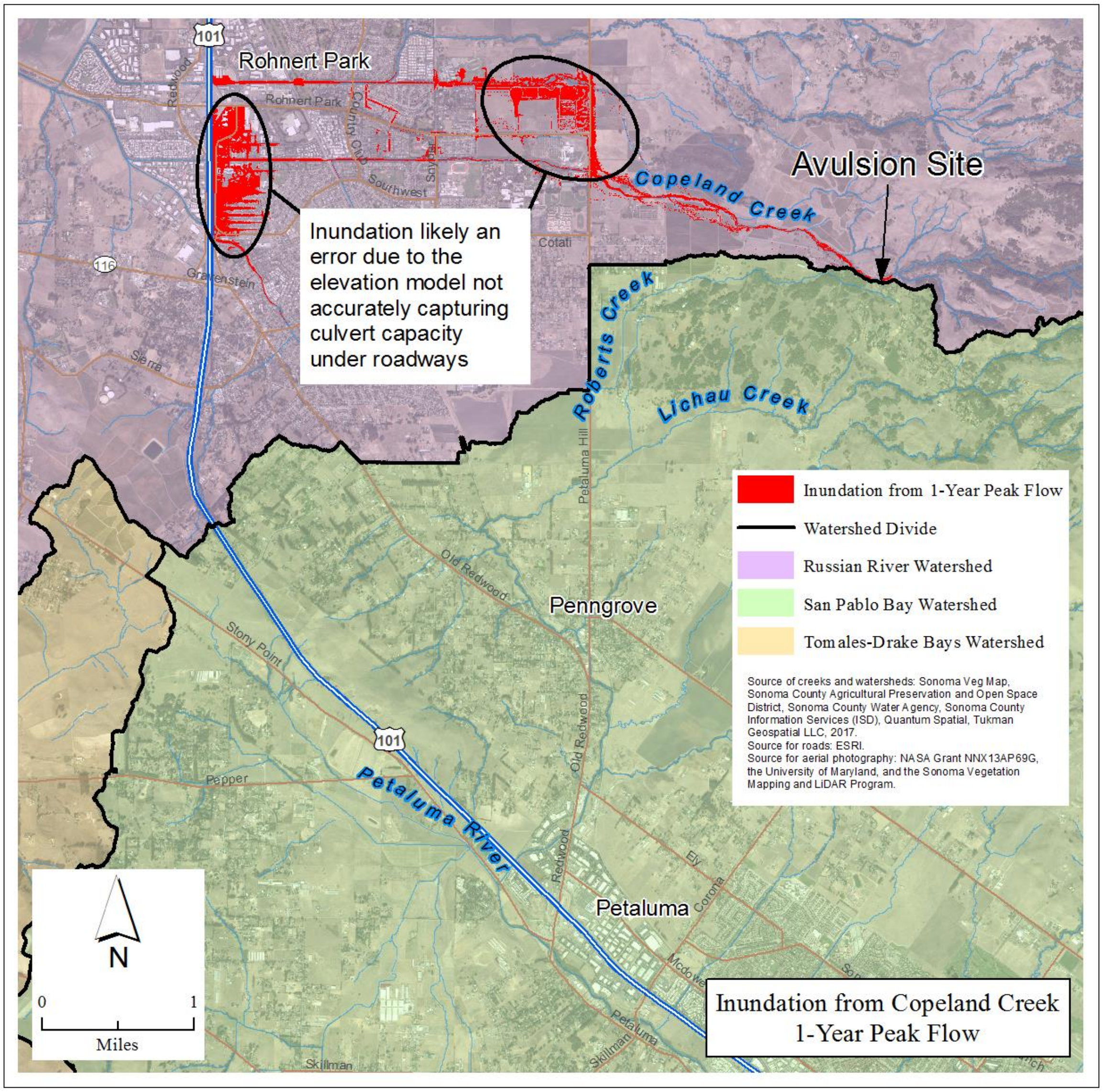


Figure 15 - Level of impact felt from Copeland Creek flooding

Model results

The HEC-RAS 2D hydraulic model results for 1-year, 2-year, 10-year, 25-year, 50-year, and 100-year peak flow events are shown below in Figures 16 through 21. Copeland Creek floodwaters from the avulsion, given the right storm conditions, can leave the Russian River watershed and enter the San Pablo Bay watershed. Overbank flow from Copeland Creek first travels across Lichau Road and the adjacent lands before entering Roberts Creek. Copeland overbank flow then travels through Roberts Creek to Lichau Creek, where it then enters the Petaluma River. The results suggest that Copeland Creek jumps its bank at the avulsion site when a storm that causes 10-year peak flow (or more) at the Lichau Road bridge crossing occurs (Figures 22 through 27). Modeled overbank flow from Copeland Creek contributes up to 1.7 feet to the river stage height of Lichau Creek near Penngrove from 10-year peak flows, up to 4.0 feet from 25-year peak flows, up to 4.5 feet from 50-year peak flows, and up to 5.2 feet from 100-year peak flows. Farther downstream, Copeland Creek overbank flow contributes to river stage height in the Petaluma River during 25-, 50-, and 100-year peak flows, adding up to 2.0 feet, 2.7 feet, and 2.9 feet respectively.

