A *Climate Adaptation Risk Analysis for the San Mateo Countywide Sustainable Streets Master Plan Technical Memorandum*

To:	Matt Fabry – City/County Association of Governments of San Mateo County
From:	Steve Carter; John Riverson – Paradigm Environmental
Date:	October 14, 2020
Re:	Climate Adaptation Risk Analysis for the San Mateo Countywide Sustainable Streets Master Plan

The San Mateo Countywide Sustainable Streets Master Plan is a collaborative effort between Caltrans and the 21 member agencies of the City/County Association of Governments of San Mateo County (C/CAG) to prioritize locations for implementation of sustainable street designs. While providing multiple community benefits, these sustainable street projects will also include the integration of green infrastructure (GI) within the public right-of-way to capture, infiltrate, and/or treat stormwater runoff. GI is primarily designed to meet stormwater capture and water quality objectives but are also able to provide a range of community benefits, ranging from urban greening and pedestrian safety to increased climate resiliency. One of the primary objectives of the Master Plan, as a project funded through a Caltrans Climate Adaptation Planning Grant, is to assess and quantify to what extent the GI components of sustainable streets can add resiliency to the county's roadways and storm drain systems in the face of climate uncertainty. Many global climate models predict the occurrence of larger and more frequent rainfall events, having the potential to adversely impact local infrastructure and disproportionately affecting vulnerable communities who rely on public or non-motorized transit. GI may help to alleviate some of these impacts while simultaneously helping to improve water quality in the region's waterbodies.

This memorandum describes the modeling analysis conducted for the Master Plan to assess hydrology under future climate scenarios, isolate the impact on roadways, and quantify the ability of sustainable streets to offset the predicted increases in roadway runoff. A countywide modeling system previously developed by C/CAG was used to model stormwater runoff and capture for a historical baseline scenario (present-day) and several future climate scenarios. The C/CAG modeling system was developed for a Reasonable Assurance Analysis (RAA) addressing PCBs and mercury pollution in stormwater runoff draining to the San Francisco Bay (SMCWPPP 2020a and 2020b). The RAA demonstrates that implementation of a future GI scenario will meet water quality requirements of the Municipal Regional Stormwater Permit (MRP) (Order No. R2-2015-0049; SFBRWQCB 2015) by 2040. Using the water quality-based GI scenario from the RAA, this modeling analysis quantifies the benefits that GI may provide to offset predicted increases on runoff overall, and specifically, the benefits that sustainable streets may provide for offsetting runoff increases from roadways.

Section 1 outlines the methods to apply the most relevant peer-reviewed climate models for the region to local precipitation data in order to draw conclusions about possible climate impacts to future storm events. Section 2 outlines the process for quantifying the climate resiliency benefits provided by the GI and sustainable streets. Section 0 discusses conclusions from this analysis.

1 QUANTIFICATION OF CLIMATE CHANGE-RELATED PRECIPITATION IMPACTS

This section describes (1) the watershed modeling system and the model parameterization for representing current-state hydrology, (2) the development of local design storm hyetographs based on historical rainfall to serve as meteorological boundary conditions for modeling flood events, (3) the climate models used to create meteorological boundary conditions for future climate scenarios, and (4) the modeled impact of climate change on countywide stormwater runoff.

1.1 Watershed Model

The historical baseline (present-day) hydrology was modeled using the watershed model from C/CAG's modeling system for the RAA. The watershed model is a Loading Simulation Program in C++ (LSPC) model (Shen et al. 2004) that is regionally calibrated and provides dynamic (hourly) simulation of hydrology and pollutant transport processes within each watershed in the county. Figure 1-1**Error! Reference source not found.** shows a map of the subwatersheds modeled in LSPC[1]. The LSPC model from the RAA is available for all subwatersheds in the county. However, in this analysis, the distinction between subwatersheds that drain to the Pacific Ocean and the San Francisco Bay is made because the stormwater capture model (discussed in Section 2) only assesses GI benefits on the bayside. This is because the RAA targets are based on PCBs (polychlorinated biphenyls) and mercury reductions required for stormwater runoff to the Bay only. Oceanside, bayside, and countywide averages are reported in this memorandum to summarize results over these distinct regions; however, all precipitation, runoff, and stormwater capture estimates in the analysis were first simulated at the subwatershed-scale.

Figure 1-1. LSPC model subwatersheds.

[1] The hydrologic boundaries of the watershed areas extend beyond county lines in some areas. However, the subwatersheds modeled in the RAA were cut off at the county boundary. The MRP only requires pollutant reductions in areas that drain to the Bay.

The model was built using datasets that describe land, meteorological, and hydrological characteristics of the subwatersheds. A Hydrologic Response Unit (HRU) is the smallest modeling unit in LSPC and represents the unique combination of physical characteristics including land use/land cover, soil type, and slope (see Figure 2). Table 1-1 lists and describes the data sources used to represent HRUs in the model. Figure 1-3 conceptually illustrates the intersection of the various layers described in Table 1-1 and summarizes the final HRU area distribution for the county. The parameters associated with HRUs are collectively used to simulate aggregated hydrologic and water quality responses which are then routed to each of the subwatersheds.

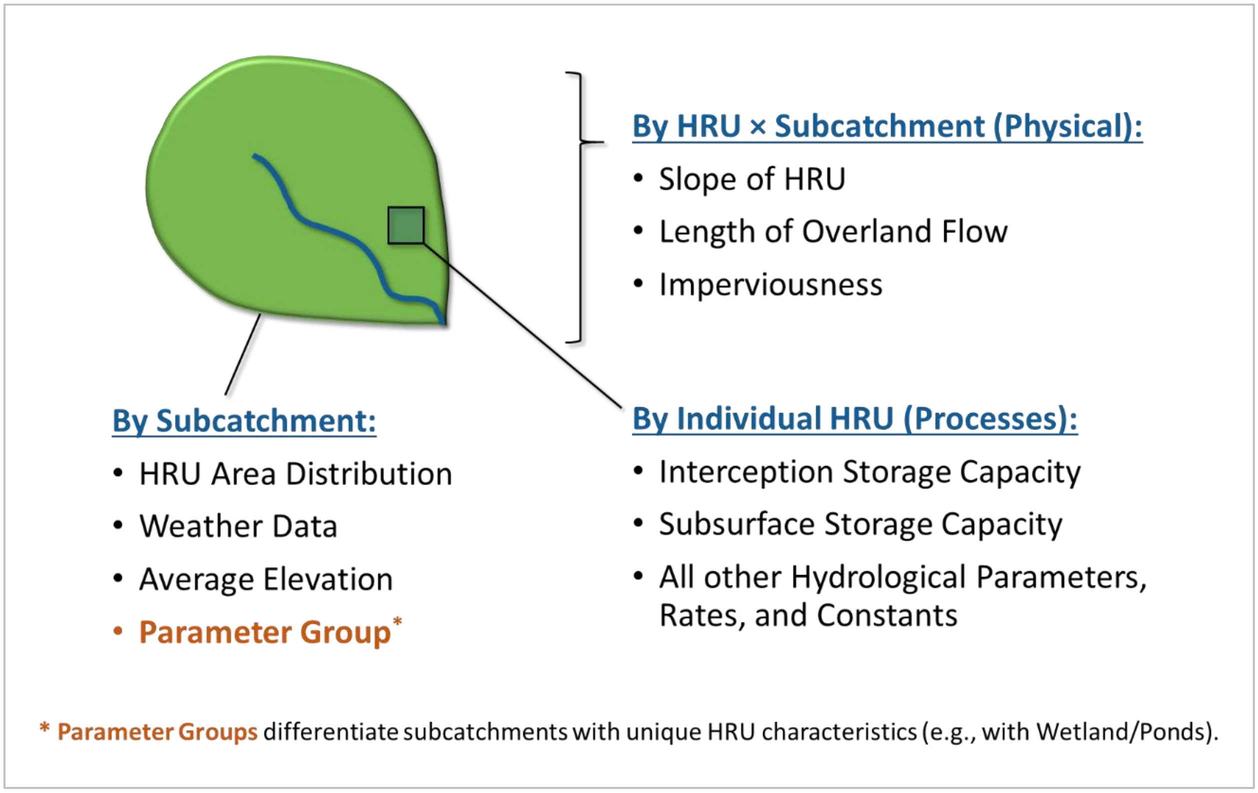
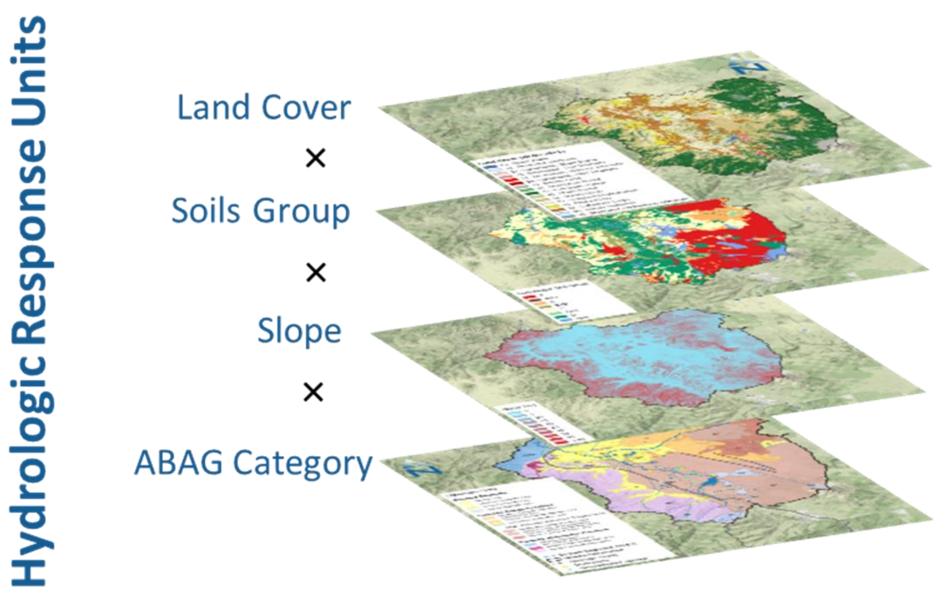


Figure 1-2. Conceptual organization of model parameters within LSPC.

Table 1-1. Data used for HRU analysis

GIS Layer	Description	Source
Land Cover	Polygon layer – contains vegetation type (if any).	National Land Cover Database
Soil Type	Polygon layer – contains soil type.	United States Department of Agriculture
Slope	Raster layer - contains slope information.	Generated from DEM
ABAG Category	Land use classification – contains land use as classified by ABAG.	Association of Bay Area Governments



Group	Description	Percent of Area (by Group)		
		Ocean	Bayside	Countywide
Land Cover	Developed	11.8%	66.5%	32.8%
	Forest	61.2%	27.0%	48.1%
	Shrub/Grass	27.0%	6.4%	19.1%
Soil Type	A	0.7%	0.0%	0.5%
	B	22.6%	1.1%	14.4%
	C	59.4%	63.1%	60.8%
	D	15.5%	15.0%	15.3%
	Impervious	1.8%	20.8%	9.1%
Slope	Low	33.7%	76.5%	50.1%
	Med	66.3%	23.5%	49.9%
ABAG Category	Open	93.4%	41.8%	73.6%
	New Urban	2.1%	3.4%	2.6%
	New Industrial	0.0%	0.6%	0.2%
	Old Industrial	0.0%	2.1%	0.8%
	Old Residential	2.4%	29.3%	12.7%
	Old Urban	1.9%	21.2%	9.3%
	Source Areas	0.2%	1.5%	0.7%
Countywide		**31%**	**19%**	**50%**

Figure 1-3. Conceptual intersection of HRU layers and the summary table of HRU distribution in San Mateo County.

1.2 Design Storms

The modeled baseline scenario for the RAA was a continuous simulation of runoff volume for water year 2002 (10/1/2001 – 9/30/2002), an average annual hydraulic condition identified in the *Bay Area Reasonable Assurance Analysis Guidance Document* (BASMAA 2017). However, because many climate models predict that high-intensity rain events will occur at increased frequency in the future, design storms typically used in flood planning were considered a more appropriate basis for assessing future climate scenarios than an average annual condition. The analyzed storm return periods include 2, 5, 10, 25, 50, and 100 years. For example, a 100-year 6-hour storm refers to a rainfall event with a duration of 6 hours and of a size that occurs only once every 100 years (1% chance of occurring any given year) based on a statistical analysis of historical precipitation data. While climate change is also expected to have a large impact on extreme weather events (200, 500-year storms, etc.), GI projects are typically designed for much smaller, more frequent events (typically for storms that occur more than once per year). The benefits of GI are not expected to be meaningful for extreme events, so these larger return periods were not evaluated in this analysis.

The design storm precipitation timeseries used in the analysis were determined by applying a 6-hour temporal distribution (unit precipitation timeseries) to storm depths associated with the recurrence intervals. The percentage of the total storm depth occurring at each time step is the same for the timeseries of all storm sizes. The temporal distribution and storm depths were both developed by a regional precipitation frequency analysis conducted by the Santa Clara Valley Water District (SCVWD 2016). The storm depths and temporal distribution were based on local historical rainfall data in the counties of San Mateo, Alameda, and Santa Clara. While this study produced distributions and storm depths for several durations up to 72 hours, a 6-hour event was considered more conservative for runoff estimation because it represents a higher intensity storm. Additionally, a separate study (Rastogi et al. 2017) examining the effects of climate change on precipitation for 6-hour through 72-hour events found that there was the least variance between simulated and conventional precipitation estimation methods for the 6-hour duration, suggesting greater confidence in 6-hour storm depths.

Figure 1-4 presents probability distributions for the cumulative percentage of precipitation to fall over a 6-hour event. The median distribution (50%), prominently featured in the graph below, was selected for use in the model because it is the most representative distribution for all storms. Essentially, 50% of observed storm events in the region were found to produce at least the reported cumulative rainfall percentage at each timestep. For example, in the figure below, at least 65% of precipitation occurs by the third hour in 50% (median) of observed storms. Figure 1-5 graphs the unit precipitation timeseries based on the median distribution used to calculate the various storm precipitation timeseries.

Time (hours)	Distributions of Cumulative Percent of Precipitation by Probability of Occurence								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	13.33	15.83	17.50	19.17	20.83	21.67	23.33	25.83	30.00
1.0	20.67	24.33	27.00	29.00	31.00	33.33	35.33	39.67	46.67
1.5	29.50	33.00	35.50	37.50	39.50	42.00	44.50	49.50	57.00
2.0	39.33	42.67	44.67	46.67	48.67	51.00	54.33	59.00	65.67
2.5	47.83	51.67	53.50	55.50	57.50	60.50	64.33	68.33	74.00
3.0	57.00	60.00	61.00	63.00	65.00	68.00	71.00	75.00	79.00
3.5	65.33	67.50	69.33	71.33	73.33	76.33	78.50	81.67	86.50
4.0	73.00	74.33	76.33	78.33	79.67	82.00	84.00	86.33	90.67
4.5	79.50	81.00	83.00	84.50	85.50	87.50	89.50	91.00	94.50
5.0	86.00	87.33	89.00	90.00	91.00	92.67	94.00	95.00	97.33
5.5	93.33	93.33	94.17	95.00	95.83	96.67	96.67	97.50	98.33
6.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

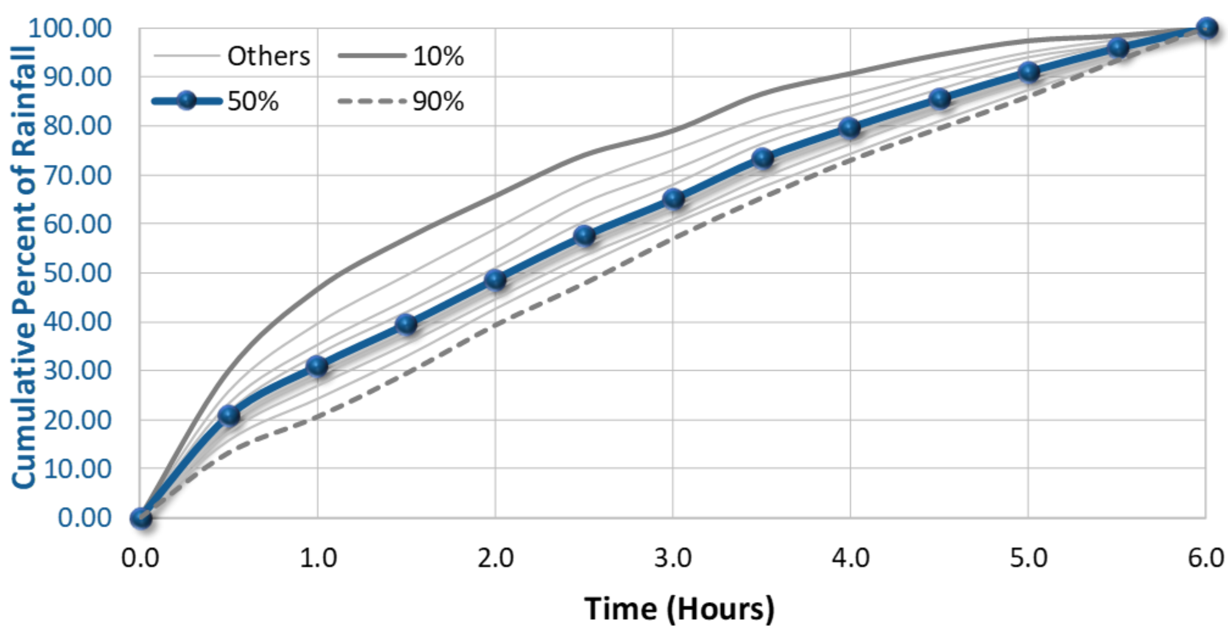


Figure 1-4. Distributions for 6-hour (2nd Quartile) storm events (SCVWD 2016).

