Final Report

STAFFORD LAKE AND NOVATO CREEK

Hydrologic and Hydraulic Analysis

Prepared for
North Marin Water District

Marin County Flood Control District

June 2025

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Stafford Lake and Novato Creek Hydrologic and Hydraulic analysis

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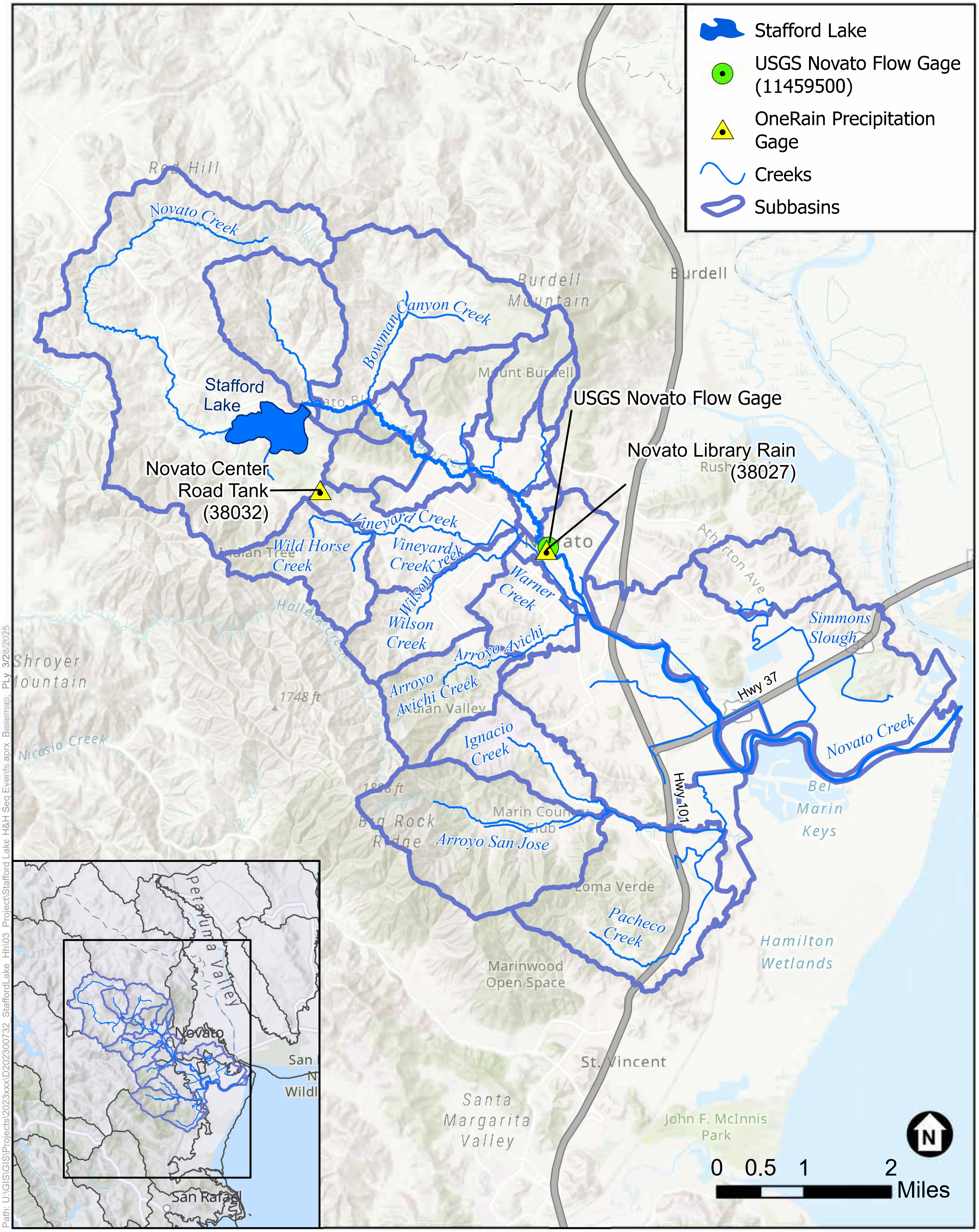
CHAPTER 1
Introduction and Background

The North Marin Water District (NMWD) is evaluating a project to increase the storage capacity of its Stafford Lake reservoir (California Dam No. 88-0 and National ID No. CA00321), located four miles west of downtown Novato. The proposed project will increase the storage capacity of the Stafford Lake dam by modifying the existing spillway with an adjustable 3-foot sluice gate. A map of the watershed including subbasins in the hydrologic model is provided in Figure 1.