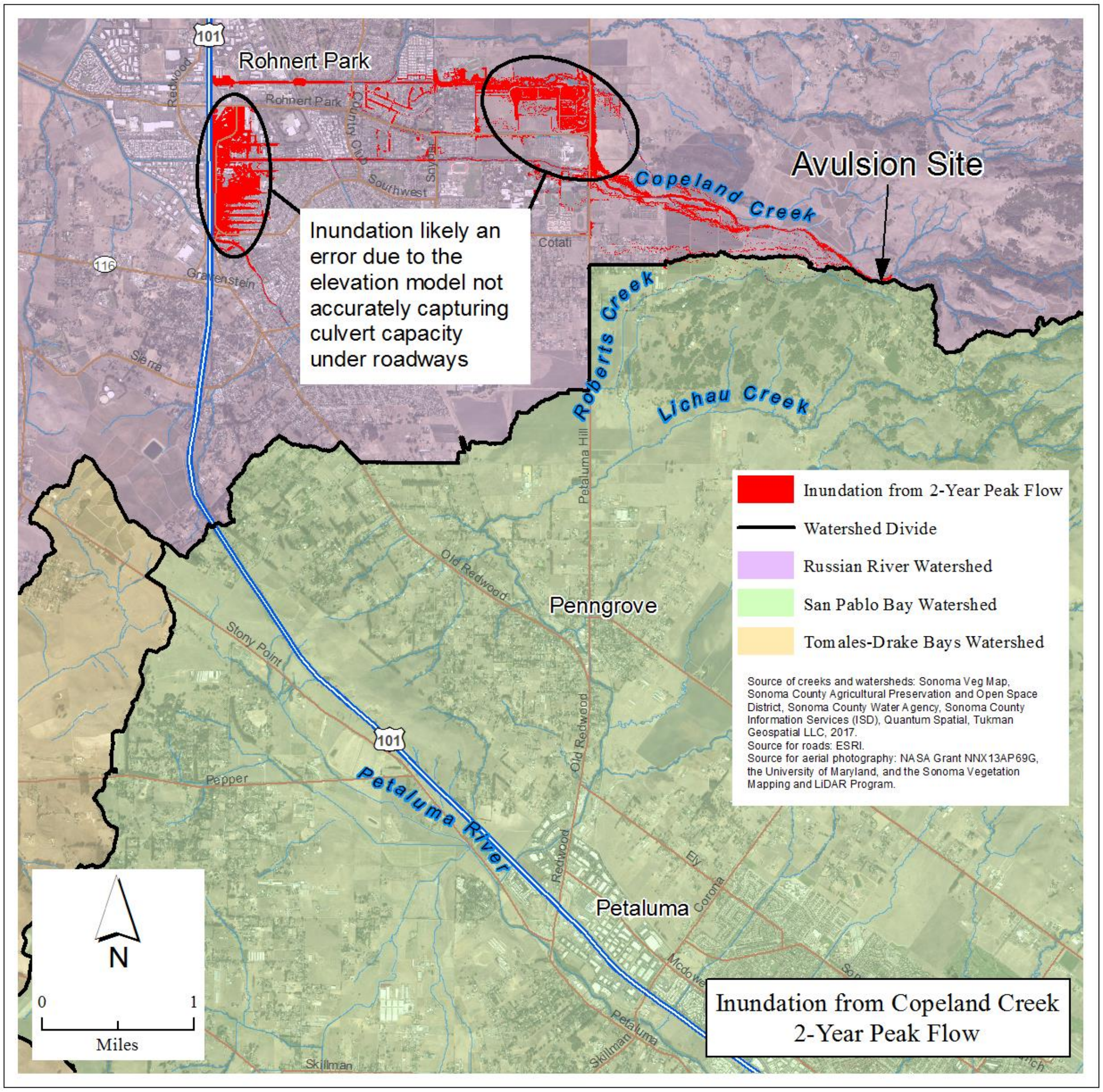
In addition to the results maps included here (Figures 16 through 27), an interactive map has been published online, accessible here: http://bit.ly/copelandflood This interactive map allows the user to display the inundation results for each peak flow that was modeled. Additionally, the user can selectively turn on and off layers, change base maps, and zoom in to an area of interest for a closer look.



Inundation likely an error due to the elevation model not accurately capturing culvert capacity under roadways

Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

Figure 16 - Inundation from 1-year peak flow

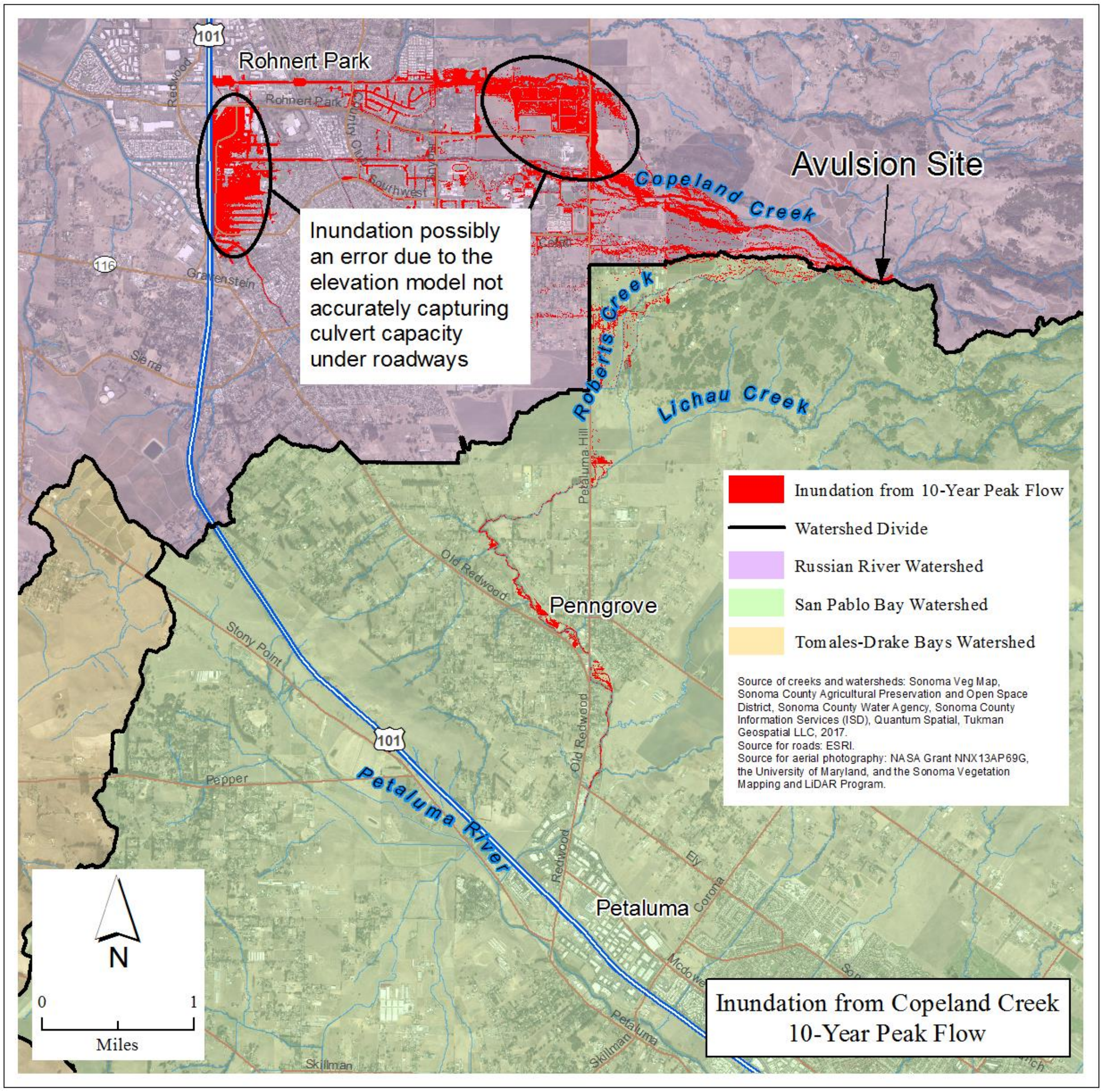


Inundation likely an error due to the elevation model not accurately capturing culvert capacity under roadways

Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

Inundation from Copeland Creek 2-Year Peak Flow

Figure 17 - Inundation from 2-year peak flow

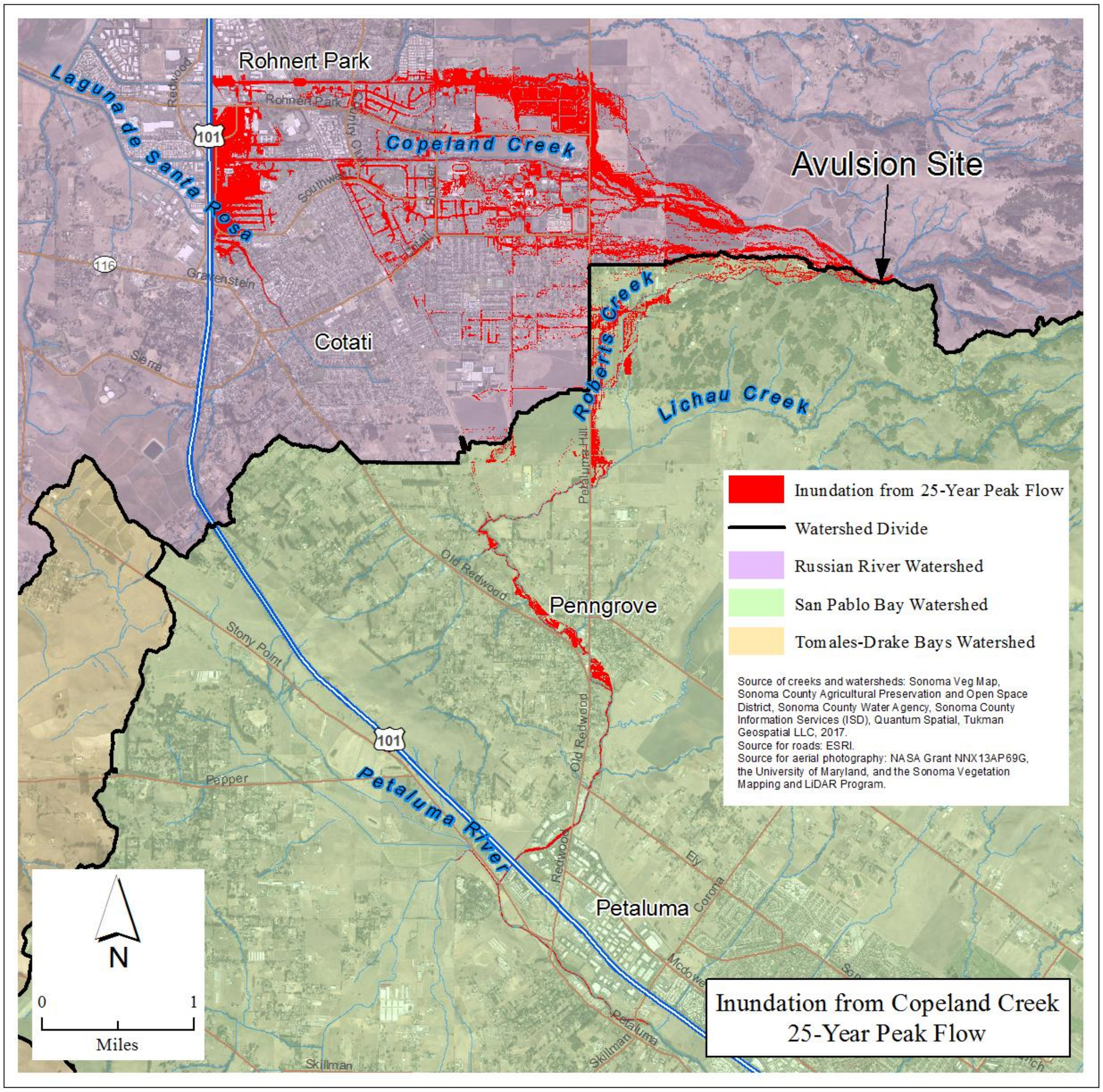


Inundation possibly an error due to the elevation model not accurately capturing culvert capacity under roadways

Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

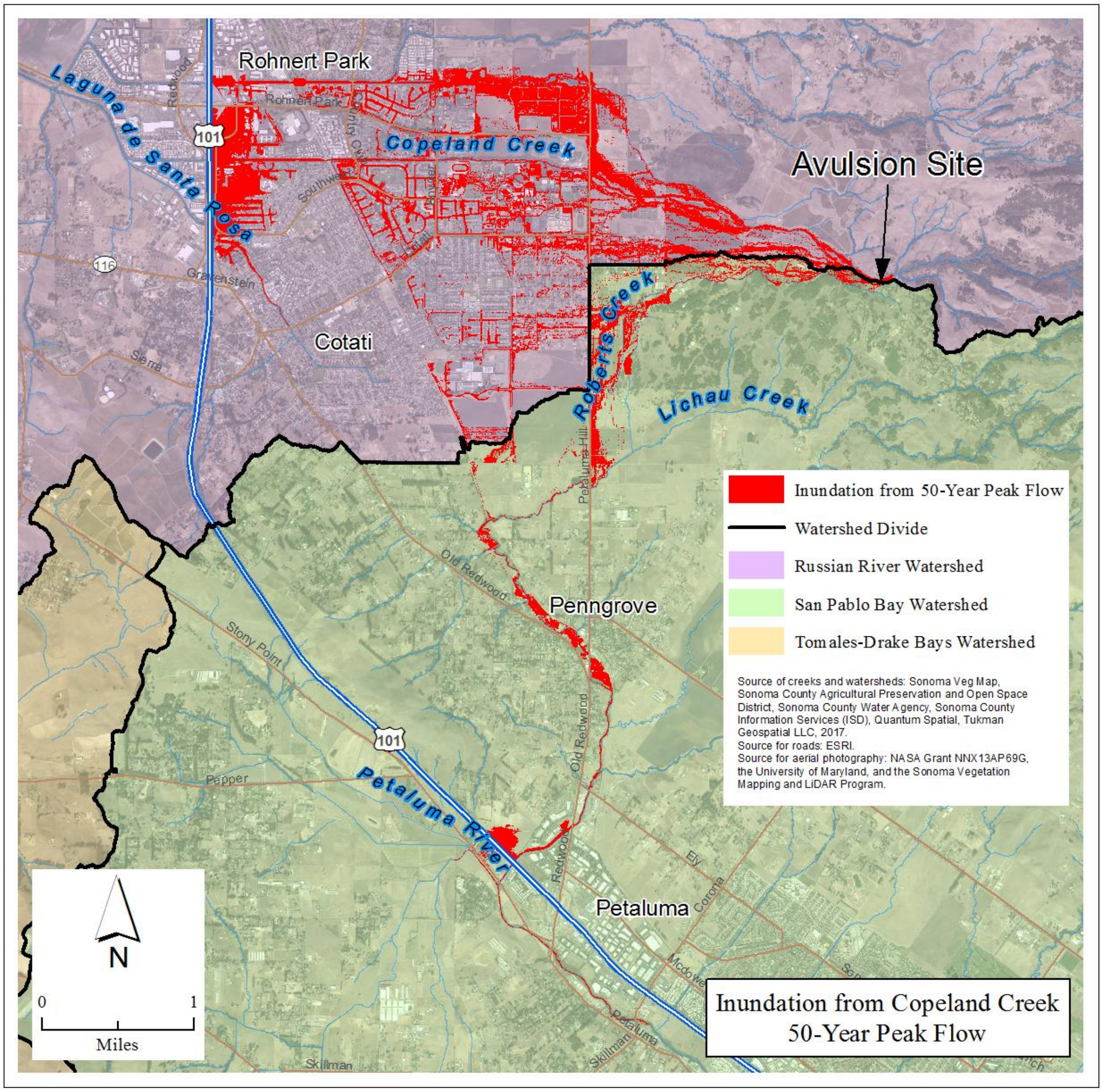
Inundation from Copeland Creek
10-Year Peak Flow