Time (hours)	Incremental % of Precipitation
0	0.00%
0.5	20.83%
1	10.17%
1.5	8.50%
2	9.17%
2.5	8.83%
3	7.50%
3.5	8.33%
4	6.33%
4.5	5.83%
5	5.50%
5.5	4.83%
6	4.17%
6.5	0.00%

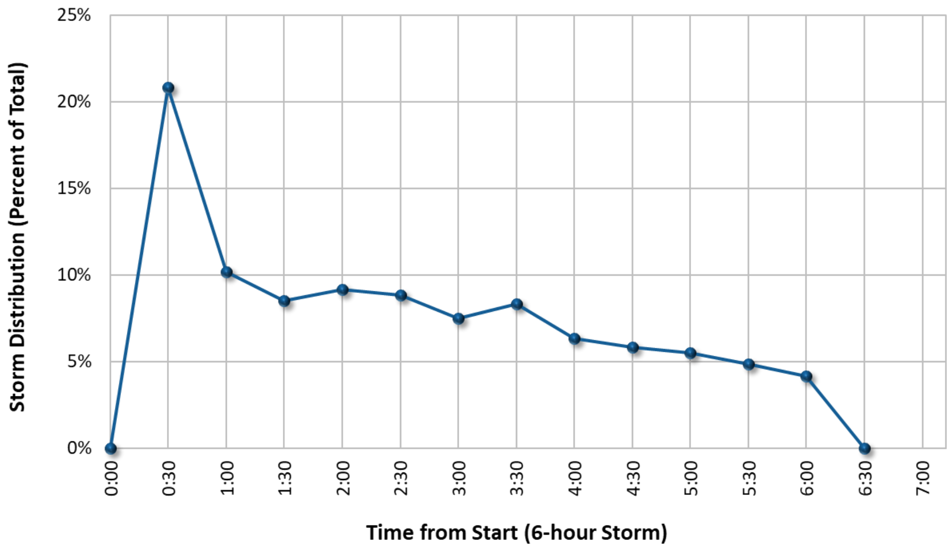


Figure 1-5. Unit precipitation timeseries for median distribution (SCVWD 2016).

Gridded products (~1,500-foot resolution), based on observed historical values from the SCVWD precipitation study, were used to determine 6-hour storm depths. Figure 1-6 shows an example of the SCVWD gridded dataset for a 10-year, 6-hour event across the county. A similar gridded dataset exists for each recurrence interval (2, 5, 10, 25, 50, 100-year). The average 6-hour storm depth was calculated for each subwatershed and applied to the temporal distribution to create a unique precipitation timeseries for each subwatershed. The resulting precipitation timeseries were used as the meteorological boundary conditions in the model to simulate associated runoff in each subwatershed. Table 1-2 summarizes the 6-hour storm depths for each recurrence interval as a countywide area-weighted average. Maps of precipitation depths by subwatershed are provided in Appendix A. The historical storm depths are used for comparisons to the future climate change scenarios described in Section 0.

Table 1-2. Average precipitation depths for 6-hour storm events across San Mateo County

Scenario	6-hour Storm Size (in.) by Recurrence Interval						
	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr
Historical	1.69	2.09	2.39	2.79	3.10	3.40	3.70

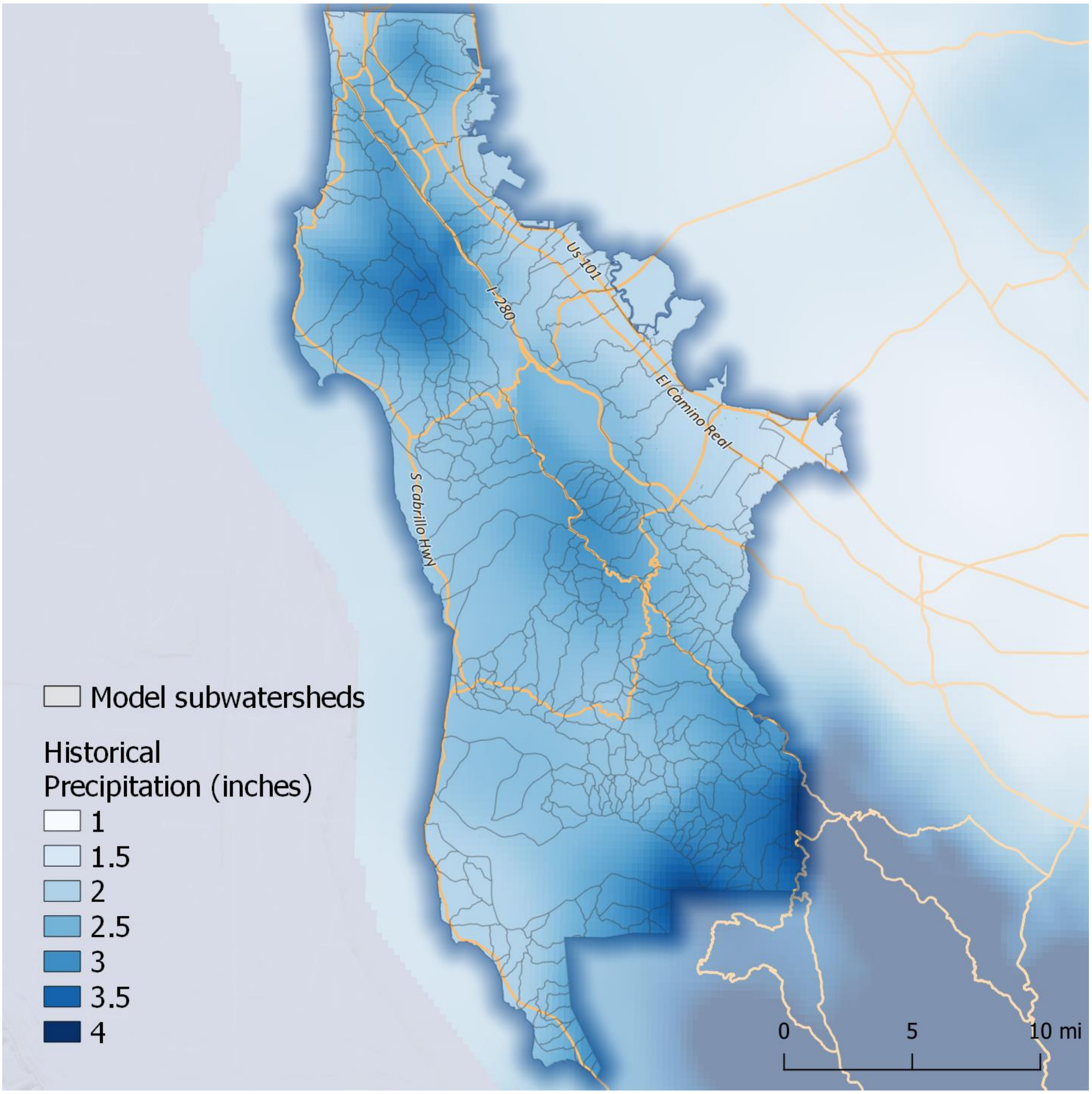


Figure 1-6. Historical 10-year, 6-hour storm depths across San Mateo County (SCVWD 2016).

1.3 Climate Change Impacts

This section describes the global climate models selected to develop the future climate scenarios and the associated projected storm sizes.

1.3.1 Global Climate Models

For this analysis, an ensemble of 20 climate change projections (i.e., 10 models × 2 future pathways) from Cal-Adapt was considered. Cal-Adapt synthesizes climate change projections and research from California's scientific community and is developed by the Geospatial Innovation Facility at the University of California, Berkeley, with funding and advisory oversight by the California Energy Commission. The projections are from two future projection scenarios, or Representative Concentration Pathways (RCPs) 4.5 and 8.5, for 10 global climate models (GCMs) as recommended by the Climate Change Technical Advisory Group. The two selected RCPs are best- and worst-case projections of future carbon emissions. RCP 8.5 represents a scenario in which carbon emissions continue to climb at historical rates, whereas the RCP 4.5 predicts a stabilization of carbon emissions by 2040 (IIASA 2009). Although these are estimated future trajectories, comparisons to actual emissions levels at the time of the IIASA study suggest that observed emissions have been outpacing the RCP 8.5 scenario (Figure 1-7).

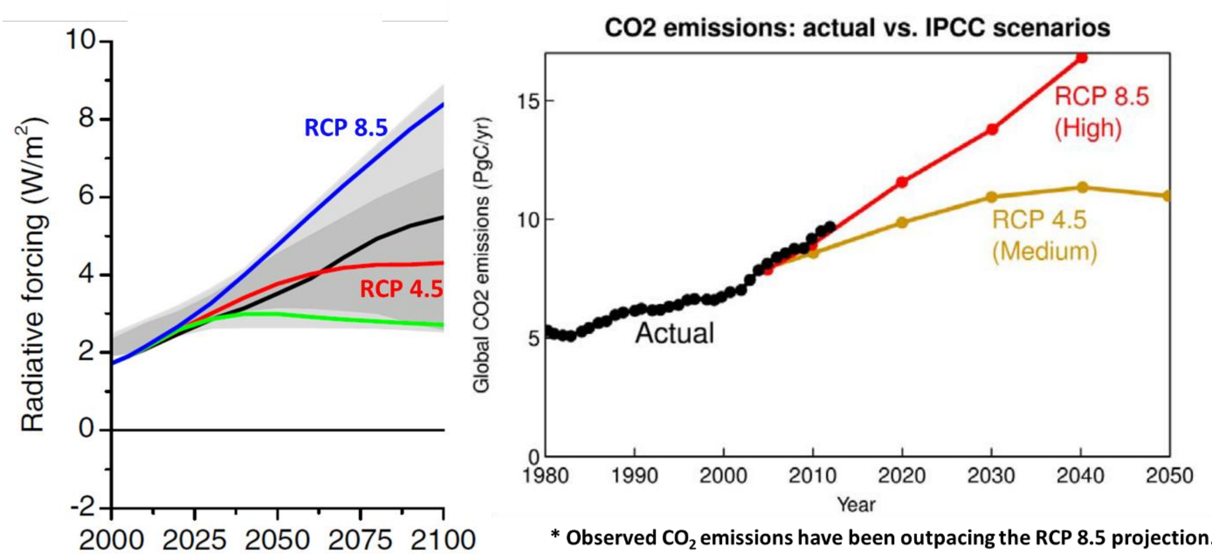


Figure 1-7. Selected Representative Concentration Pathways for climate change analysis (IIASA 2009).

Table 1-3. Description of global climate model scenarios

Global Climate Model		Description
Scenario	Historical Baseline (SCVWD 2016)	Precipitation frequency estimates based on a total of 45 rain gauges in San Mateo County, with periods of record ranging from 1850 to 2016.
	RCP 4.5 *Stabilization*	Radiative forcing level stabilizes at 4.5 W/m^2 before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions.
	RCP 8.5 *Business-as-Usual*	Radiative forcing level reaches 8.5 W/m^2 before 2100 as greenhouse gas emissions continue to rise on the current trajectory.
Model	ACCESS1-0	One of 10 models selected by California's Climate Action Team
	CanESM2	One of 10 models selected by California's Climate Action Team
	CCSM4[1]	Priority model representing Average[5] scenario
	CESM1-BGC	One of 10 models selected by California's Climate Action Team
	CMCC-CMS	One of 10 models selected by California's Climate Action Team
	CNRM-CM5[2]	Priority model representing Cool/Wet[5] scenario
	GFDL-CM3[3]	Priority model representing Warm/Dry[5] scenario
	HadGEM2-CC[4]	Priority model most dissimilar to other three priority models[5]
	HadGEM2-ES	One of 10 models selected by California's Climate Action Team
	MIROC5	One of 10 models selected by California's Climate Action Team

1: Cal-Adapt, National Science Foundation, US Department of Energy, US National Center for Atmospheric Research
2: Cal-Adapt, Centre National de Recherches Meteorologiques
3: Cal-Adapt, NOAA Geophysical Fluid Dynamics Laboratory
4: Cal-Adapt, United Kingdom Meteorological Office
5: California Energy Commission

1.3.2 Projected Storm Sizes

For each climate projection, 6-hour storm precipitation timeseries were generated. The climate models are downscaled at a 7-kilometer resolution, resulting in 32 grids across the county. For each grid, the daily timeseries for a modeled historical (1950-2005) and future (2006-2100) period were retrieved from each GCM. Storm depths based on the simulated historical and future periods were calculated using the daily timeseries from the GCMs. The ratio of simulated future to historical storm depth was calculated for each of the 32 grids (see example in Figure 1-8) and averaged across each subwatershed in the model. These ratios are then applied to the SCVWD historical precipitation timeseries based on observed data (described in Section 1.2) to determine the future timeseries. Ratio grids were developed for each set of GCM, RCP, and recurrence interval. Table 1-4 summarizes the projected storm sizes by climate change scenario averaged across the county. Additionally, the mean and median rainfall depth for all ten GCMs for RCP 4.5, RCP 8.5, and all climate futures were calculated. Projected future storms that exceed the greater historical storm sizes (e.g., future 50-year storm exceeds historical 100-year storm) are highlighted in red to illustrate the extreme conditions anticipated with climate change scenarios. Projected future storms that fall below the historical equivalent storm size are highlighted in blue (e.g., future 50-year storm is less than the historical 50-year storm).

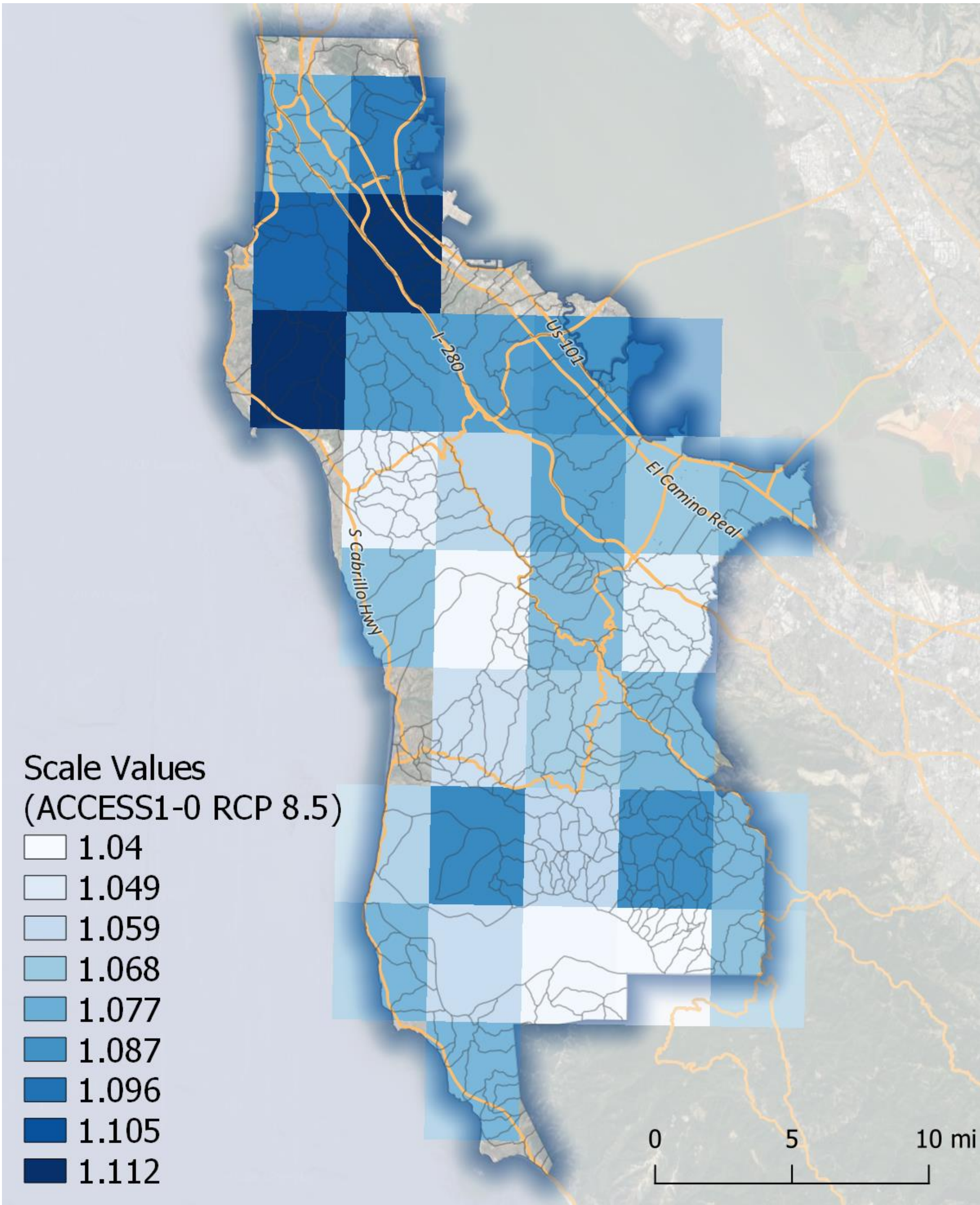


Figure 1-8. Example ratios of future to historical precipitation for GCM ACCESS1-0, RCP 8.5 for a 10-year, 6-hour storm.