This technical report provides the basis and methodology for updating the PMF to reflect more modern changes in this methodology, provides analysis of the impact of consecutive design storm events (sequential events) of flood inundation, characterizes extreme event hydrology to evaluate the performance of the existing and proposed spillway (with a gate), and summarizes the key results of the coupled hydrologic and hydraulic modeling of extreme events under present day and future climate conditions in HEC-HMS and HEC-RAS. All model files are included under Digital Appendix B.



SOURCE: ESRI Aerial Imagery (2024), USGS discharge gage (2024);
County of Marin OneRain precipitation gage (2024), ESA model subbasins and creeks (2024)

D202300732.00 - Stafford Lake Hydrology and Hydraulics

Figure 1
Map of Novato Creek Watershed and Study Area

ESA

1.1 Background

The Stafford Dam[1], constructed in 1951, is located four miles west of Novato in Marin County and serves as an impoundment structure for runoff with a drainage area of approximately 8.3 square miles. The reservoir underwent modifications to its spillway in 1985 to improve hydraulics and increase temporary storage behind the dam. The modified spillway consists of a lower control crest weir (elev. 196.0 feet NGVD29) measuring 10 feet wide by 3 feet high and an upper emergency spillway (elev. 199.0 feet NGVD29) measuring 32 feet in width. Figure 2 shows the existing spillway and illustrates the proposed adjustable gate.

Figure 2. Dam spillway and proposed spillway modification

The proposed adjustable gate described above would be used within the control crest weir only. In addition to the dam's spillway, stored water can be released through an intake tower located within the lake just inboard of the dam's embankment and discharged through a 30-inch diameter conduit to Novato Creek downstream of the dam structure and spillway chute.

The PMF serves as the design basis for the Stafford Lake Reservoir, which is generated by the runoff through the project drainage basin to produce an inflow PMF for the project reservoir and

[1] Known as the Novato Creek Dam (Dam Number. 88-0) in the DSOD inventory of state dams

routing the inflow hydrograph through the reservoir. The existing PMP was developed in 1961 using guidance provided by the National Weather Service (NWS) under Hydrometeorological Reports (HMR) 36 and 49 (NWS, 1961). The NWS has since released new guidance for PMP determination in California published as HMRs 58 and 59 (NWS, 1999).

The Marin County Flood Control District (MCFCD) developed a HEC-HMS and HEC-RAS model of the watershed as documented in a 2013 memorandum (MCFCD 2013). This was updated to calibrate design flow events (WRECO 2013). These models were used to evaluate PMF flood inundation extents under the existing and proposed spillway. In addition to the PMP analysis required by the Division of Safety of Dams (DSOD), additional extreme hydrologic scenarios were evaluated, including the 100-year event under existing and end-of-century climate conditions as well as sequential or back-to-back extreme rainfall events as part of this study.

1.2 Key Findings

ESA conducted modeling to evaluate a range of extreme events. Key findings for the PMP analysis include:

- Using the updated HMR 59 methodology, which accounts for convergence, convection, and seeder-feeder effects observed in orographic regions like the Marin Headlands, the 72-hour PMP estimate increases from 23.05" (current design basis) to 31.28".
- Hydrograph shape parameters including time of concentration and watershed storage coefficient were updated for this study to more accurately reflect physical conditions in the drainage upstream of the lake.
- ESA developed new spillway rating curves for the project condition with the sluice gate raised. The proposed sluice gate project when raised in place reduces outflow by 160 cubic feet per second (cfs) at 199 ft NGDVD29 (spillway crest) and 500 cfs at 214 ft NGVD29 (dam crest) compared to existing conditions. Under the PMF, the raised sluice gate configuration increases the peak reservoir stage by 0.6 feet. However, freeboard remains at 2.6 feet.
- The proposed updated PMF inflow and outflow developed for this study are compared to the current design values in the 1985 design report for current and raised-gate spillway conditions.
- The lake maintains freeboard greater than 2-feet for the PMF under both current and raised-gate conditions.