Figure 18 - Inundation from 10-year peak flow



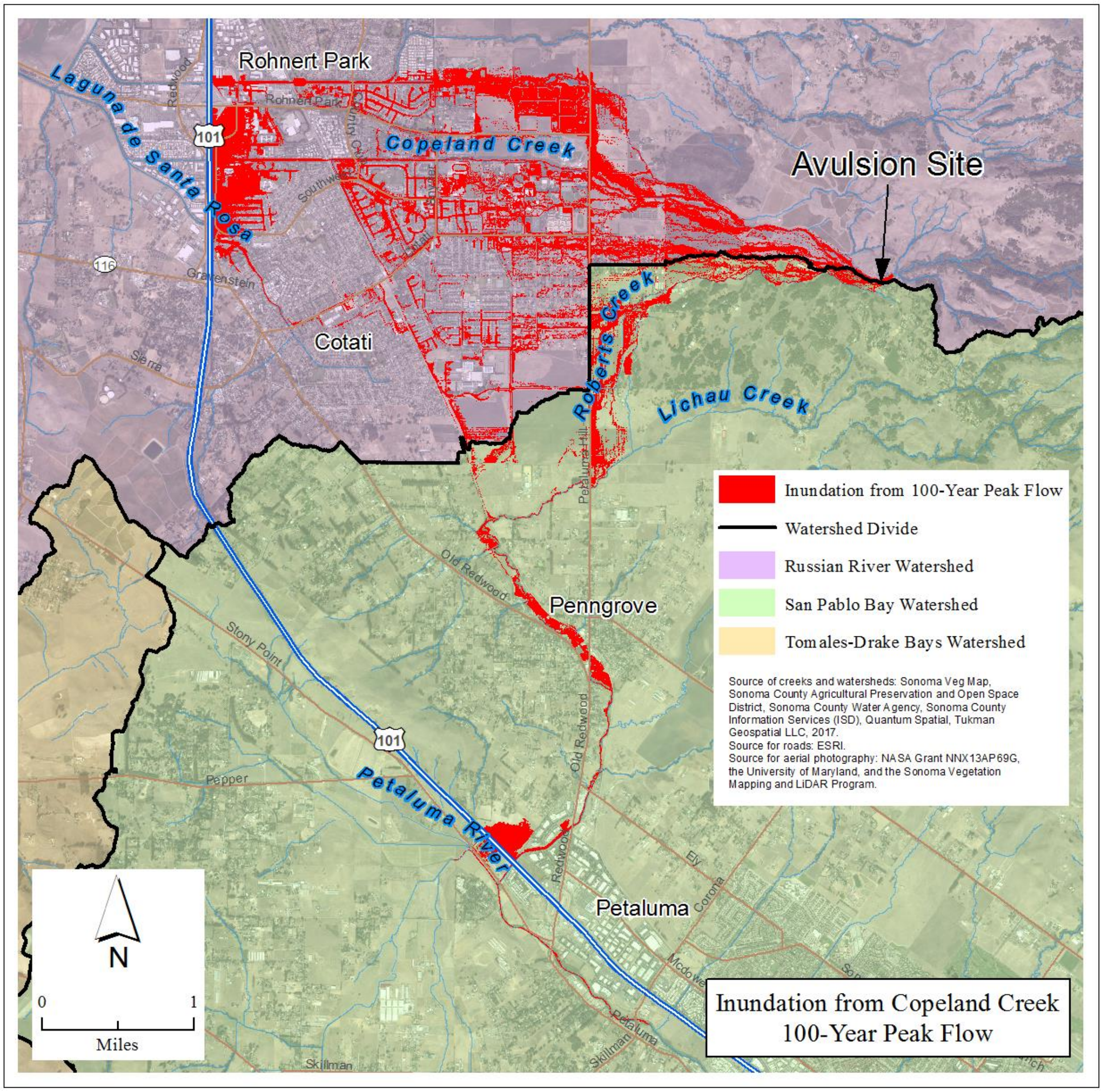
Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

Figure 19 - Inundation from 25-year peak flow



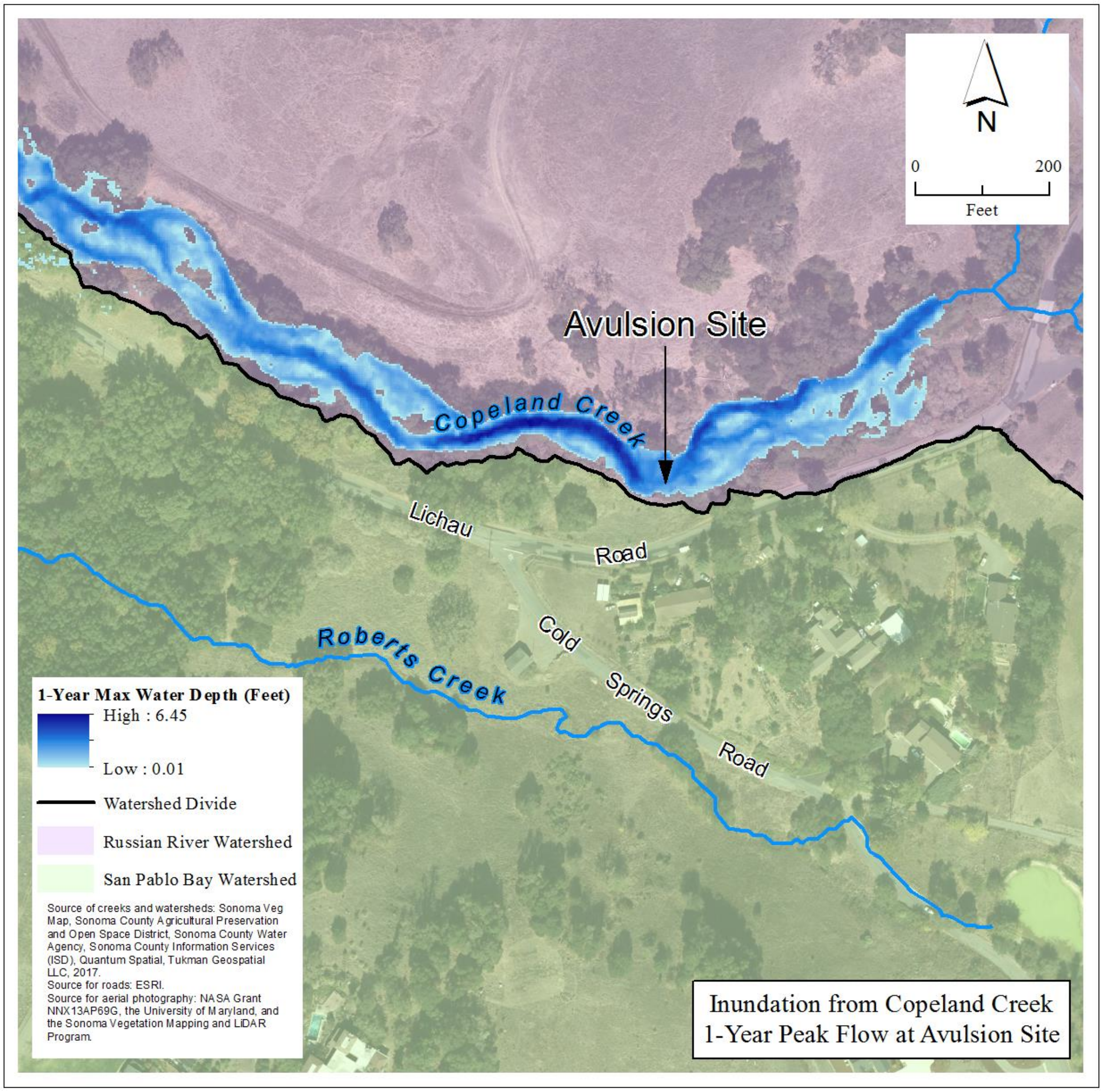
Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