Table 1-4. Summary of design storm sizes by climate change scenario averaged across San Mateo County

Climate Change		6-hour Storm Size (in.) by Recurrence Interval					
Scenario	Model	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Current (Historical)		1.69	2.09	2.39	2.79	3.10	3.40
All	Median (All)	1.84	2.33	2.71	3.28	3.77	4.29
	Mean (All)	1.87	2.40	2.82	3.41	3.89	4.41
RCP 4.5	Median (4.5)	1.81	2.27	2.61	3.10	3.52	3.97
	Mean (4.5)	1.84	2.34	2.73	3.27	3.71	4.18
	ACCESS1-0	1.84	2.27	2.62	3.14	3.57	4.03
	CanESM2	1.96	2.59	3.07	3.75	4.30	4.88
	CCSM4	1.78	2.26	2.58	2.97	3.24	3.48
	CESM1-BGC	1.93	2.42	2.87	3.57	4.22	4.95
	CMCC-CMS	1.91	2.39	2.71	3.09	3.35	3.59
	CNRM-CM5	2.20	2.96	3.56	4.40	5.10	5.84
	GFDL-CM3	1.75	2.11	2.38	2.76	3.06	3.37
	HadGEM2-CC	1.66	2.17	2.56	3.08	3.49	3.92
	HadGEM2-ES	1.70	2.09	2.46	3.03	3.56	4.15
	MIROC5	1.66	2.11	2.44	2.88	3.22	3.56
RCP 8.5	Median (8.5)	1.87	2.39	2.86	3.58	4.16	4.78
	Mean (8.5)	1.91	2.47	2.92	3.55	4.08	4.64
	ACCESS1-0	1.82	2.27	2.68	3.32	3.90	4.56
	CanESM2	2.14	2.91	3.53	4.39	5.11	5.88
	CCSM4	1.84	2.31	2.65	3.07	3.40	3.71
	CESM1-BGC	2.02	2.54	3.02	3.74	4.38	5.10
	CMCC-CMS	2.02	2.71	3.20	3.82	4.28	4.73
	CNRM-CM5	2.23	3.05	3.70	4.65	5.44	6.31
	GFDL-CM3	1.75	2.17	2.47	2.84	3.12	3.38
	HadGEM2-CC	1.80	2.38	2.87	3.59	4.23	4.93
	HadGEM2-ES	1.89	2.38	2.84	3.56	4.22	4.97
	MIROC5	1.56	1.94	2.20	2.49	2.70	2.88

[1] Historical 200-year, 6-hour rainfall depth is 3.70 inches.
Dark Red = Exceeds two or more higher historical storm sizes or the 200-year, 6-hour storm
Light Red = Exceeds next highest historical storm size
Blue = Below equivalent historical storm size

To assess the impact of climate change on historical runoff and the benefit of GI on climate resiliency of county roads, a single representative future climate scenario was selected for the remainder of the analysis. The median of the 10 GCMs for RCP 8.5 was selected for all subsequent comparisons between historical and future storms. RCP 8.5 represents a conservative estimate of future carbon emissions, while the median of the 10 GCMs blends the output of all modeled futures including hot/dry and cool/wet scenarios.

1.4 Projected Impact to Runoff

The historical and selected future climate scenario (median RCP 8.5) discussed in Section 0 were used to model the stormwater runoff for the selected flood design storms. This section summarizes the model results and compares the runoff from historical and future storms generated from total county area and from roads only.

1.4.1 Countywide Impact

The impact of climate change to runoff from all county area is summarized in Table 1-6, in terms of depth in inches. Maps of increased runoff by subwatershed are provided in Appendix B. Countywide, percent increase in runoff ranges from 15% (2-year) to 50% (100-year). The precipitation storm depths in Table 1-5 produce the runoff depths in Table 1-6. The difference between the values in the two tables represent losses due to infiltration, evaporation, interception, and depression storage.

Table 1-5. Projected climate impact on cumulative subwatershed precipitation depth

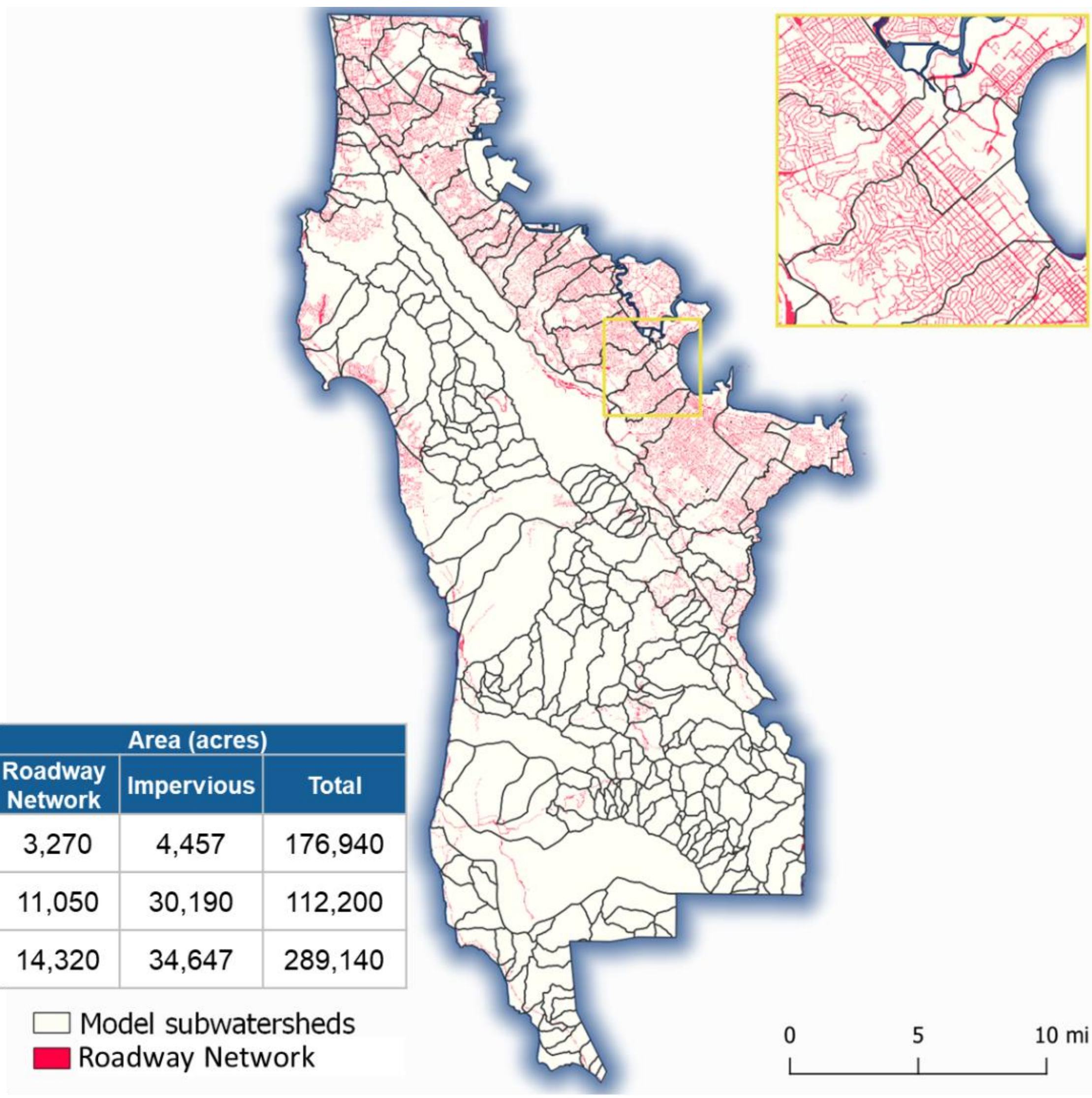
Region	Scenario	6-hour Precipitation Depth (in.) by Return Period					
		2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Ocean	Historical	1.76	2.18	2.49	2.91	3.24	3.56
	Median (RCP 8.5)	1.96	2.51	3.00	3.76	4.38	5.03
Bayside	Historical	1.58	1.96	2.23	2.60	2.88	3.15
	Median (RCP 8.5)	1.73	2.20	2.63	3.28	3.81	4.38
Countywide	Historical	1.69	2.09	2.39	2.79	3.10	3.40
	Median (RCP 8.5)	1.87	2.39	2.86	3.58	4.16	4.78

Table 1-6. Projected climate impact on cumulative subwatershed runoff depth

Region	Scenario	6-hour Runoff Depth (in.) by Return Period					
		2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Ocean	Historical	1.13	1.50	1.79	2.17	2.47	2.77
	Median (RCP 8.5)	1.31	1.80	2.25	2.97	3.56	4.18
	Percent Change	*15%*	*20%*	*26%*	*37%*	*44%*	*51%*
Bayside	Historical	0.97	1.30	1.56	1.90	2.17	2.44
	Median (RCP 8.5)	1.10	1.53	1.94	2.56	3.07	3.62
	Percent Change	*14%*	*17%*	*24%*	*34%*	*41%*	*49%*
Countywide	Historical	1.07	1.43	1.70	2.07	2.36	2.64
	Median (RCP 8.5)	1.23	1.70	2.13	2.81	3.37	3.97
	Percent Change	*15%*	*19%*	*25%*	*36%*	*43%*	*50%*

1.4.2 Roadway Impact

Because the roads were not explicitly delineated in the land use dataset used to develop the HRUs for the LSPC model, a methodology was devised to estimate the amount of runoff generated from the countywide roadway network. The area of the roadway network was estimated from GIS analysis that identified secondary roads from street centerlines and estimated street width using the outline of the rights-of-way using County of San Mateo GIS data. The conservative assumption was made to assume 100% of the area within the right-of-way is impervious, when likely this area may include pervious buffers, landscape strips, medians, etc. This assumption provides a more conservative estimate of runoff generated from roads. Figure 1-9 is a map of the resulting layer used to estimate the roadway network area and a comparison of road area to total impervious area (includes roads, sidewalks, buildings, parking lots, etc.). Runoff from the roadway network was estimated by conducting a model run with the estimated area of the roads only and zeroing out all other land uses. The impact of climate change to road runoff is summarized in Table 1-7, in terms of runoff depth in inches. Countywide, percent increase in road runoff ranges from 11% (2-year) to 40% (100-year).



Region	Area (acres)		
	Roadway Network	Impervious	Total
Ocean	3,270	4,457	176,940
Bayside	11,050	30,190	112,200
County wide	14,320	34,647	289,140

Figure 1-9. Layer used to estimate total area from the roadway network.

Table 1-7. Projected climate impact on cumulative runoff volume from the roadway network

Region	Scenario	6-hour Runoff Depth (in.) by Return Period					
		2-yr	5-yr	10-yr [1]	25-yr	50-yr	100-yr
Ocean	Historical	0.030	0.037	0.043	0.050	0.055	0.061
	Median (RCP 8.5)	0.033	0.043	0.051	0.065	0.077	0.089
	Percent Change	*12%*	*15%*	*21%*	*30%*	*38%*	*46%*
Bayside	Historical	0.144	0.180	0.206	0.241	0.268	0.295
	Median (RCP 8.5)	0.158	0.203	0.244	0.306	0.355	0.409
	Percent Change	*10%*	*13%*	*18%*	*27%*	*32%*	*39%*
Countywide	Historical	0.074	0.092	0.106	0.124	0.138	0.151
	Median (RCP 8.5)	0.081	0.104	0.126	0.158	0.184	0.212
	Percent Change	*11%*	*14%*	*19%*	*28%*	*34%*	*41%*

[1] There is approximately 20% increase in runoff from the roadway network for the 10-year storm. Storm drain systems in the county are typically sized for the 10-year storm.

2 QUANTIFICATION OF STORMWATER CAPTURE BENEFITS

This section describes the stormwater capture model used to estimate the performance of GI under the various combinations of design storms and climate scenarios, the estimated volume capture for the 6-hour storm events if the GI implementation scenario defined in the RAA is implemented, and the methodology for extrapolating the benefit of GI on the roadway network.

2.1 Stormwater Capture Model

The climate resiliency benefits of GI were estimated using the stormwater capture model from the C/CAG modeling system based on the U.S. Environmental Protection Agency's (EPA) System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) model. SUSTAIN was developed by EPA's Office of Research and Development as a decision-support system for the selection and placement of GI projects at strategic locations in urban watersheds. It includes a process-based continuous simulation module for representing hydraulic and pollutant transport routing through various types of GI projects (USEPA 2009, Riverson et al. 2014).

The runoff estimates generated from LSPC in Section 1 serve as input into the SUSTAIN model. SUSTAIN was used to simulate the physical processes within the GI (e.g., infiltration, evapotranspiration) to provide estimates of stormwater capture and runoff reduction from the GI implementation scenario identified in the RAA, which was developed to meet water quality requirements by 2040. Because GI planning efforts in San Mateo County are driven by PCBs and mercury reduction requirements to the Bay, the focus on this future GI scenario is only on bayside subwatersheds. However, the model results demonstrate that GI in general may have positive impacts on climate resiliency and can be extrapolated to other areas of the county where GI is implemented.

2.2 GI Benefit to Bayside Subwatersheds

The RAA identified a cost-optimal suite of GI projects that will meet the requirements of the MRP by 2040. This implementation scenario included: (1) existing facilities consisting primarily of new and redevelopment since 2005 that have been mandated to incorporate GI, (2) MRP-required GI for projected future new and redevelopment areas by 2040, (3) five large regional projects that provide opportunities for stormwater capture, infiltration, and treatment from multiple jurisdictions, (4) identified opportunities for green streets, and (5) other GI projects that are yet to be determined. Because the MRP only regulates stormwater runoff to the Bay, the implementation scenario only applies to bayside subwatersheds. This implementation scenario was modeled in SUSTAIN using the design storms described in Section 1.2 to stress-test the impact of climate change on the GI's effectiveness in reducing stormwater runoff from bayside subwatersheds. The RAA reported GI "capacities" in acre-feet within each model subwatershed and municipal jurisdiction, which represent the cumulative available stormwater storage volume for the hundreds of individual GI projects determined to provide cost-effective pollutant reductions to meet MRP goals by 2040. Table 2-1 provides a summary of the combined capacities for each GI project type. The GI capacities summarized in Table 2-1 were used to model stormwater capture for the historical storm events and the storm events associated with median of all 10 GCMs for RCP 8.5.

Table 2-1. Modeled green infrastructure capacities for bayside subwatersheds

Modeled Green Infrastructure Capacity (acre-feet)					
Total Capacity	Existing Projects	Future New & Redevelopment	Regional Projects (Identified)	Green Streets	Other GI Projects (TBD)
385.3	72.1	115.8	73.6	112.1	11.8

For comparison to the total GI capacity, the total runoff from all land uses on the bayside for each storm size is reported in Table 2-2.

Table 2-2. Runoff volume in acre-feet from bayside subwatersheds

Scenario	6-hour Runoff Volume (ac-ft) by Recurrence Interval					
	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Bayside Historical	8,767	11,784	14,121	17,230	19,645	22,039
Bayside Median (RCP 8.5)	9,966	13,816	17,515	23,175	27,740	32,775

Table 2-3 shows the modeled effectiveness of GI in offsetting the impact of climate change on runoff from all land uses (i.e., difference in runoff between median RCP 8.5 and historical) on the bayside. GI offsets runoff increases by as much as 29.9% for the 2-year (more frequent) storm, and reduces for larger and less frequent storm events with 3.3% for the 100-year storm. Figure 2-1 further illustrates that GI may be a considerable benefit to climate resiliency by offsetting runoff increase, especially for the smaller, more frequent storm events. Recall that the GI scenario from the RAA was designed to attain pollutant reduction goals set by the MRP by 2040, and were not planned to maximize climate change impact offsets. If more GI is implemented beyond goals set by the MRP, the results below indicate that greater offsets of climate change impacts will likely be realized. It is also important to note that these calculations consider runoff from areas from the bayside that are both treated and untreated by GI. As a result, GI is expected to capture a greater percentage of the storm runoff in the areas directly treated by GI. Additionally, benefits of GI are not spatially uniform, and the relative benefits will be a function of the spatial variability of climate impacts and where GI opportunities are located. Figure 2-2 shows the percentage of projected runoff increases from all land uses that can be offset by all GI in the RAA scenario by subwatershed.