TABLE 1. SUMMARY OF PMF FLOWS UNDER PRESENT-DAY AND FUTURE CONDITIONS

<table>
<tr><th>Hydrologic Scenario</th><th>Spillway Configuration</th><th>Climate Condition</th><th>Peak Inflow at Stafford Lake (cfs)</th><th>Peak Outflow at Stafford Lake (cfs)</th><th>Peak Flow at USGS Gage 11459500 (cfs)</th></tr>
<tr><td>PMF</td><td>Gate lowered</td><td rowspan="2">Present Day</td><td>10,900</td><td>5,480</td><td>14,290</td></tr>
<tr><td>PMF</td><td>Fully raised sluice gate</td><td>10,900</td><td>5,460</td><td>14,240</td></tr>
<tr><td>PMF</td><td>Gate lowered</td><td>Late-century (High emissions - model mean)</td><td>12,580</td><td>6,610</td><td>16,910</td></tr>
</table>

Key findings related to sequential events include:

- Modeling of sequential events based on the timing of the January 2023 storms shows that Stafford Lake can attenuate the initial peak and control the outflow prior to the start of larger subsequent peaks. While an initial storm peak can increase the peak flow and flooding impact of subsequent storm peaks, Stafford Lake’s attenuation ability reduces the full impact of the subsequent peak to downstream flooding in the city of Novato.

- Compared to a singular 100-year event, a sequential scenario where the 100-year is preceded by a 10-year event increases floodplain inundation extents by 17%, and by 23% when preceded by a 50-year event.

Key findings for extreme event hydrology under future climate conditions include:

- ESA extracted the annual maxima rainfall series and, following the rainfall frequency methodology from NOAA's Atlas 14 (NOAA, 2018), fit generalized extreme value (GEV) distribution curves for historical and future periods from each downscaled climate model under climate pathways SSP 2-4.5 and 5-8.5. Percent scalars for the high emissions (model mean) and E++ scenario (model mean plus two standard deviations) were calculated under SSP2-4.5 and SSP 5-8.5, and the higher percent change scalars from SSP 2-4.5 were used.

- Based on extreme value analysis of downscaled projected rainfall data from 2050-2100, the 100-year design rainfall event increases approximately 31% under a high emissions scenario (model mean). Given that the 13 climate models analyzed show a range of projections, an extremely high-risk scenario representing the model mean plus two standard deviations, referred to as the E++ scenario, was also analyzed. For the 100-year design rainfall event, the E++ scenario shows future increases of 105%. This low-likelihood, high-risk, scenario representing the upper margins of the climate projections is provided as an advisory scenario for considering possible actions to address future climate risk under uncertain future conditions.

- At the Novato Creek USGS gage (1149500), the present-day 100-year peak discharge is 4,830 cfs. Under the high emissions scenario, the estimated 100-year peak discharge is 6,890 cfs (+43%), and under the E++ scenario, the estimated peak discharge is 12,120 cfs (+150%).

- Using the same downscaled rainfall climate dataset, the 72-hour PMP is estimated to increase by 15% under the high emissions.

- Under the high emissions scenario, the updated PMF peak inflow and peak outflow at Stafford Lake is estimated to increase from 10,900 cfs and 5,480 cfs, respectively (present day), to 12,580 cfs and 6,610 cfs (2100), respectively, reducing the freeboard to 1.5 feet (gate-lowered condition).

- The future-climate scenario for the PMF is included as an advisory scenario for NMWD's future planning purposes. The modeling indicates that the Stafford Lake dam is resilient to future projected climate change, meeting DSOD's minimum residual freeboard requirement of 1.5 ft (DSOD, 2018).

CHAPTER 2
Extreme hydrology analysis

2.1 Probable maximum precipitation

The Probable Maximum Precipitation (PMP) is currently defined as the theoretically greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographic location at a certain time of year (HMR 59, NWS 1999). From the PMP, the Probable Maximum Flood (PMF) is derived from rainfall-runoff models and is commonly applied in the design of critical infrastructure. Two PMP studies were used for the design of the Stafford Lake Dam raising that occurred in 1985: Hydrometeorological Report (HMR) 36 and HMR 49 (NWS 1961 and 1977). The former document outlines the procedure for developing the PMP for a general storm or a 72-hour duration storm while the latter document summarizes the procedure for developing the PMP for a local or a 6-hour duration storm. The following summarizes the methodology for estimating the PMP depths based on HMR 58 and HMR 59, the latest reports available for updating the PMP for California.