Figure 20 - Inundation from 50-year peak flow



Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

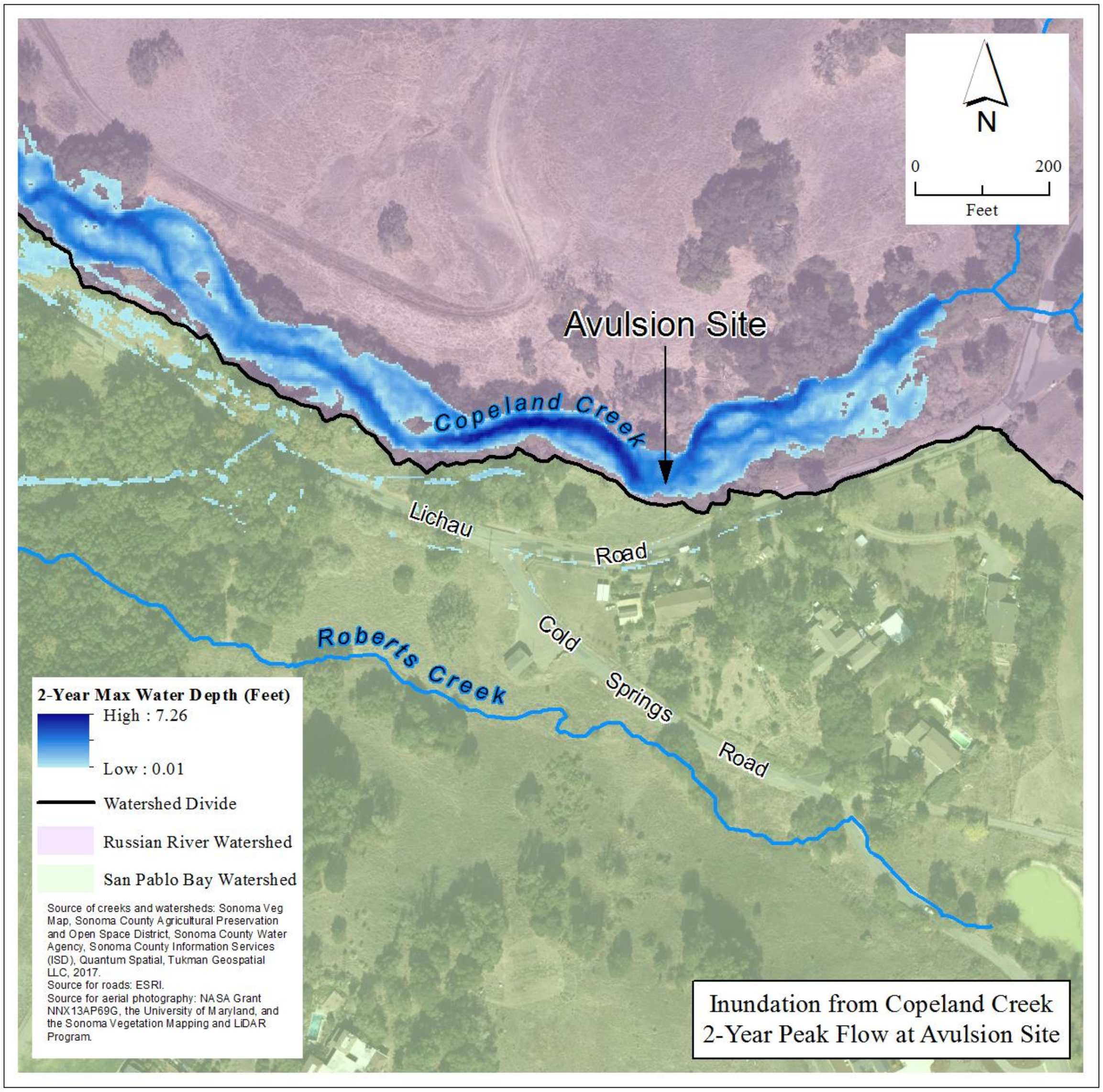
Figure 21 - Inundation from 100-year peak flow



Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

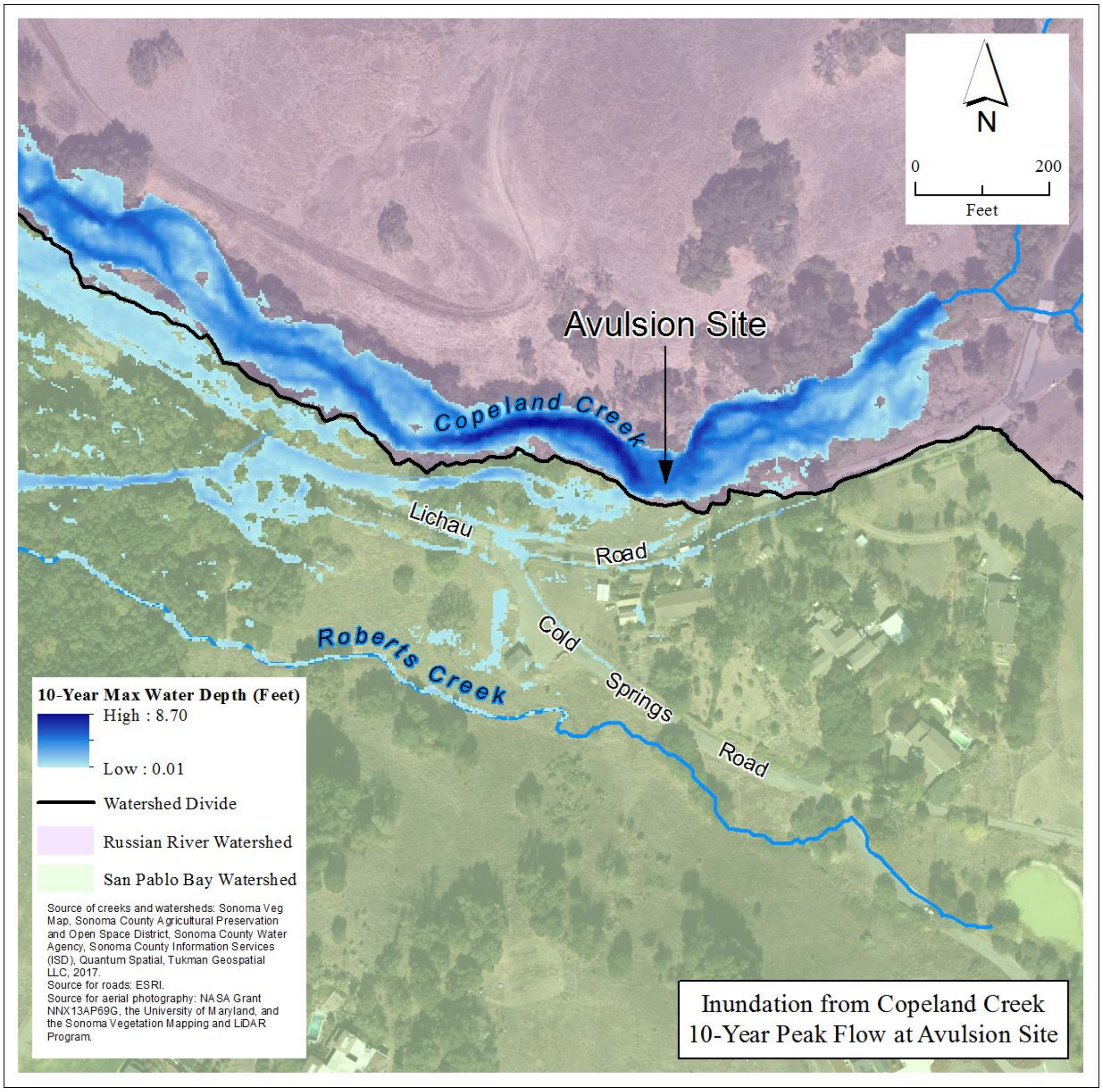
Inundation from Copeland Creek
1-Year Peak Flow at Avulsion Site