Table 2-3. Runoff captured by GI in the bayside subwatersheds

Climate Change		6-hour Runoff Depth (in.) by Return Period					
Model	Implementation Scenario	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Runoff Depth Captured by GI		0.040					
Historical	Runoff Depth	0.97	1.30	1.56	1.90	2.17	2.44
	% Capture	4.1%	3.0%	2.5%	2.1%	1.8%	1.6%
Median (RCP 8.5)	Runoff Depth	1.10	1.53	1.94	2.56	3.07	3.62
	% Capture	3.6%	2.6%	2.0%	1.5%	1.3%	1.1%
Runoff Increase		***0.133***	***0.225***	***0.375***	***0.657***	***0.895***	***1.19***
GI offsets the impact of climate change by		***29.9%***	***17.6%***	***10.5%***	***6.0%***	***4.4%***	***3.3%***

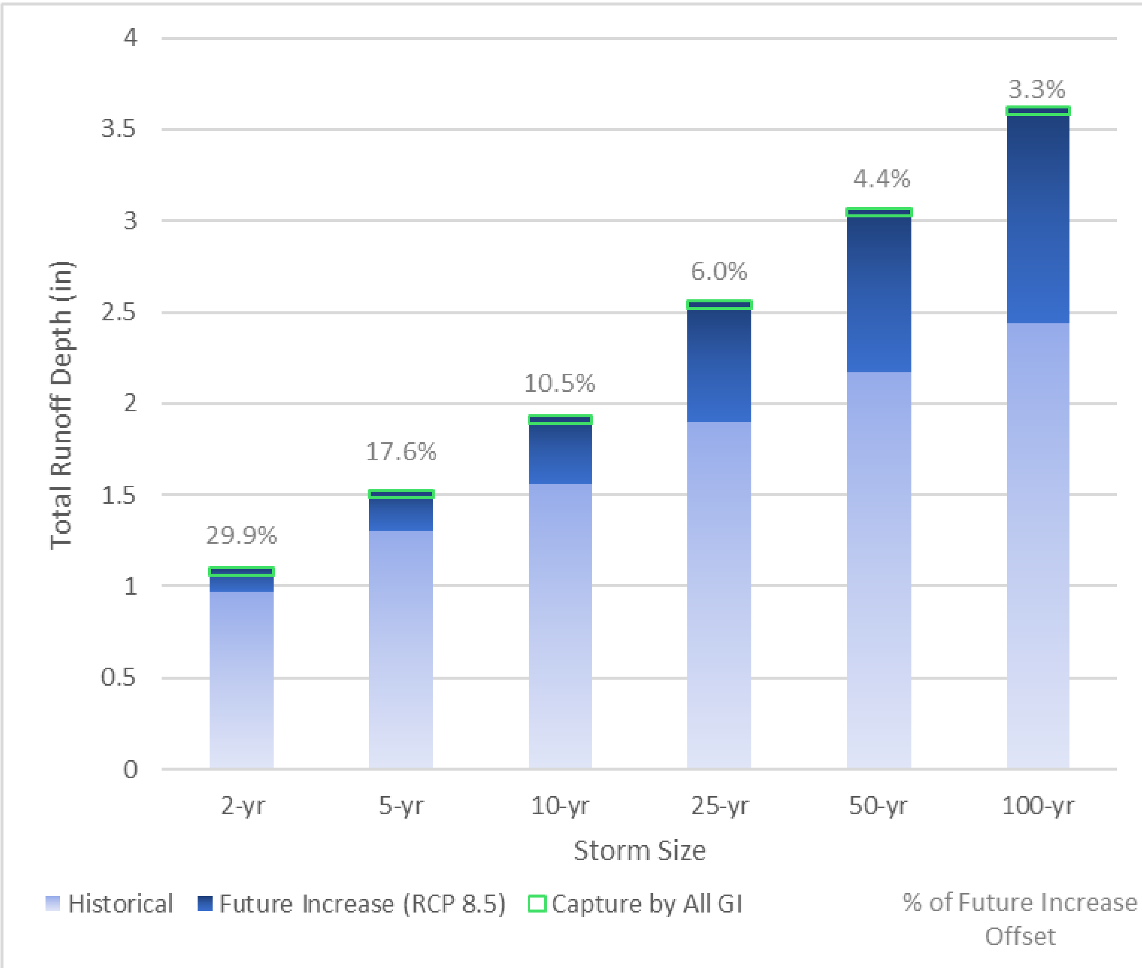


Figure 2-1. GI effectiveness in mitigating runoff increases due to climate change.

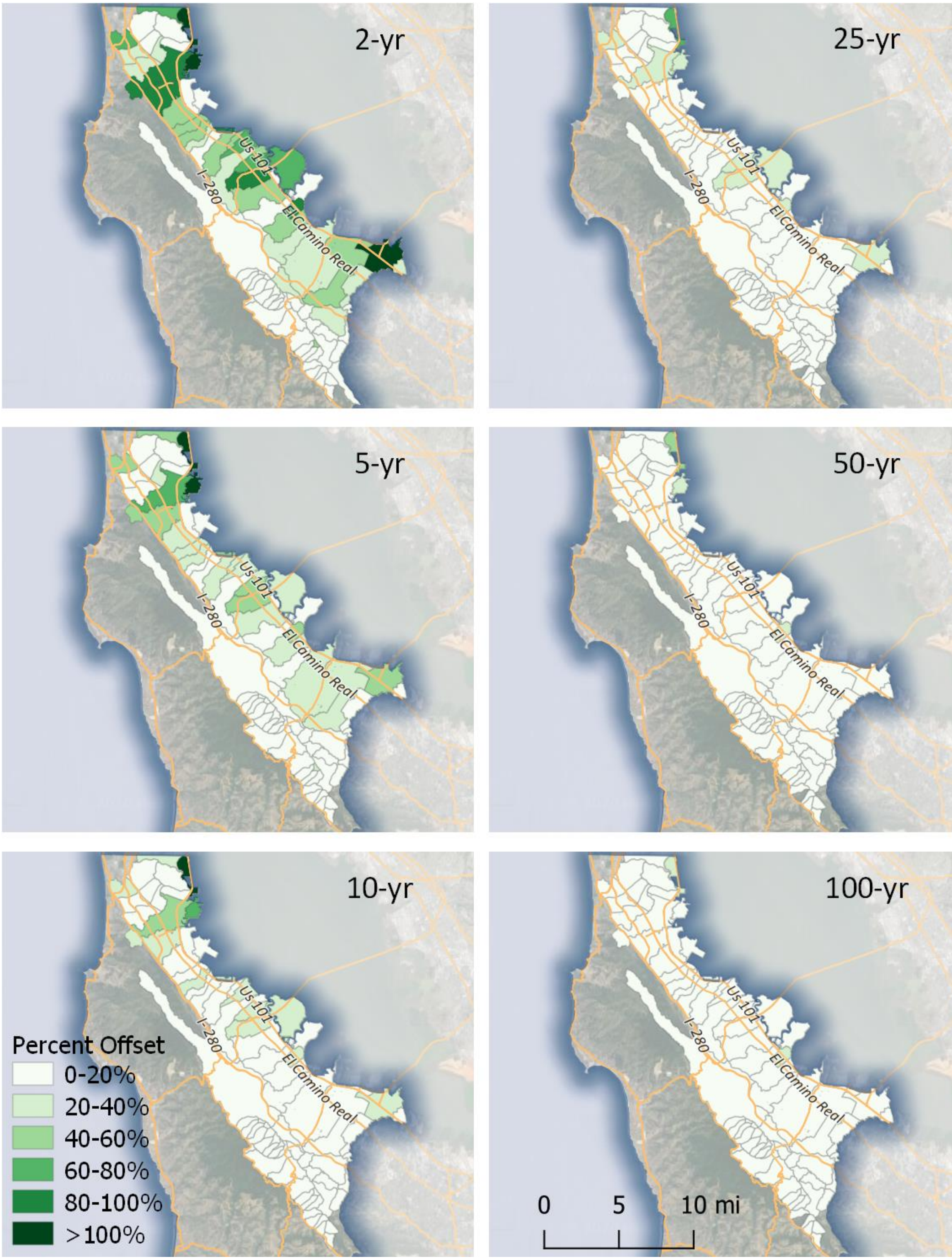


Figure 2-2. Percentage of projected runoff increase from all land uses that will be captured by the 2040 GI implementation scenario from the RAA.

2.3 GI Benefit to the Roadway Network

Runoff from the roadway network is primarily treated through distributed practices in the rights-of-way. In order to estimate the benefit sustainable streets may have on reducing road runoff, stormwater capture was quantified for a scenario with only green streets identified in the RAA. Green streets are essentially the GI component of sustainable streets. Table 2-4 summarizes the road runoff in the bayside subwatersheds under historical and future conditions, and the runoff capture from the roadway network by green streets. Figure 2-3 further illustrates the benefit of green streets to offset increases in road runoff due to climate change. Green streets identified in the RAA are projected to completely offset the road runoff increases for the 2-year storm on the bayside. Green streets are also estimated to offset the increase in road runoff during a 10-year storm, the typical design criteria for storm drain systems in the county, by as much as 39.5 percent on the bayside. These estimates include runoff from all bayside roads, both treated and untreated by green streets. It is likely that when considering runoff from only roads treated by green streets, the percent of storm runoff captured along those roads will be even higher. This demonstrates that GI may provide significant benefits for climate resiliency for county roads, especially at the smaller range of storm sizes. Additionally, benefits of GI are not spatially uniform, and the relative benefits will be a function of the spatial variability of climate impacts and where GI opportunities are located. Figure 2-4 shows the percentage of projected runoff increases from roadways that can be offset by green streets in the RAA scenario by subwatershed.

Table 2-4. Estimated volume capture from the roadway network by distributed GI

Climate Change		6-hour Runoff Depth (in.) by Return Period					
Model	Implementation Scenario	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Road Runoff Depth Captured by Green Streets		0.015					
Historical	Road Runoff Depth	0.144	0.180	0.206	0.241	0.268	0.295
	% Capture	10.4%	8.3%	7.3%	6.2%	5.6%	5.1%
Median (RCP 8.5)	Road Runoff Depth	0.158	0.203	0.244	0.306	0.355	0.409
	% Capture	9.5%	7.4%	6.1%	4.9%	4.2%	3.7%
Road Runoff Increase		***0.0146***	***0.023***	***0.038***	***0.065***	***0.086***	***0.114***
Green streets offset the impact of climate change by		***102.4%***	***62.6%***	***39.5%***	***23.2%***	***17.3%***	***13.1%***

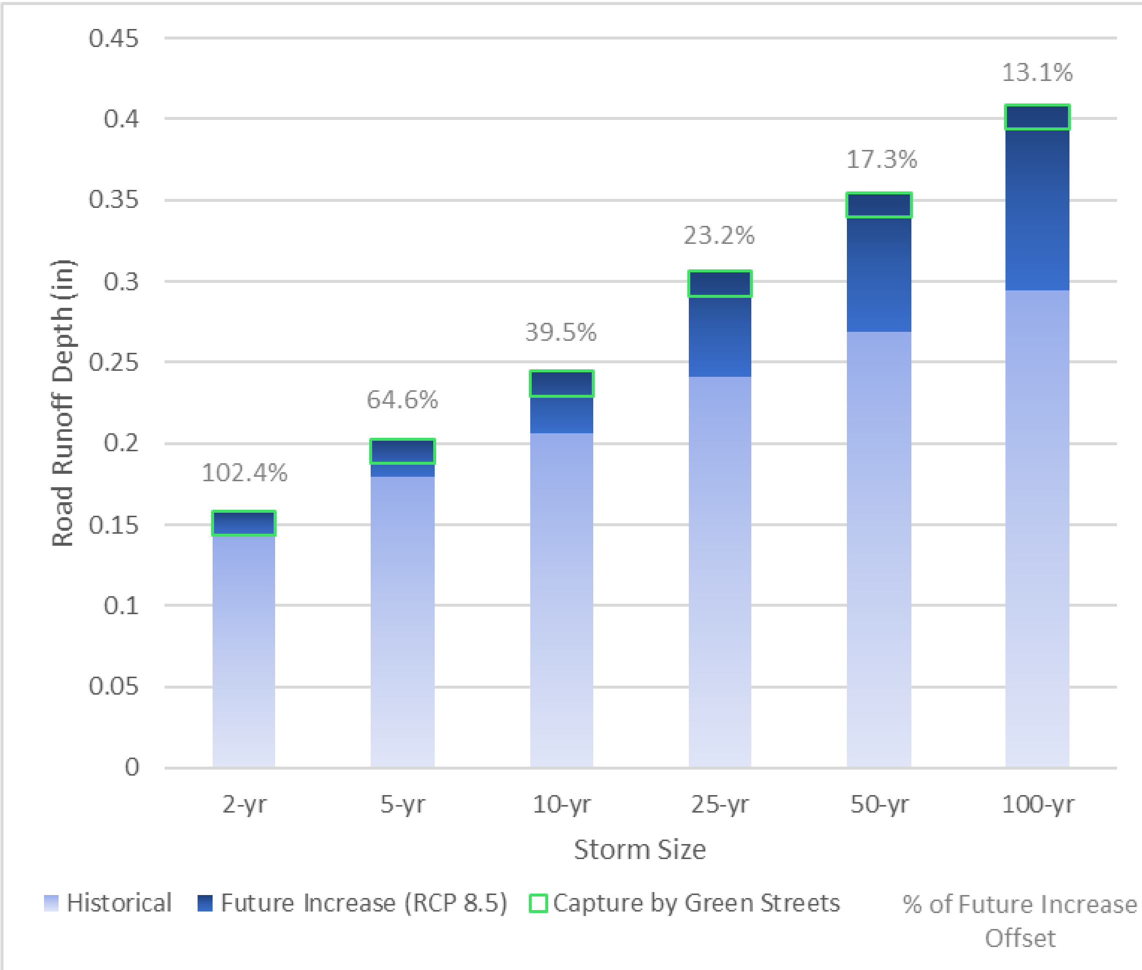


Figure 2-3. Green street effectiveness in mitigating road runoff increases due to climate change.

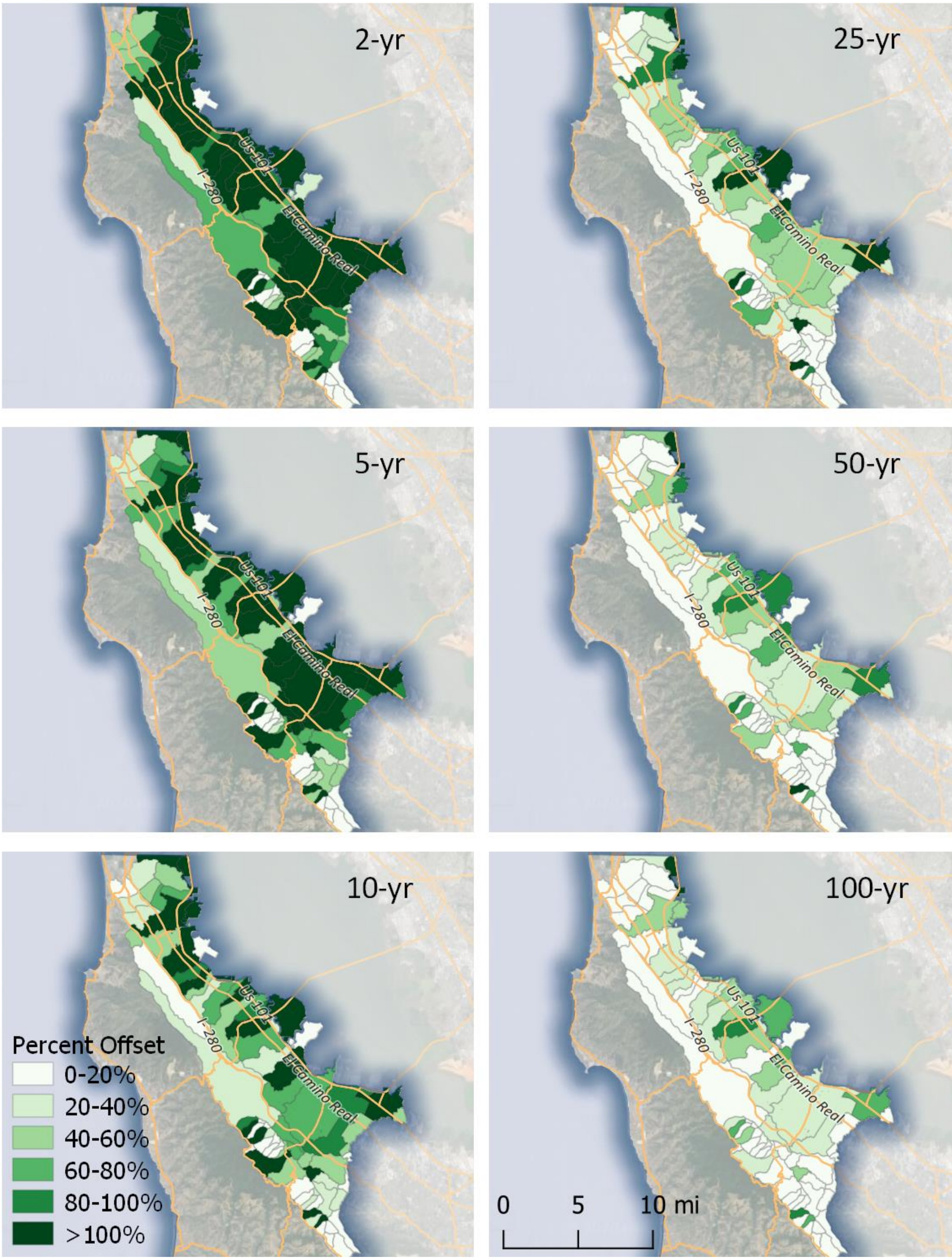


Figure 2-4. Percentage of projected runoff increase from roadways captured by green streets in the 2040 GI implementation scenario from the RAA.