Development of the Updated PMP Estimate

The existing PMP for Stafford Dam is 23.05 inches and was derived based on prior National Weather Service (NWS) HMRs 36 and 49. These older HMRs have been superseded by HMRs 58 and 59[2]. Intense storms that have occurred since the publication of HMR 36 have had precipitation amounts that approached, and in some instances, exceeded the PMP estimates calculated by HMR 36. Thus, HMRs 58 and 59 were developed to include the latest storm data and update techniques for calculating the PMP in particularly orographic regions such as Novato Creek and the Stafford Lake watershed (NWS, 1999). These latest HMR methodologies account for convergence, convection, and seeder-feeder effects observed in orographic regions. As a result, increases in PMP based on HMR 59 are observed in mountainous areas. From HMR 59, the change in PMP shows increases as high as 12 inches in the Novato Creek watershed[3]. To determine the PMP under HMR 59 for watersheds less than 500 square miles (Stafford Lake watershed area is 8.3 square miles), the procedure requires determining the PMP under the general 72-hour storm (the “General Storm”) and local 6-hour storm (the “Local Storm”) and taking the larger of the two PMP depth estimates. Both storms require estimating a baseline 24-hour PMP from isohyetal curves provided in the methodology and adjusting the baseline value for duration and subbasin area.

For the General Storm, the all-season 24-hour PMP isohyetal lines were downloaded as a GIS shapefile from the NWS then converted to a triangulated irregular network surface to spatially

[2] HMR 59 provides technical documentation for estimating the PMP in California, whereas HMR 58 outlines the procedure for calculating the PMP for both the general (72-hour) and local (6-hour) storms.
[3] See page 208, Figure 11.2a of HMR 59 for a graphic comparing changes in PMP depth between HMR 36 and HMR 59.

extend the data over the watershed. The 24-hour PMP at the centroid of the Stafford Lake drainage basin was estimated to be 18.4 inches. To calculate the 72-hour PMP, the 24-hour depth was scaled up by a factor of 1.7 based on Table 13.11 from HMR 59 which provides depth-duration relations for the Midcoastal Region. The calculated 72-hour PMP is 31.3 inches. Because the drainage basin above Stafford Lake is less than 10 square miles, an areal reduction factor was not required.

For the Local Storm procedure an isohyetal map of the 1-hour, 1 mi^2 storm (Figure 13.21, HMR 59) was used to interpolate a value of 5.1 inches for the Stafford Dam watershed. To translate this depth to a 6-hour duration for the watershed area of 8.3 square-miles, the 1-hour PMP was scaled by 1.3 (estimated using Figures 13.23, 13.24, and 13.27 from HMR 59) with a depth-area reduction factor of 0.95 (from Figure 13.27 in HMR 59) resulting in an estimated 6-hour PMP of 6.6 inches. As the 6-hour cumulative PMP depth for the General Storm was 8.3 inches, the General Storm methodology was selected as the watershed's PMP.

A 72-hour hyetograph with 15-min increments provided in the 1981 DSOD report was used to set the temporal distribution of the new PMP. The 72-hour PMP hyetographs for the existing PMP standard and our updated estimated PMP are compared in Figure 3.[4]