Figure 22 - Inundation from 1-year peak flow at the avulsion site



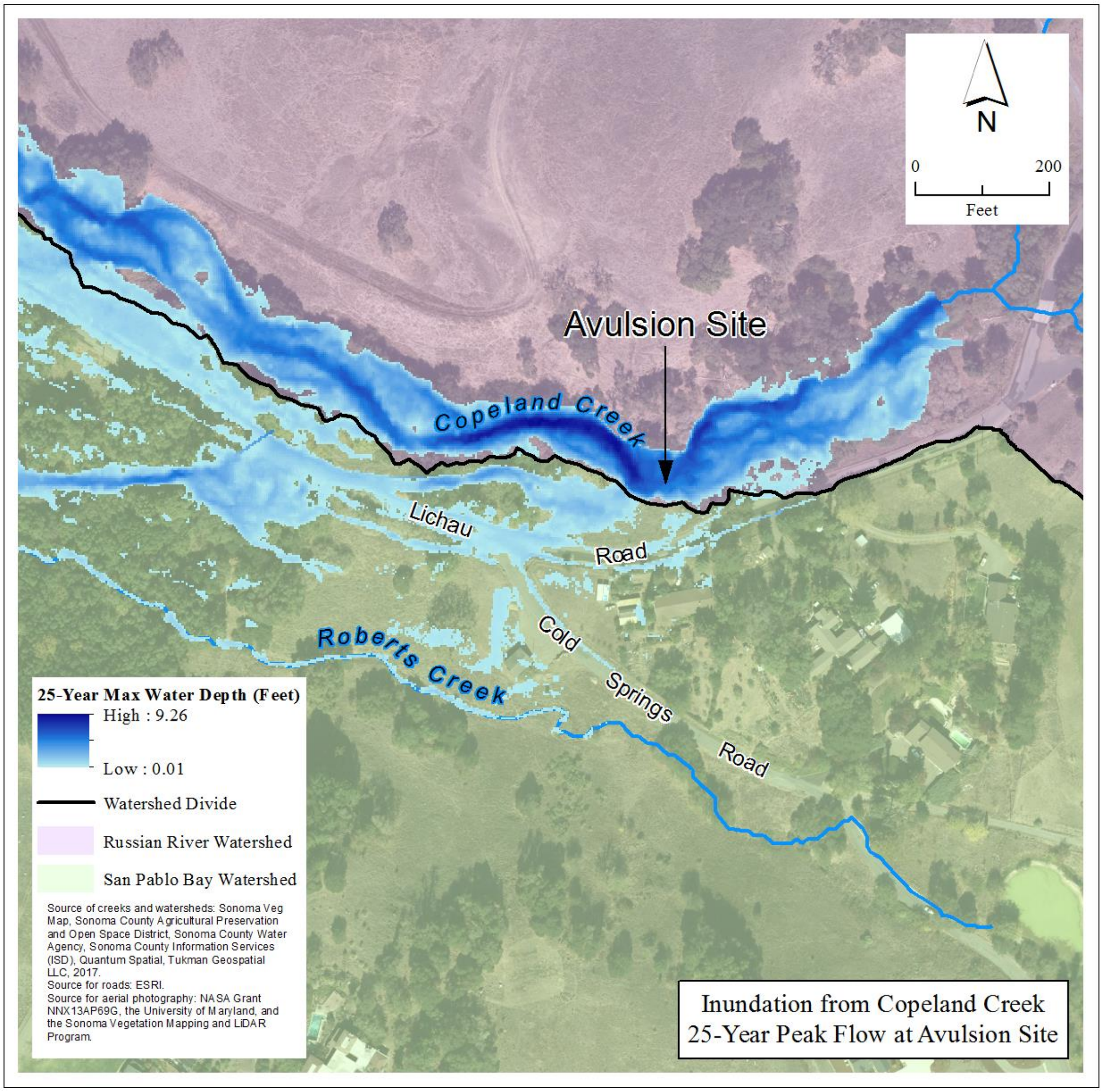
Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