3 CONCLUSIONS

The model results demonstrate that, when considering runoff from the roadways, the GI components of sustainable streets (green streets in the RAA) can have a meaningful impact on providing climate resiliency – especially for smaller, more frequent storm events. The sustainable streets are capable of completely offsetting the future increased runoff from the 2-year storm, 65% of runoff increase for the 5-year storm, and 40% of the increase for the 10-year storm. Since GI is capable of offsetting 40% of the future increased runoff for the 10-year storm, the design standard for most storm drains in the county, this may translate to fewer dollars required for expensive storm drain retrofits that would be needed to adapt to climate change. This analysis was conducted with the following key assumptions:

- The future climate scenario is based on the median of the 10 GCMs in Cal-Adapt for a conservative carbon emission scenario (RCP 8.5) where present-day carbon emissions remain constant. Improvements in clean technology and introduction of more aggressive regulations on carbon emissions in the future may improve the outlook on climate impacts and GI may, on a relative basis, be able to offset a greater portion of future runoff increases.
- The GI scenario evaluated in this analysis was not designed to meet specific climate resiliency goals. This is because the existing models leveraged for this analysis were developed for the RAA, which was meant to address water quality requirements in the San Francisco Bay. The scenario prescribes green streets with the capacity to store 36.5 gallons across 1,200 miles of roads on the bay side of the county, which only accounts for 43% of the total roadway in the county. Additional opportunities for GI that may be identified in the future may improve the amount of climate resiliency that can be provided by GI. Additionally, GI is just one possible solution for climate resiliency and addressing the county's adaptation needs will likely require a combination of solutions, including improvements to the county's gray infrastructure (expanded storm drain capacity, sea walls, pump stations, etc.).

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APPENDIX A: PRECIPITATION DEPTH MAPS

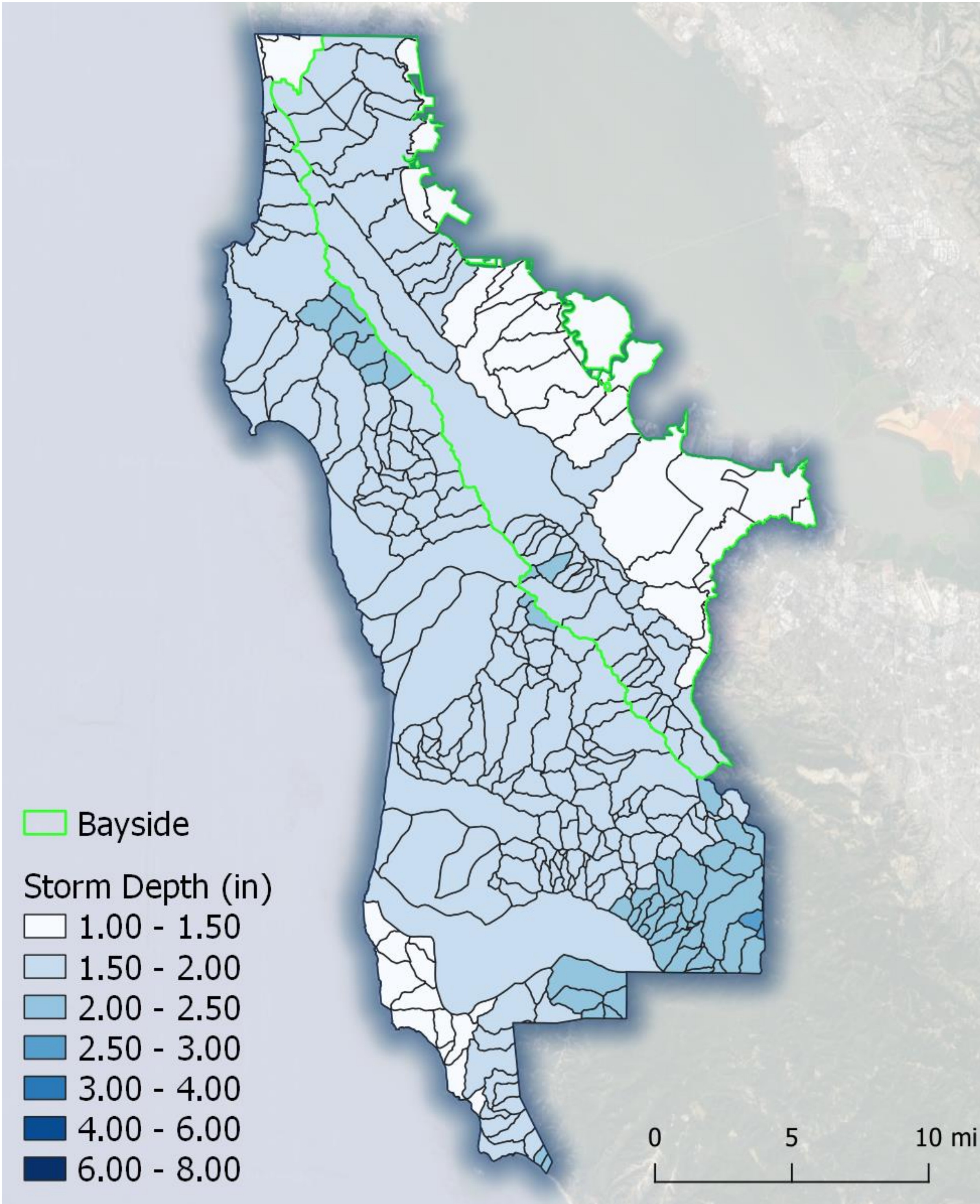

Figure A-1. Historical storm depths for the 2-year, 6-hour storm.

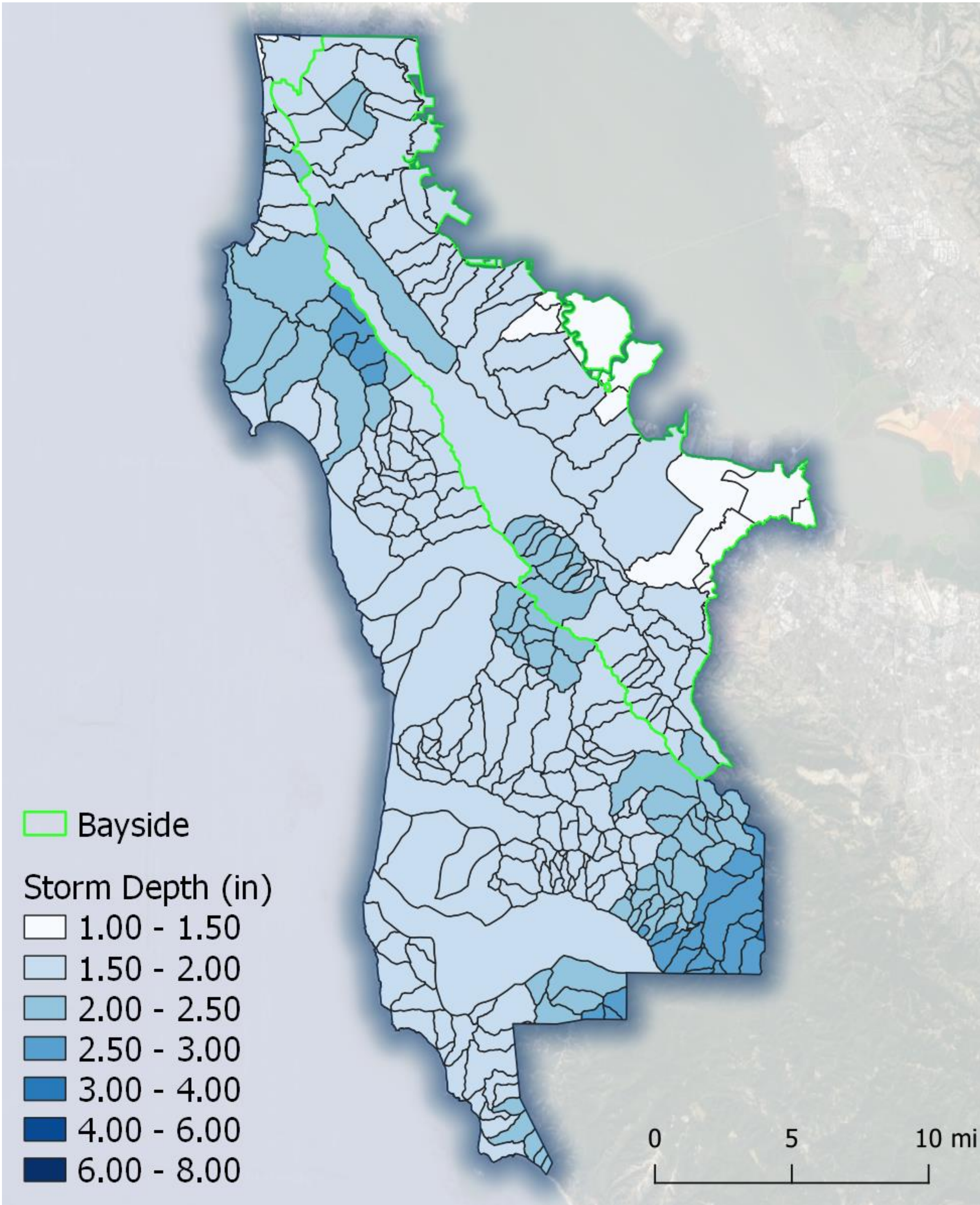

Figure A-2. Future (median RCP 8.5) storm depths for the 2-year, 6-hour storm.

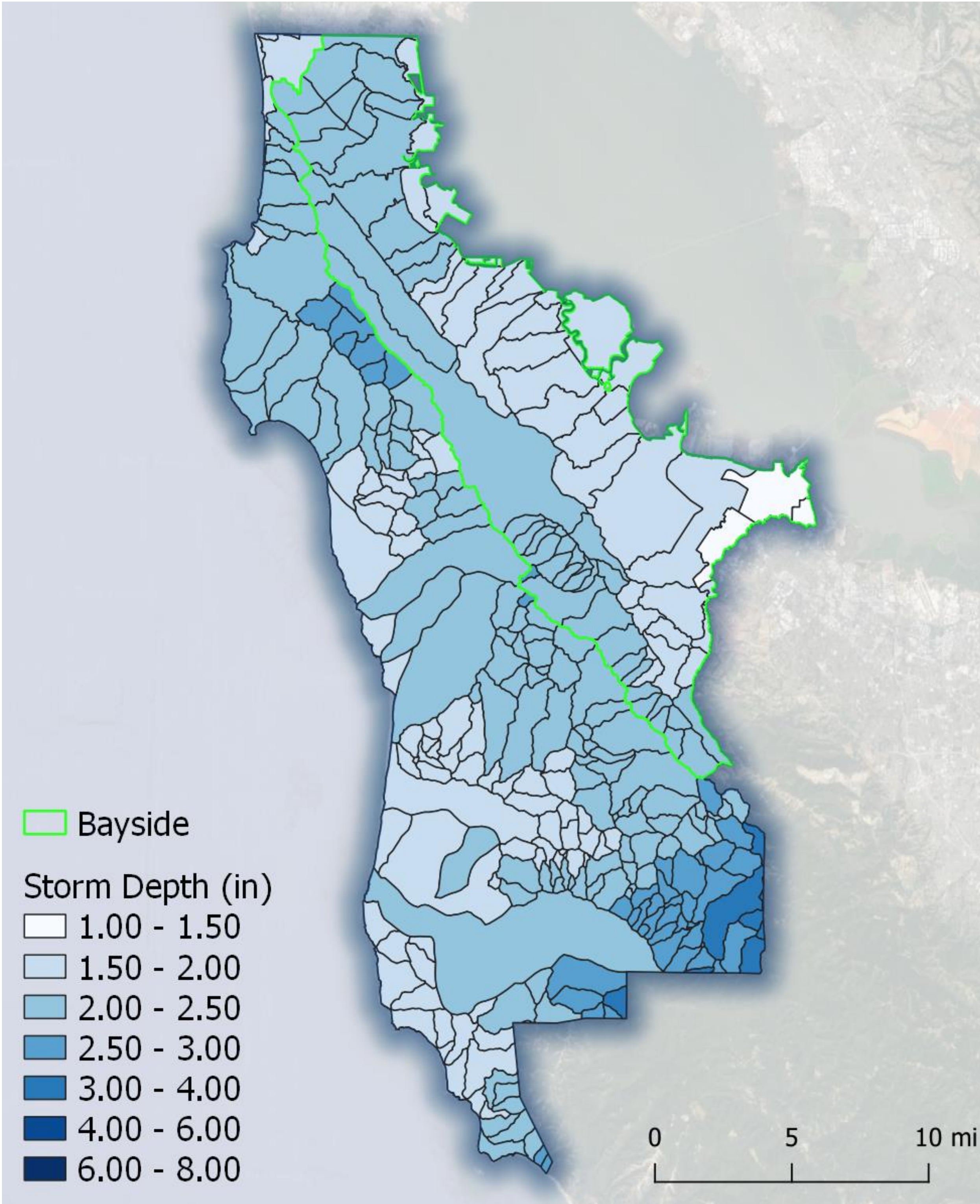

Figure A-3. Historical storm depths for the 5-year, 6-hour storm.

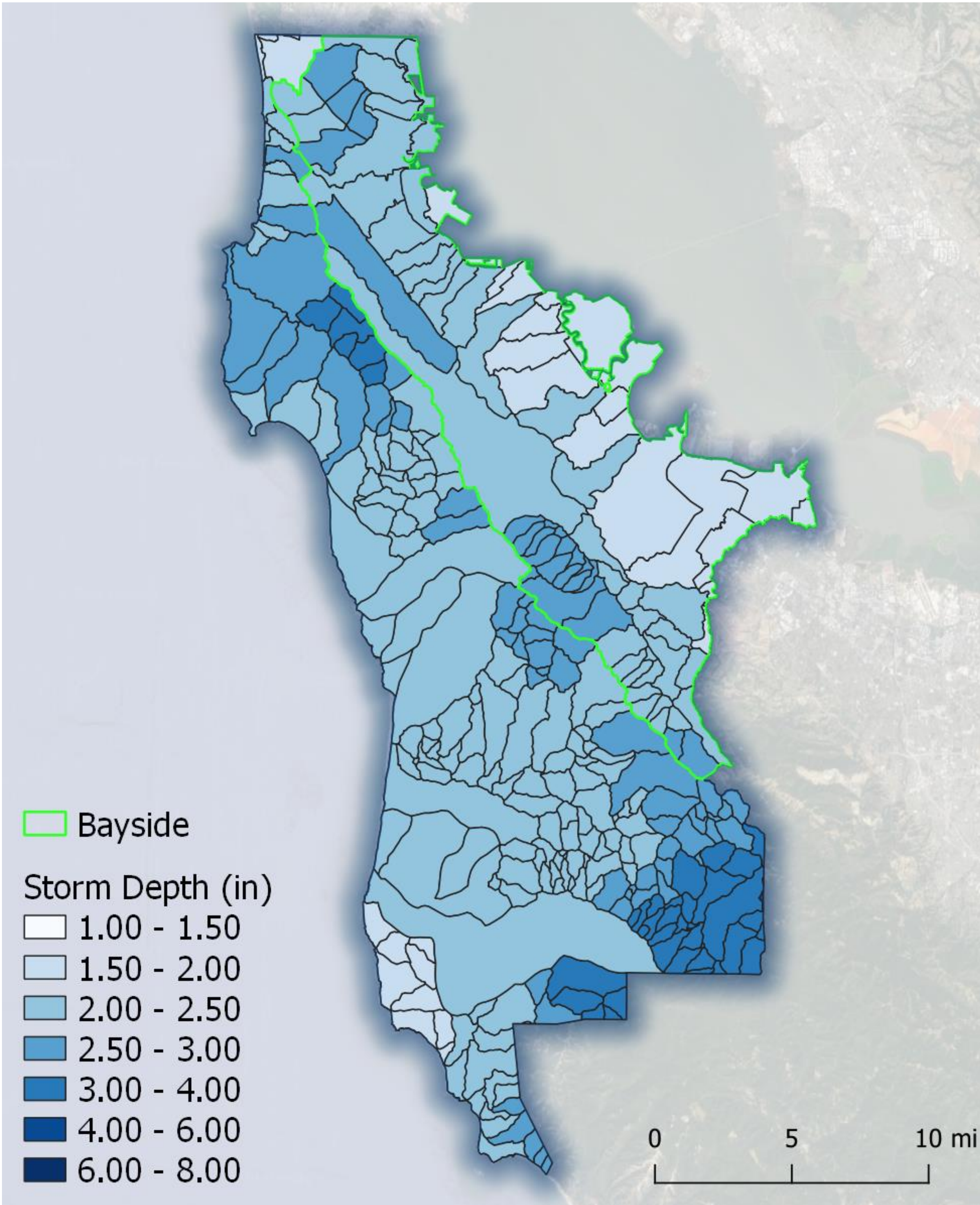

Figure A-4. Future (median RCP 8.5) storm depths for the 5-year, 6-hour storm.