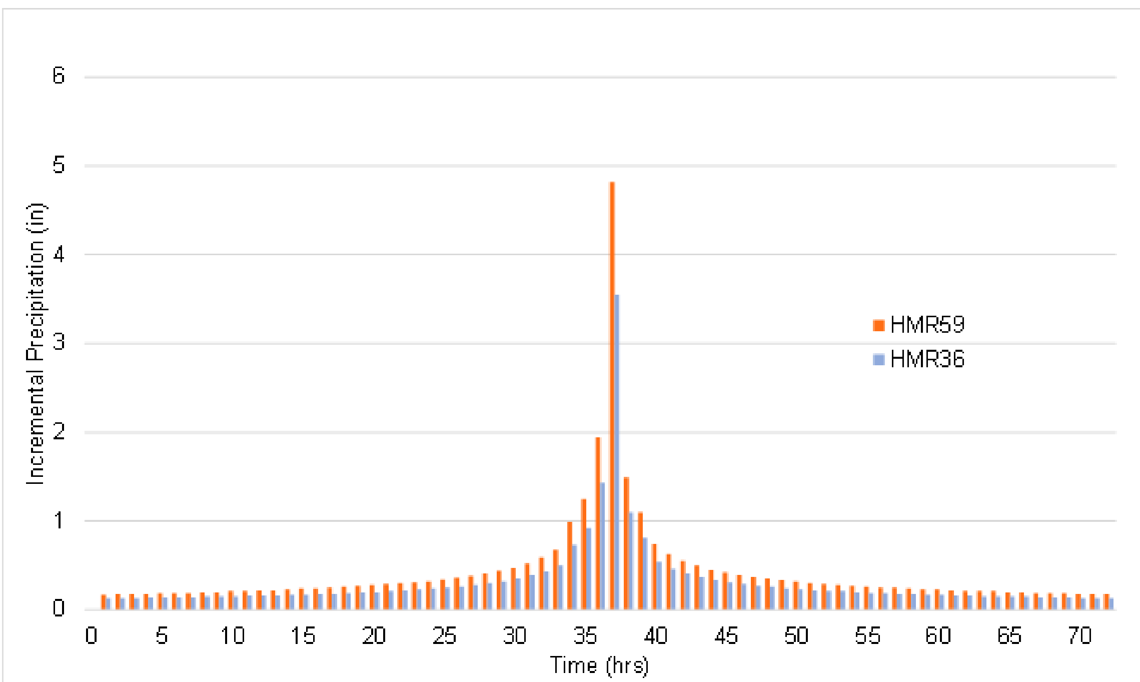


Figure 3: Comparison of General Storm (72-hour) PMP hyetograph under HMR 36 and HMR 59

[4] See Appendix B, Sheet 2 of 10 of the 1981 DSOD inspection report for the accumulated precipitation hyetograph. To match the timing of the peak inflows, ESA converted the accumulated precipitation hyetograph to an incremental hyetograph and entered the depth values into the Frequency Storm method of HEC-HMS to produce a balanced hyetograph.

Development of the Updated PMF Hydrograph

ESA was provided with an HEC-HMS model (version 4.2) of the Novato Creek watershed from the FCD and updated the model to HEC-HMS version 4.11. To ensure the hydrologic model could reproduce the inflow/outflow PMF hydrograph from the 1985 Design Report, ESA entered in the hydrological parameters (Clark Unit Hydrograph method with time of concentration [Tc] = 0.43 hours; storage coefficient [R] = 0.56 hours)[5] from the 1981 inspection report (DSOD, 1981) and used the 1985 spillway rating curve (Harlan Miller Tait, 1985). A comparison of the inflow/outflow PMF hydrographs for the PMP standard of 23.05 inches from the 1985 design report and results from our application of this storm in the HMS model are shown in Figure 4.