Figure 23 - Inundation from 2-year peak flow at the avulsion site



Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

Figure 24 - Inundation from 10-year peak flow at the avulsion site



Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

Figure 25 - Inundation from 25-year peak flow at the avulsion site

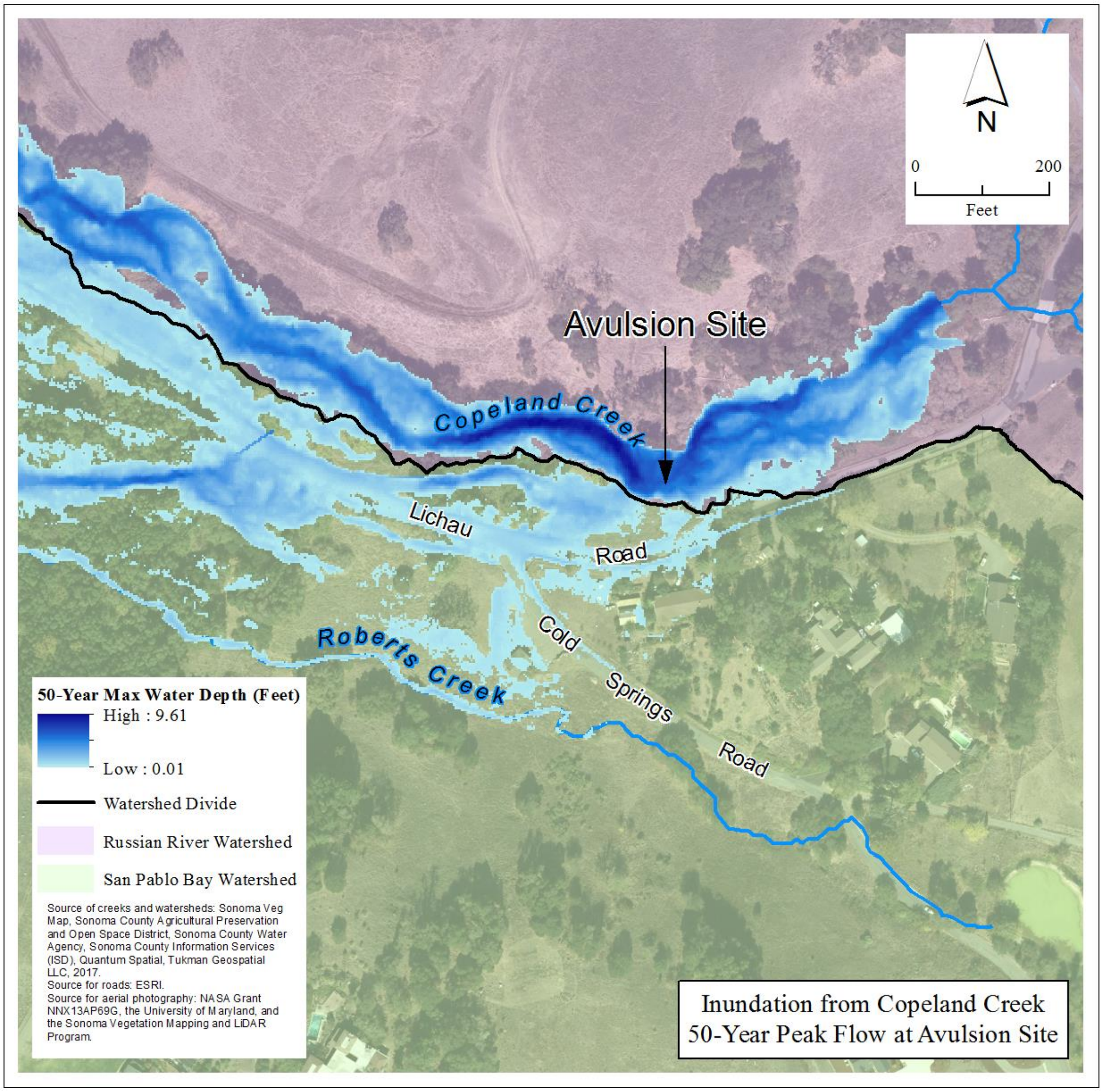
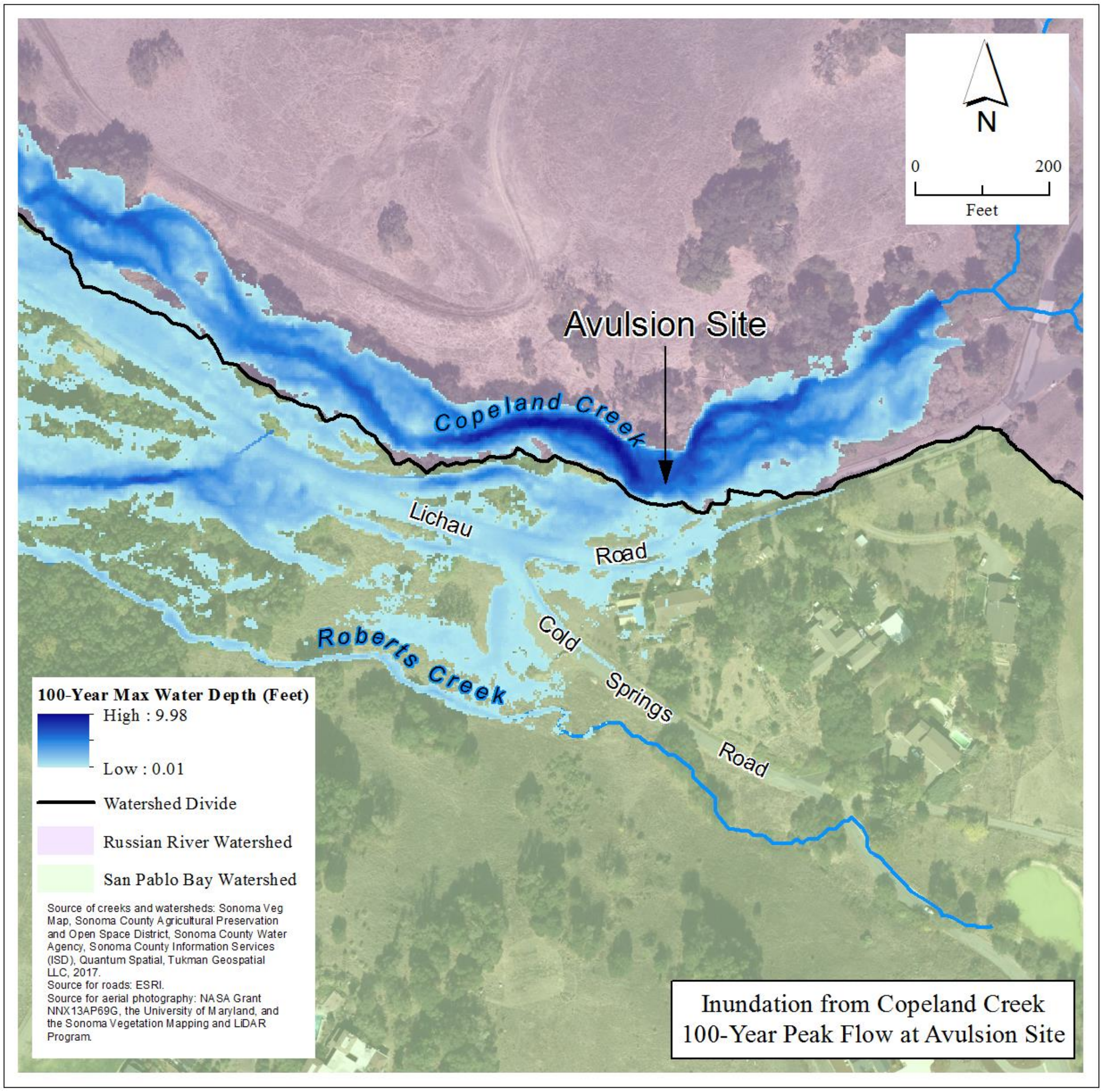


Figure 26 - Inundation from 50-year peak flow at the avulsion site



Inundation from Copeland Creek
100-Year Peak Flow at Avulsion Site

Source of creeks and watersheds: Sonoma Veg Map, Sonoma County Agricultural Preservation and Open Space District, Sonoma County Water Agency, Sonoma County Information Services (ISD), Quantum Spatial, Tukman Geospatial LLC, 2017.
Source for roads: ESRI.
Source for aerial photography: NASA Grant NNX13AP69G, the University of Maryland, and the Sonoma Vegetation Mapping and LiDAR Program.