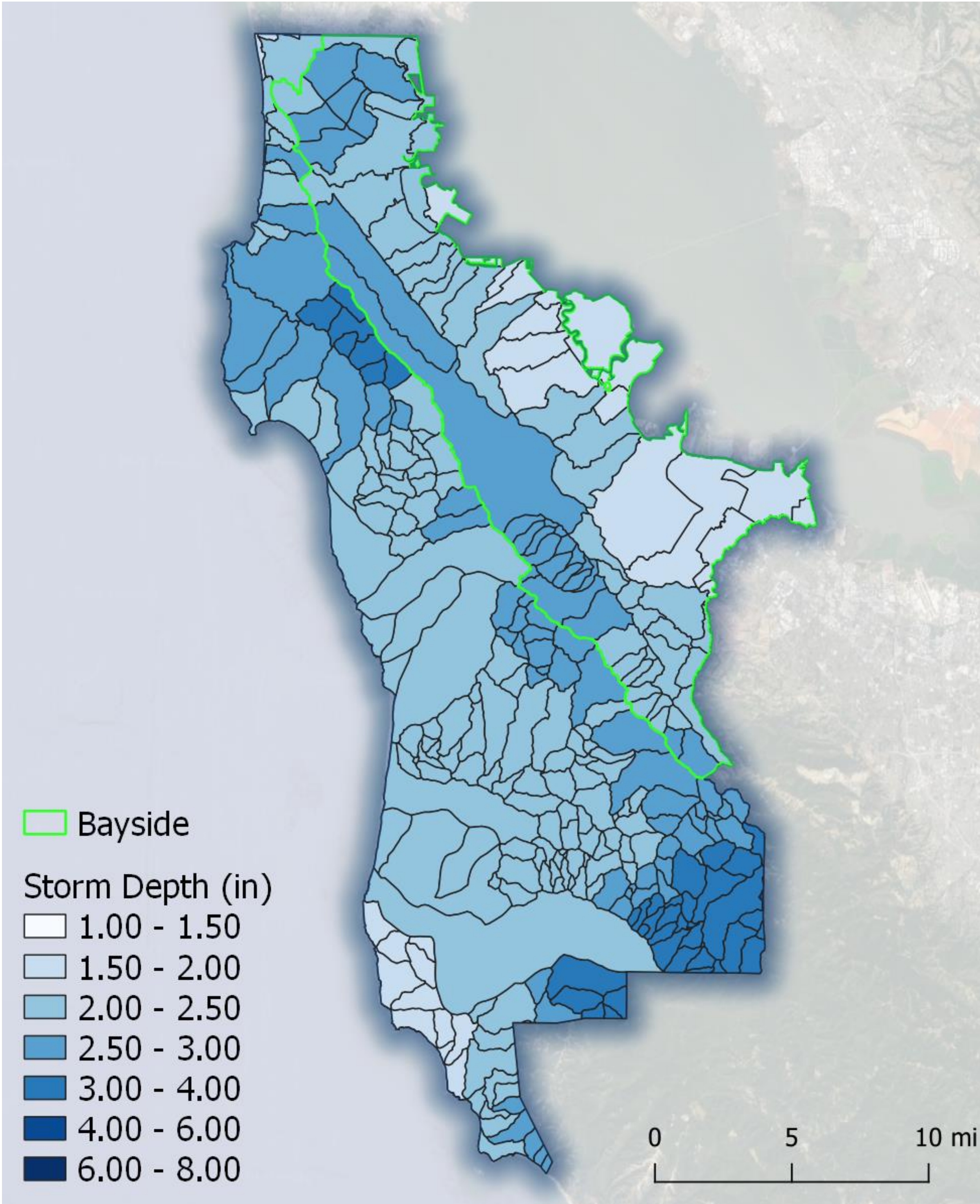

Figure A-5. Historical storm depths for the 10-year, 6-hour storm.

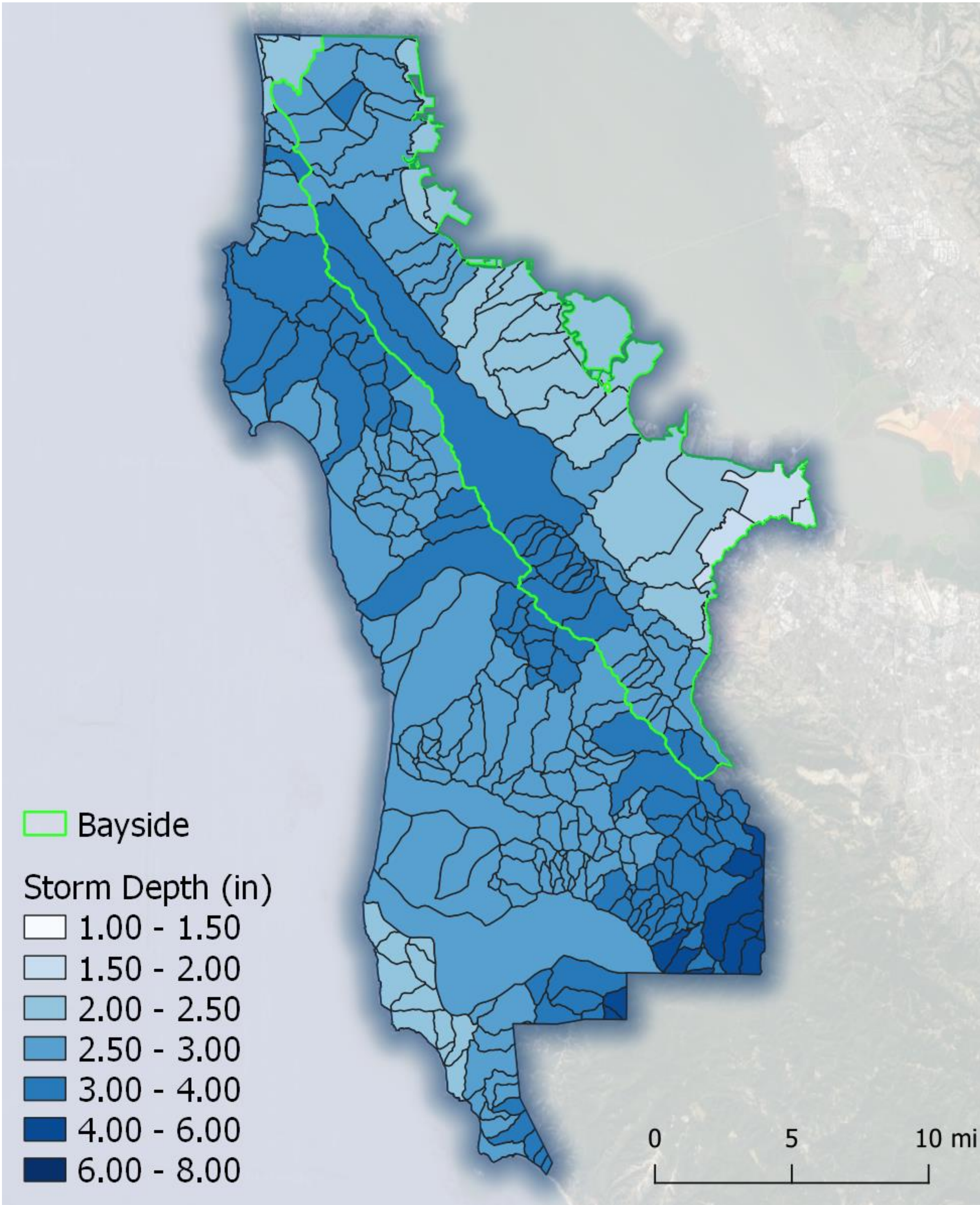

Figure A-6. Future (median RCP 8.5) storm depths for the 10-year, 6-hour storm.

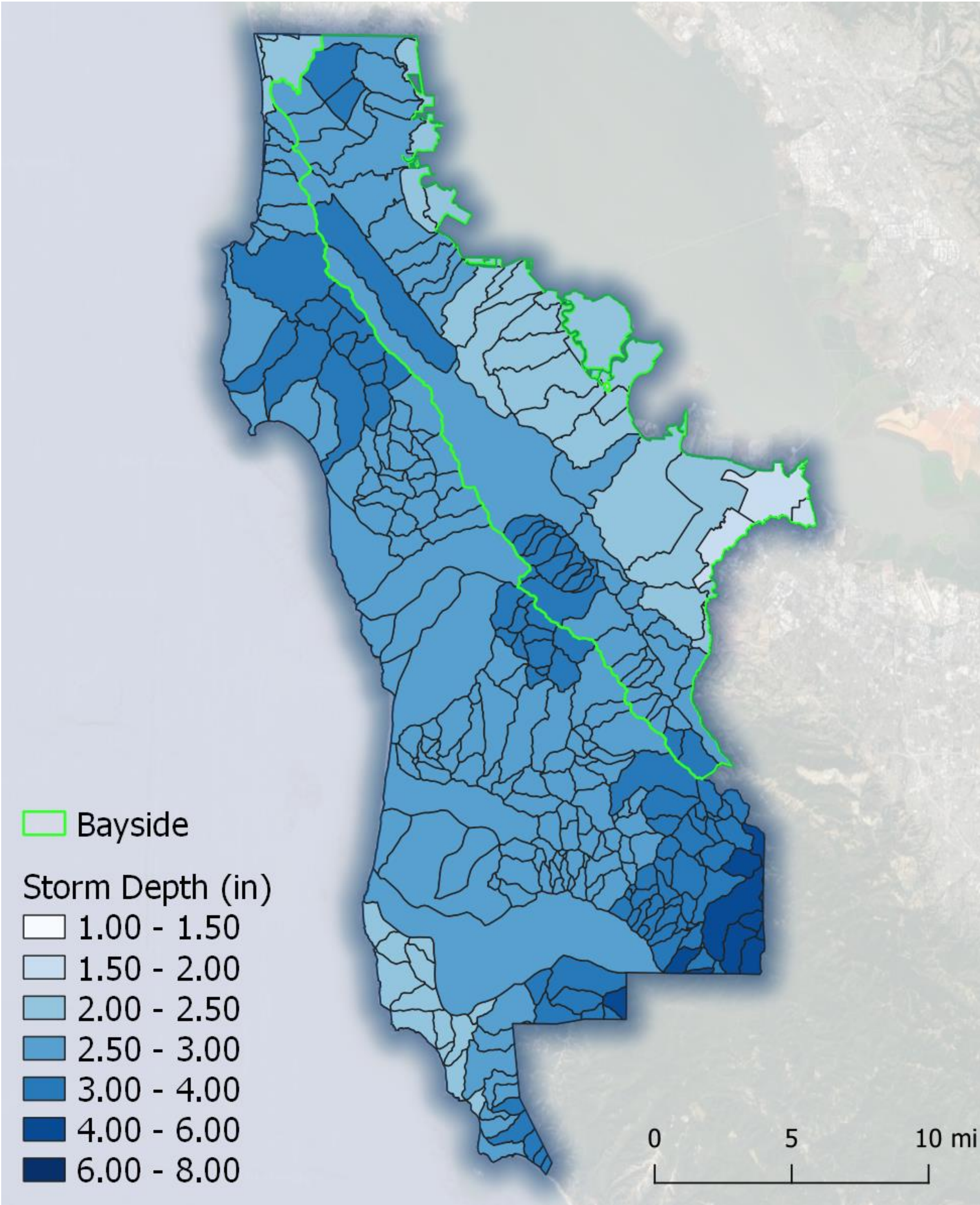

Figure A-7. Historical storm depths for the 25-year, 6-hour storm.

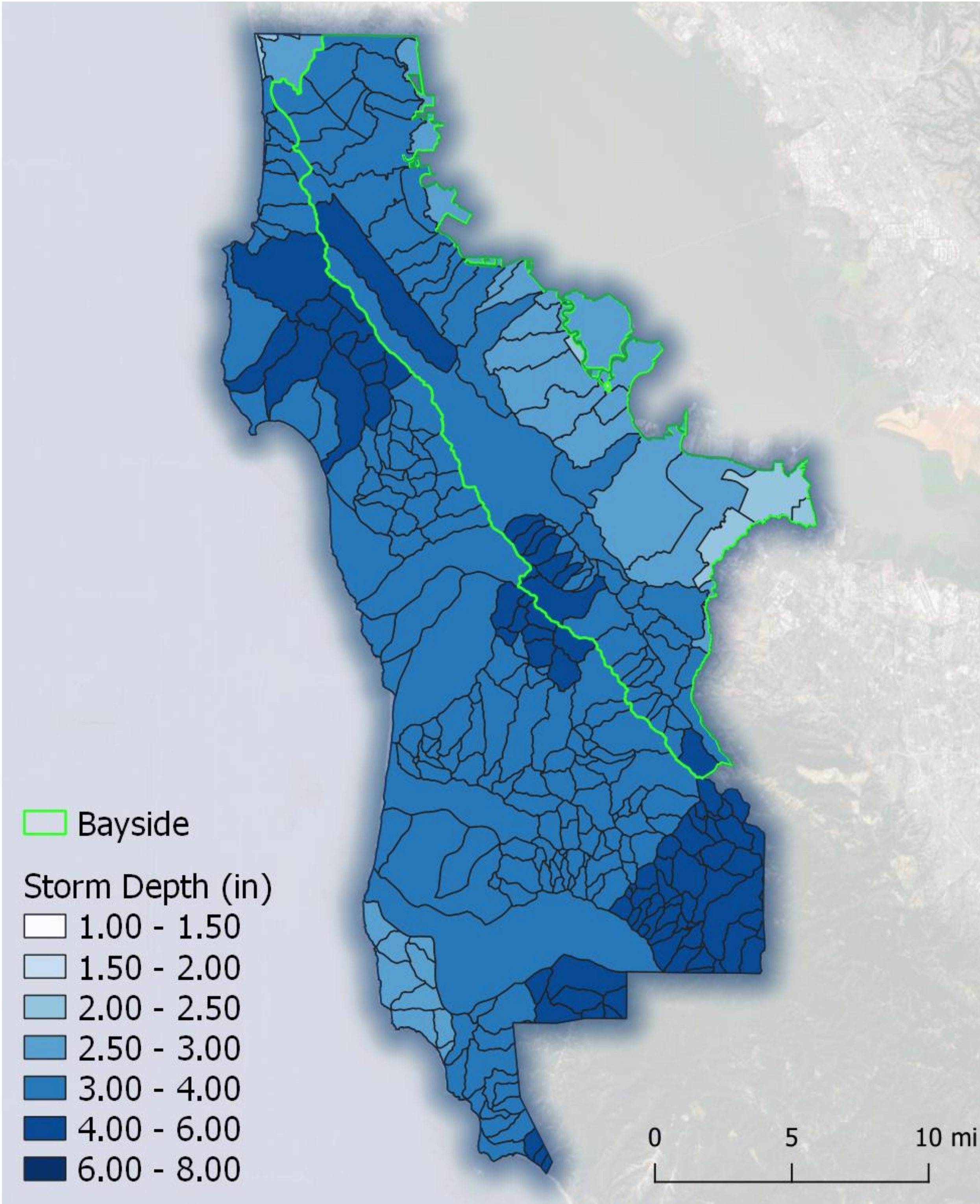

Figure A-8. Future (median RCP 8.5) storm depths for the 25-year, 6-hour storm.

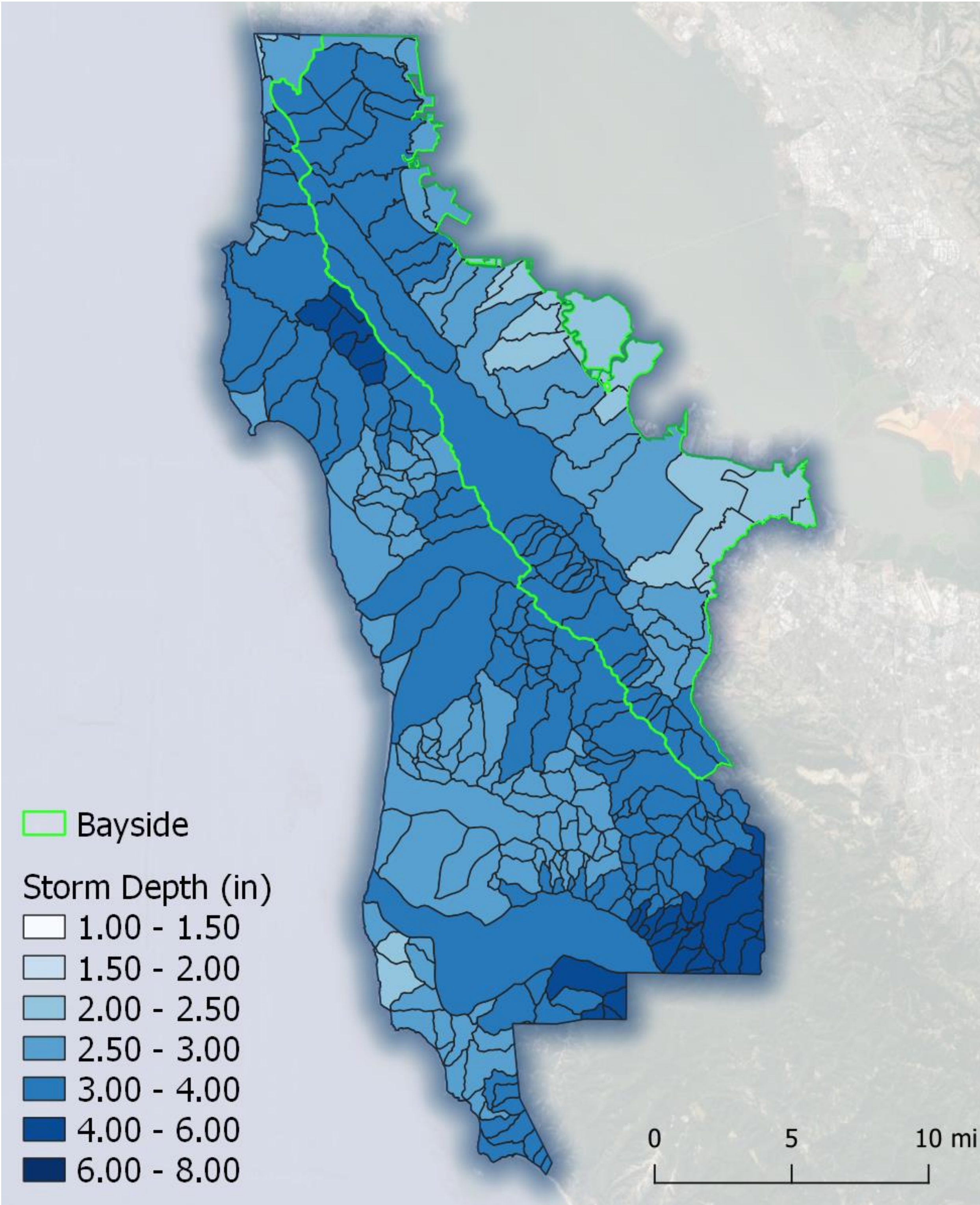

Figure A-9. Historical storm depths for the 50-year, 6-hour storm.

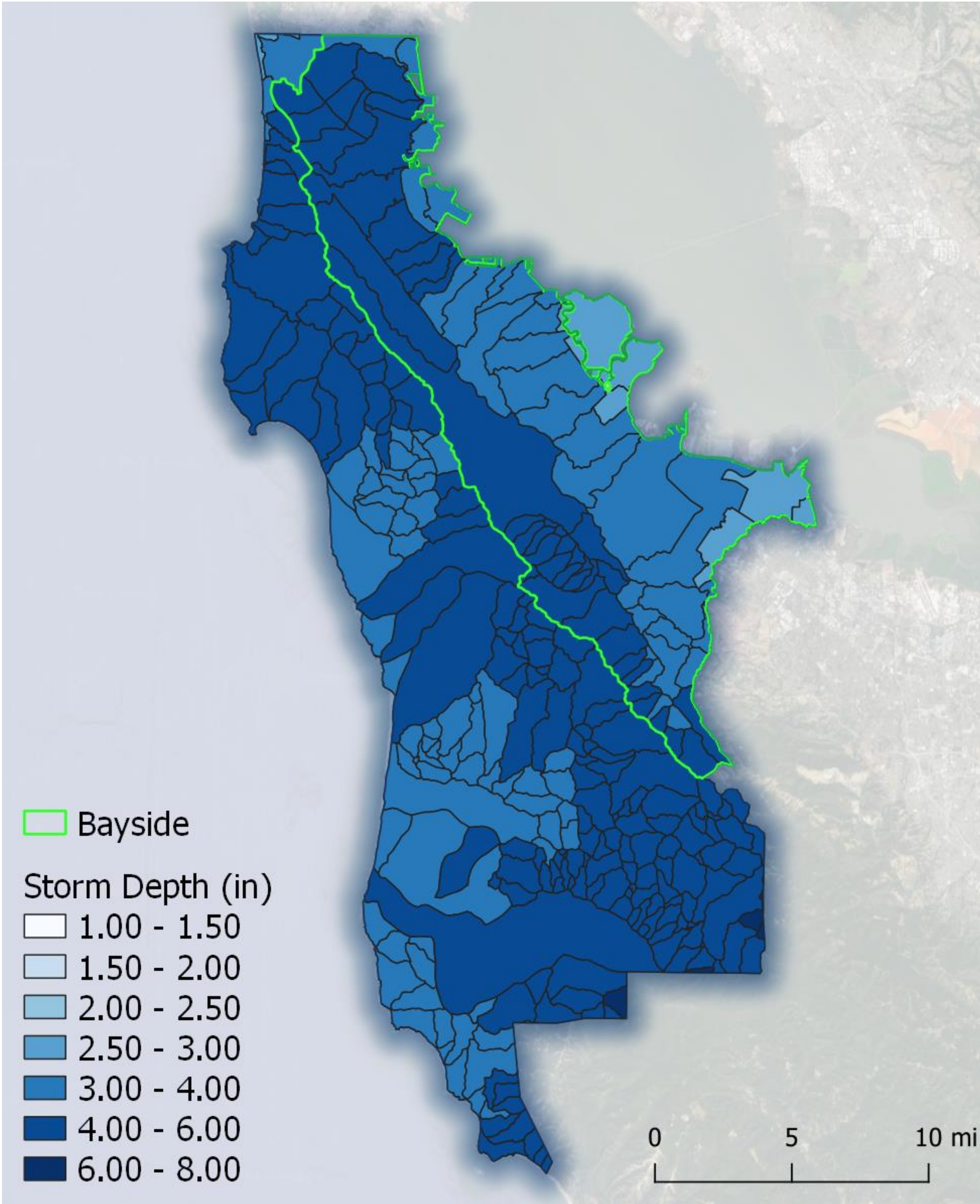

Figure A-10. Future (median RCP 8.5) storm depths for the 50-year, 6-hour storm.

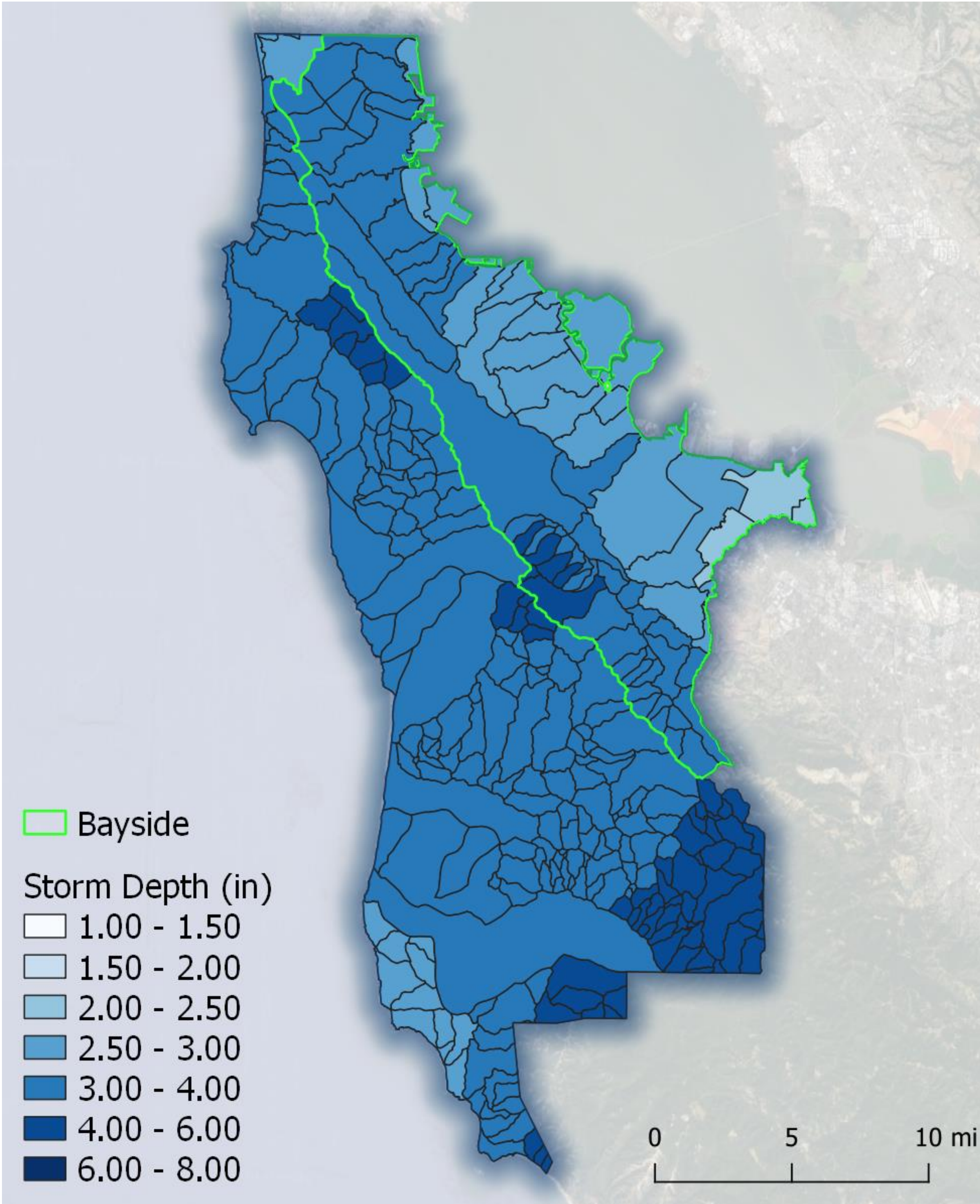

Figure A-11. Historical storm depths for the 100-year, 6-hour storm.

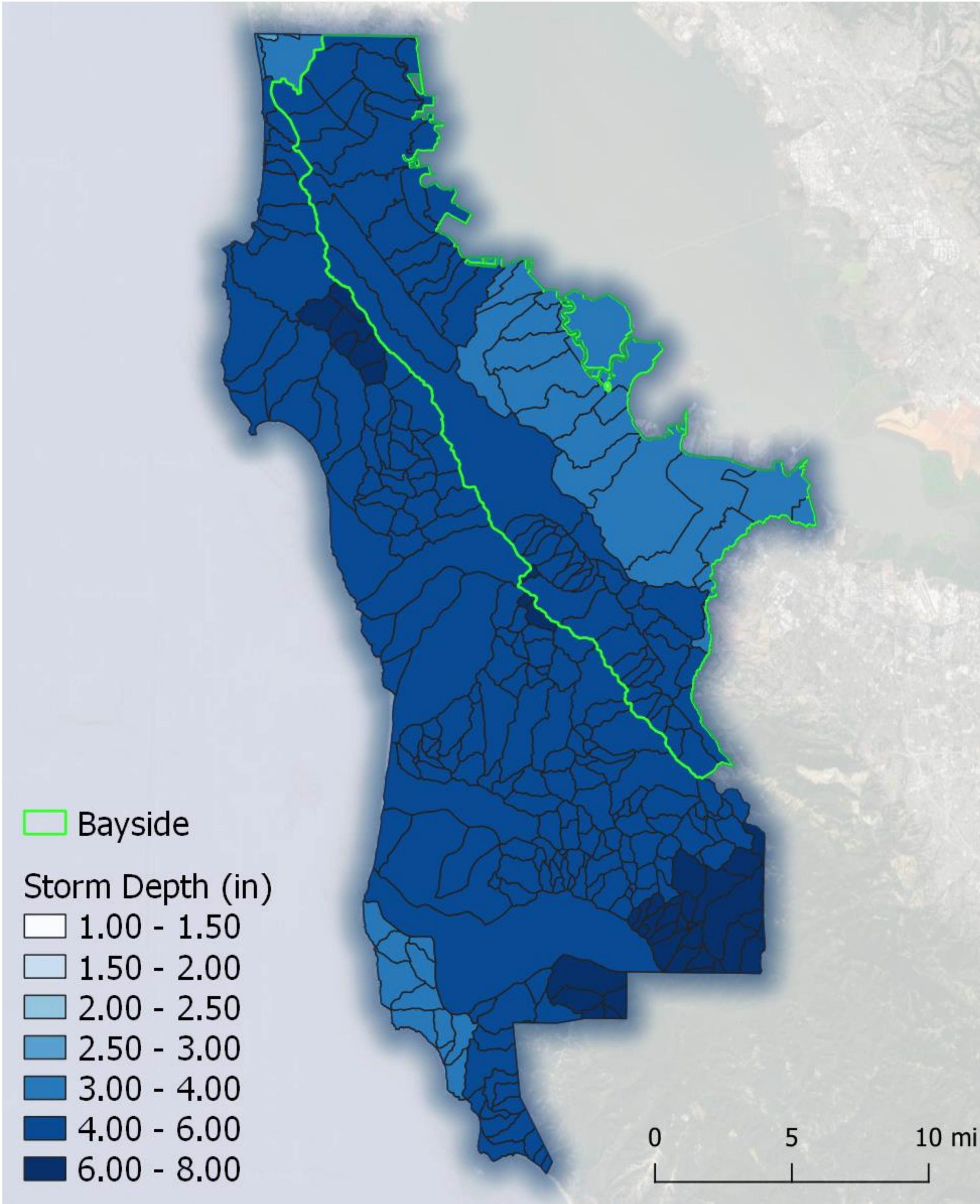

Figure A-12. Future (median RCP 8.5) storm depths for the 100-year, 6-hour storm.

APPENDIX B: RUNOFF INCREASE MAPS

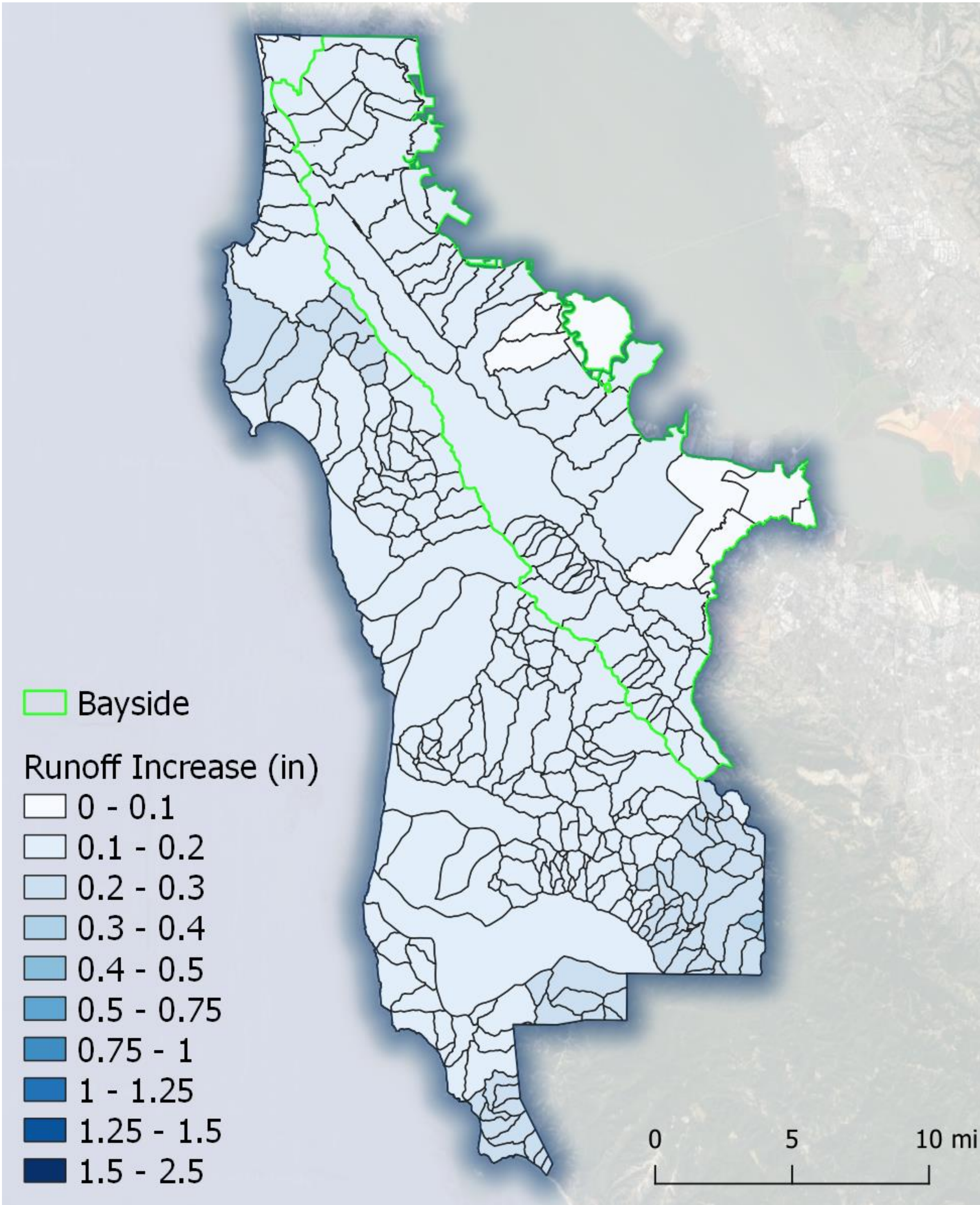

Figure B-1. Increase in runoff due to climate change (median RCP 8.5) for the 2-year, 6-hour storm.