Figure 27 - Inundation from 100-year peak flow at the avulsion site

Discussion

The intention of this pilot study was to identify the conditions that cause Copeland Creek to avulse, where overbank flow travels, and the associated human and societal impacts. It's important to note that this study is intended for discussion purposes only; the hydraulic model was not analyzed or overseen by a professional engineer. The model results indicate that Copeland Creek overbank flow from the avulsion site becomes inter-watershed flow as it migrates from the Russian River watershed to the San Pablo Bay watershed from 10-year peak flow and higher events. The 2-year peak flow and higher model results show significant Copeland Creek overbank flow occurring at another avulsion site about 1,000 feet downstream of the study avulsion site (Figures 17 and 23). This downstream avulsion site warrants further investigation, as it appears it is at least partially responsible for the flooding seen by many residents along Chester Drive, between Petaluma Hill Road and Roberts Road.

Limitations and assumptions

The 2-year peak flow model shows some overbank flow on the south side of the watershed divide and along the south side of Lichau Road (Figure 23). The water is not shown to be contiguous to the creek, and is therefore likely an error called "leaking," whereby topography along the streambank may not have been accurately captured by the computational mesh (even though breaklines were added to improve the model). HEC-RAS version 5.0.4, released after modeling for this study had concluded, includes a tool to incorporate polygonal areas with higher computational mesh densities embedded within the larger flow area. Using this new functionality in the model would likely solve the leaking issue shown in Figure 23. Moreover, the model shows excessive flooding during 1-year and 2-year peak flow events where Copeland Creek goes under Roberts Road, under Petaluma Hill Road, and under Highway 101. Flooding of this magnitude at these locations during low flow events is most certainly an error in the model. The issue likely stems from the hydro-enforced DEM not adequately capturing the conveyance capacity of culverts beneath roadways, causing the water to back up and flood the banks. Future two-dimensional models should field verify the conveyance capacities of all culverts in the system and update the model accordingly.

The hydraulic model is limited to overbank flow from Copeland Creek, and, as such, does not capture inundation that may occur as a result of excess water contributions from Copeland Creek to other stream systems. For example, if a small tributary was at capacity from a given storm event, contributions from Copeland Creek may cause that tributary to flood its banks. To capture this type of scenario, a full watershed model would have to be created, incorporating elements of precipitation on the landscape and flows for each stream.

The flow hydrograph used may not accurately represent runoff response in the mountainous headwaters of Copeland Creek. The time of concentration of runoff from rainfall is likely much shorter in the headwaters than that of the USGS streamgage located in a flat urban area. As such, the method used to develop a flow hydrograph for the return interval peak flows may not accurately describe the hydrology of Copeland Creek at the Lichau Road bridge. However, every storm is different; the flow hydrograph used, could, in theory, be a possible response to some storm event creating the ascribed peak flows modeled by GHD (2017). The HEC-HMS modeled flow hydrographs were unavailable at the time of this study. Should those be made available, the model could be re-run to understand if a) there are any differences in inundation, and b) what affects flow timing and river stage height have on flood events for the avulsion site.

Recommendations

Flood mitigation projects and solutions are not as simple as once thought. In 1896, the State suggested that a "very moderate expenditure" to improve Copeland Creek's channel banks would resolve the problem (Price and Nurse 1896). While keeping Copeland Creek waters within its currently defined channel would prevent the natural process of flooding at the avulsion site, it would worsen flooding that already occurs in Rohnert Park near Commerce Boulevard. The culvert that conveys Copeland Creek under highway 101 is of limited capacity, and causes flooding between Avram Avenue and Enterprise Drive at Commerce Boulevard during high flow events (Figure 28). At this time, CalTrans is unwilling to increase the conveyance capacity of the culvert due to potential unknown effects of increased water flow downstream (Michael Thompson, personal communication, Upper Copeland Creek Watershed Tour, December 2, 2017).

Figure 28 - Flooding at Commerce Boulevard and Enterprise Drive (Source: Game of Drones 2017)

Complicating potential mitigation projects are several ecological factors – Copeland Creek is habitat to anadromous fish, such as the threatened and protected Steelhead (Department of Fish and Wildlife n.d.), which make their way upstream from the Pacific Ocean to spawn. Any disturbance to the stream must have environmental oversight from state and federal agencies.

A potential remedy to Copeland Creek overbank flow is the improvement of the stream bank at the avulsion site combined with the construction of a stormwater detention facility capable of attenuating at least a 100-year peak flow. The sediment catchment facility to be constructed just east of Petaluma Hill Road was originally planned to be capable of attenuating such high flows, but it was later decided that the berm height required to construct such a facility would be too unsightly (GHD 2017). The facility is now designed for a 10-year storm. Ostensibly, the solution proposed here is to either enlarge the Petaluma Hill Road facility to the original 100-year specification or construct an additional stormwater detention basin elsewhere along the creek. This would likely entail a public-private partnership or procurement of privately held lands.

Another potential solution would allow stream processes to function as they have but include engineered structures and facilities to attenuate flood water impacts. This solution would include the procurement of the lot south of the avulsion site for the construction of a stormwater detention facility. Lichau Road could then be raised and a culvert (or a series of culverts) installed whose invert elevation is that of the existing roadway. This would allow what would previously have been overbank flow to instead flow through the culvert(s) into the stormwater detention basin where the flows can be controlled, slowed, and released into the San Pablo Bay watershed. This holistic approach would allow the channel to function as it has – floodwaters entering the San Pablo Bay watershed – while mitigating flood impacts downstream in both watersheds.

Conclusion

The hydraulic model, though limited, is in agreement with observed overbank flow and historical documentation of Copeland Creek flooding. A portion of Copeland Creek floodwaters for a 25-year peak flow event or higher jump from the Russian River watershed to the San Pablo Bay watershed, likely exacerbating flooding of Lichau Creek and possibly the Petaluma River. However, the creek has likely functioned in this capacity for millennia, as evidenced by the existence of the alluvial fan, which begins at precisely the location where overbank flow is modeled and observed to occur (the avulsion site). Human settlements have complicated the natural function of the creek, and, as such, actions should be taken to mitigate property damage and risk to human life.

This pilot study indicates further research of Copeland Creek flood processes should be conducted. Mike Thompson of the SCWA gave a presentation to the Petaluma City Council on March 6, 2018, where he addressed the need for a two-dimensional hydraulic model to understand Copeland Creek flood processes. In his presentation, he stated that Sonoma County Flood Zone 1A and Flood Zone 2A are each budgeting $250,000 to study Copeland Creek and prepare a hydraulic model. Future two-dimensional hydraulic models should incorporate complete watershed processes to understand how Copeland Creek overbank flow affects downstream watercourses during high precipitation events. Any future model should incorporate field verification of culverts to assure accurate modeling of conveyance systems. Alternate modeling techniques may be more holistic. For example, rather than using a flow hydrograph as the upstream boundary condition, a future model could simulate precipitation falling on the landscape to model both Russian River and San Pablo Bay watersheds. This modeling method, or others, should simulate the system with and without potential solutions to ascertain the effectiveness, benefits, and potential negative consequences of those potential solutions.

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