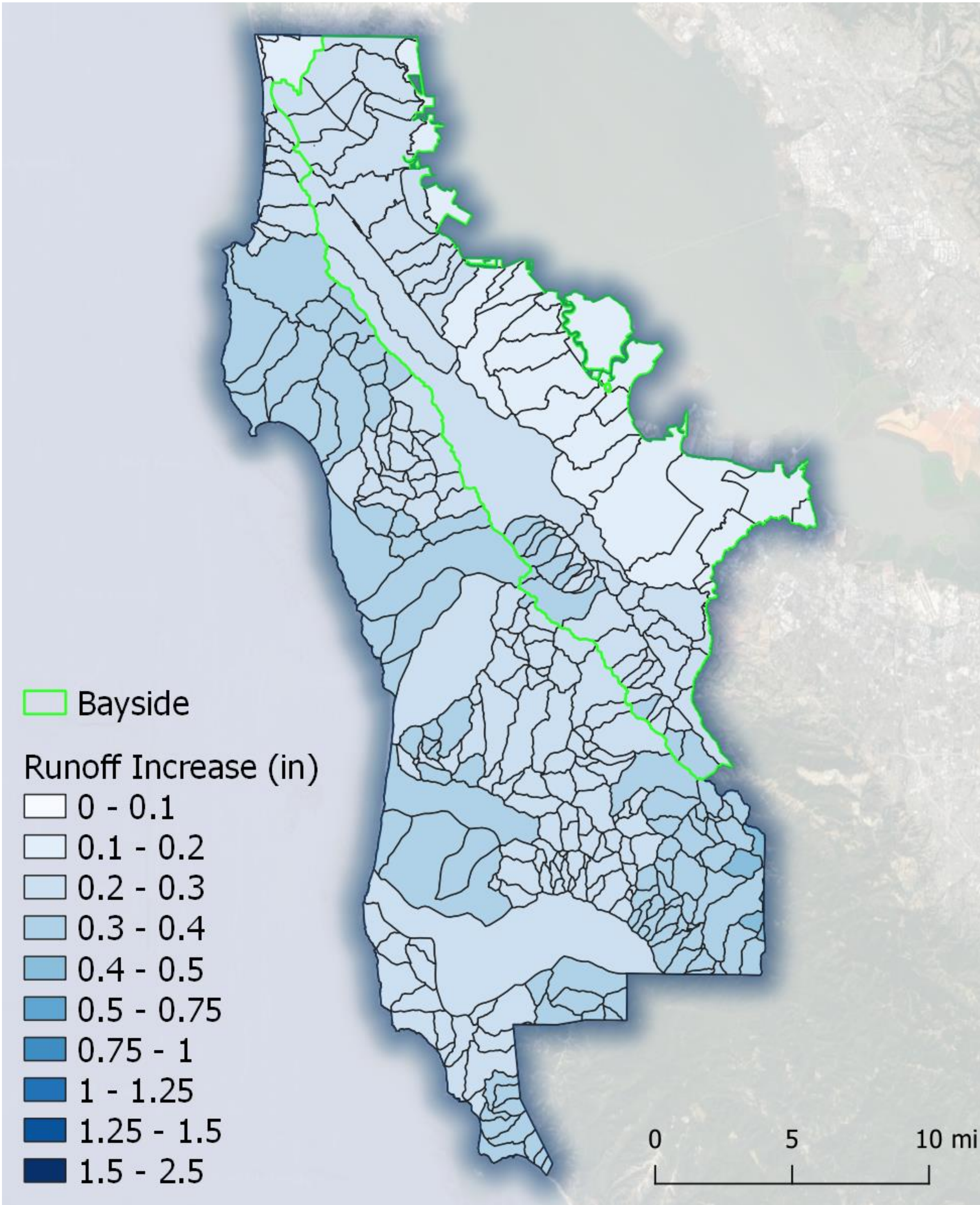

Figure B-2. Increase in runoff due to climate change (median RCP 8.5) for the 5-year, 6-hour storm.

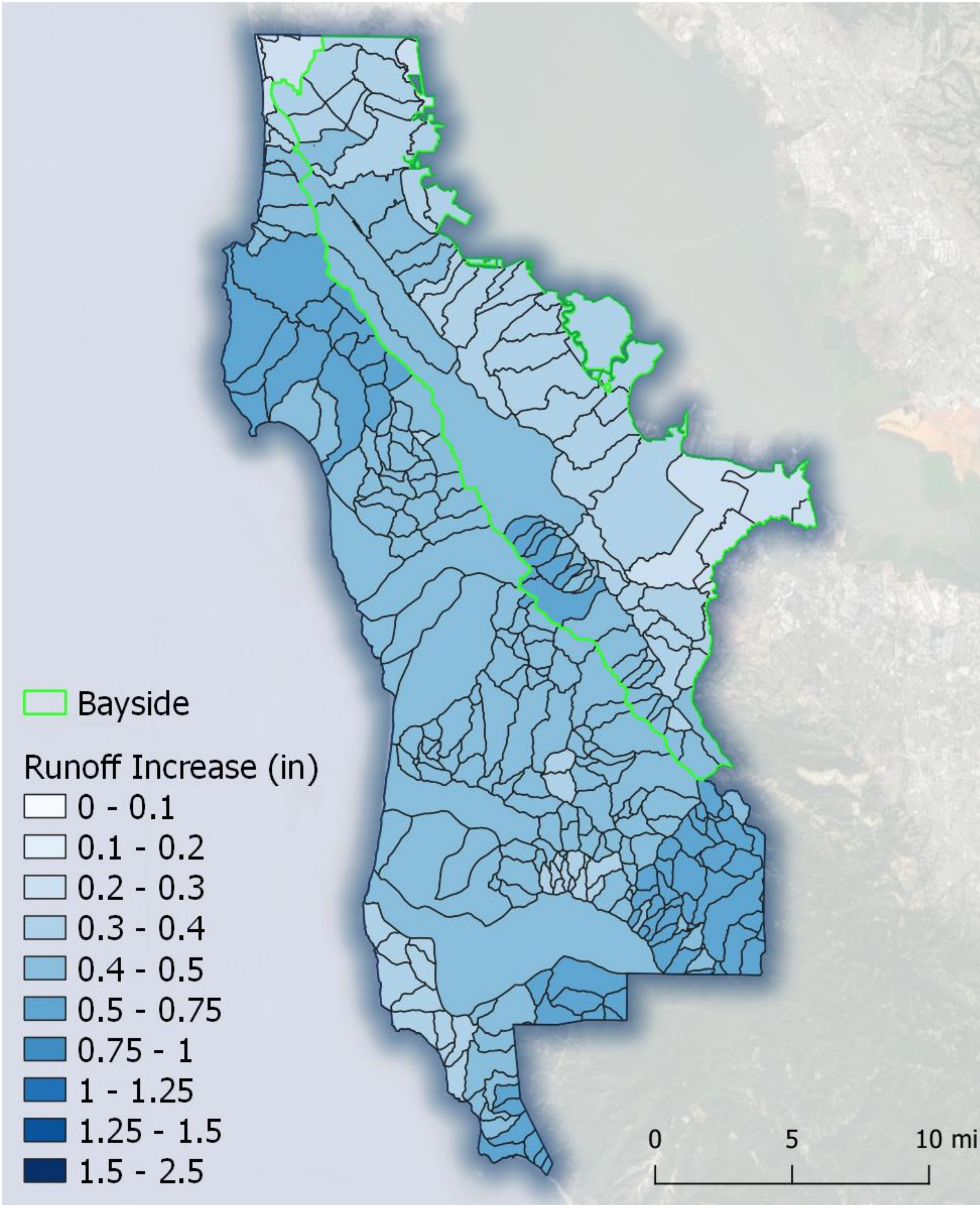

Figure B-3. Increase in runoff due to climate change (median RCP 8.5) for the 10-year, 6-hour storm.

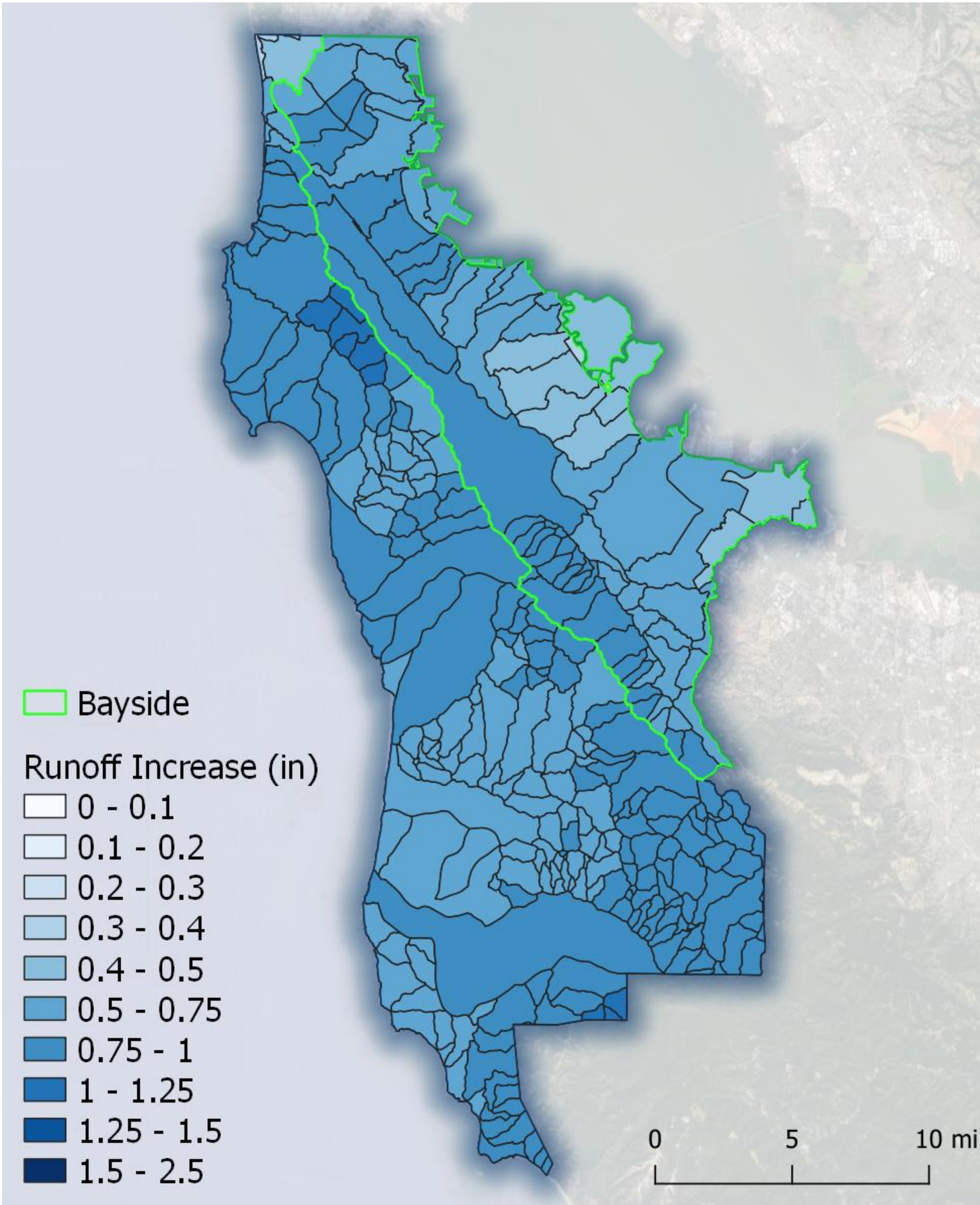

Figure B-4. Increase in runoff due to climate change (median RCP 8.5) for the 25-year, 6-hour storm.

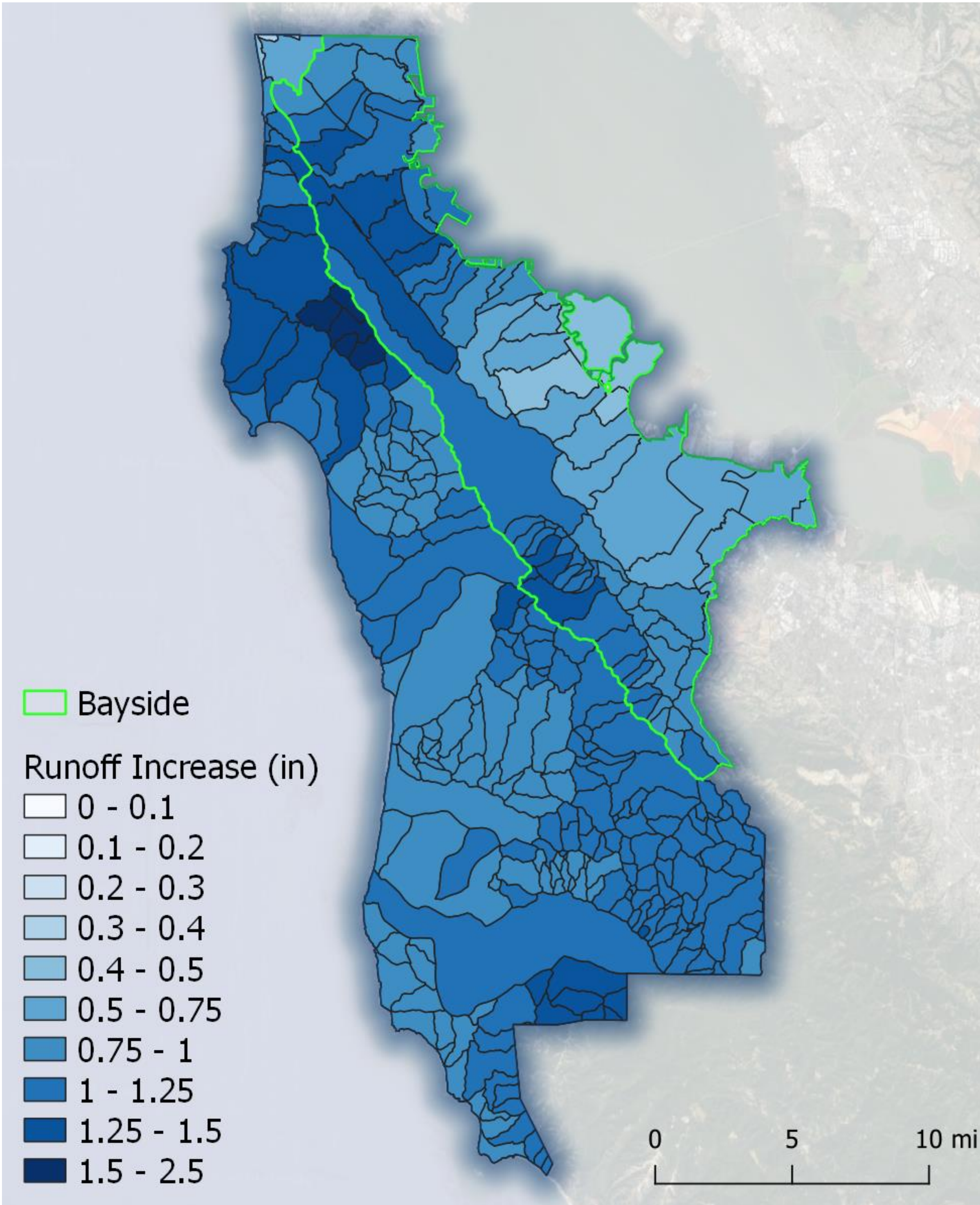

Figure B-5. Increase in runoff due to climate change (median RCP 8.5) for the 50-year, 6-hour storm.

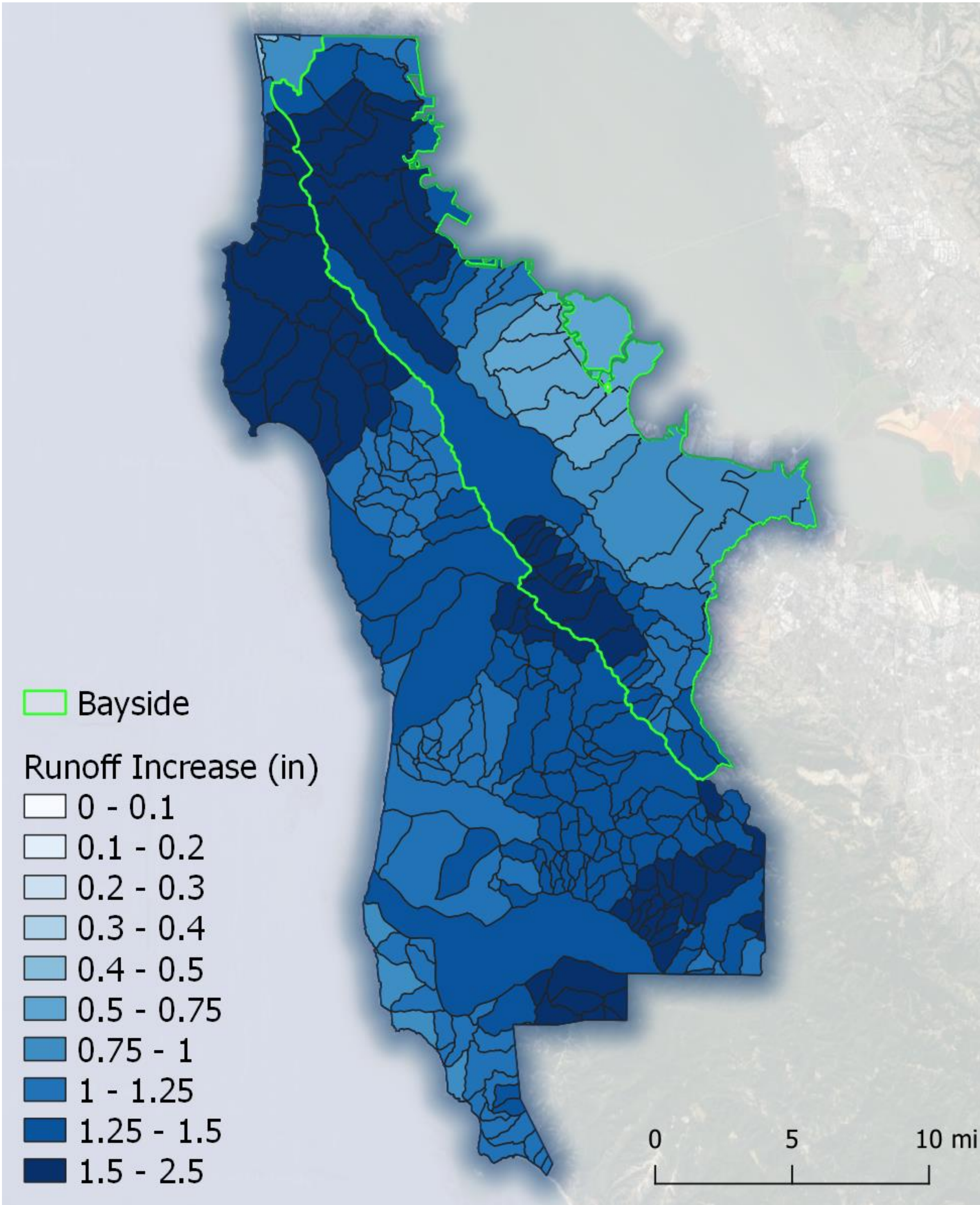

Figure B-6. Increase in runoff due to climate change (median RCP 8.5) for the 100-year, 6-hour storm.