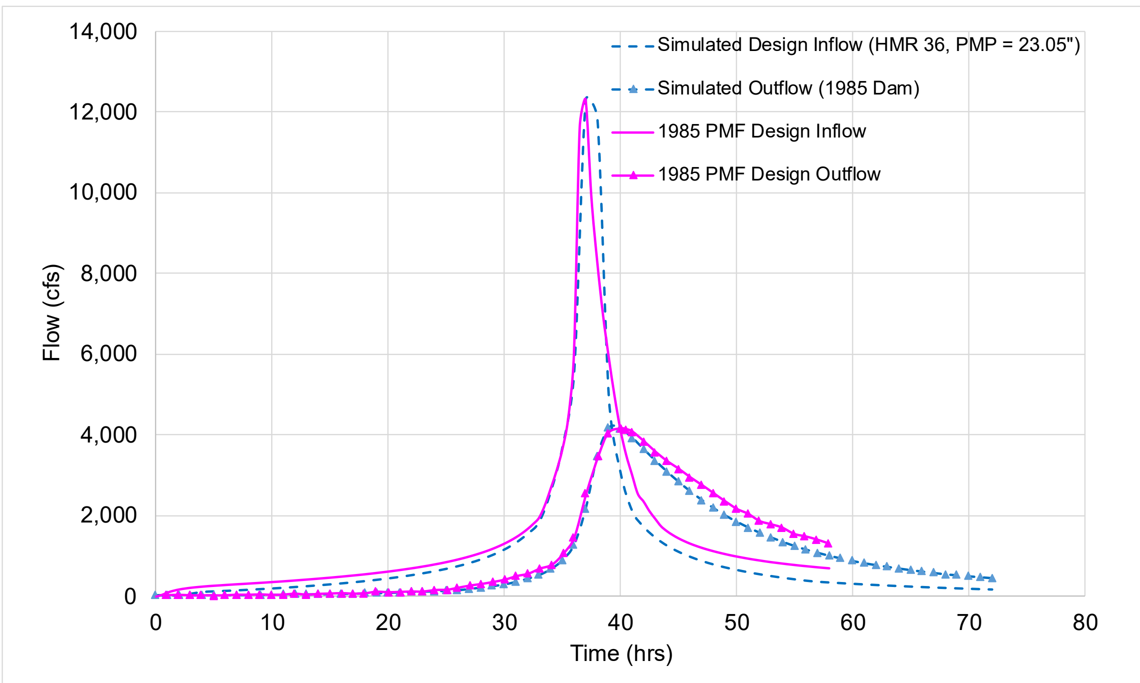


Figure 4: Comparison of 1985 design report PMF inflow/outflow hydrograph and simulated HMS PMF inflow/outflow hydrograph

From Figure 3, the HMS model closely follows the hydrographs from the 1985 design report. The peak inflow and outflow from the 1985 design report were 12,305 cubic feet per second (cfs) and 4,148 cfs while the HEC-HMS model produced a peak inflow of 12,314 cfs and peak outflow of 4,172 cfs.

Updated PMP Hydrologic Parameters

ESA noted that the time of concentration of 0.43 hours given in the 1981 inspection report appeared unrealistically short given an estimated flowpath length of 7.7 miles for the subbasin draining into Stafford Lake. Using the Soil Conservation Service (SCS) Unit Hydrograph

[5] See page 5-11 of National Dam Inspection for Novato Creek Dam, 1981, Division of Safety of Dams. R/T_c ratio provided as 1.31 and used to calculate R.

methods described in Technical Report 55 (SCS, 1986) and the National Engineering Handbook (SCS, 1971), ESA calculated an updated T_c using the following equations relating lag time (T_l, hours), Curve Number (CN), longest watershed flowpath (L, ft), and watershed slope (Y, in %):

$$T_l = L^{0.8}\frac{\left(\frac{1000}{CN} - 10 + 1\right)^{0.7}}{1900\sqrt{Y}}$$

$$T_c = 0.6T_l$$

A curve number (CN) value of 75 was estimated for the subbasin using the latest Soil Survey Geographic (SSURGO) dataset from the NRCS and 2021 National Land Cover Dataset (NLCD, Dewitz, J., 2023). We used GIS to estimate the longest watershed flowpath and watershed slope (40,880 ft and 37.2% respectively) from a 2019 LiDAR dataset prepared for the Golden Gate National Parks Conservancy covering the entirety of Marin County (QSI, 2019). Using these values and the equations above, we estimated an updated time of concentration of 1.95 hours (approximately 3.8 times the 1981 value).

The storage coefficient (R) was then recalculated based on the following relationship developed by Sabol (1988):

$$\frac{T_c}{R} = 1.46 - 0.0867L^2/A$$

The equation includes longest flowpath in miles (L, 7.7 miles), and drainage area in square miles (A, 8.3 square miles) resulting in an R value of 2.34. The updated estimates of storage coefficient and time of concentration result in a similar R/Tc ratio of 1.20.[6]

Loss rates were parametrized in the HEC-HMS model using the Initial and Constant Loss method. Loss rates were initially estimated using the hydrologic soil group for the soil types within each basin and then calibrated to match the December 2005 New Year's Eve event by WRECO, which is the third largest recorded event in the watershed (WRECO, 2013). Baseflow parameters were parametrized using the Recession method and were calibrated to the December 2005 New Year's Eve event by WRECO. Hydrologic inputs into the HEC-HMS model are summarized in Table 2.

TABLE 2. PMP TRANSFORM, LOSS, AND BASEFLOW PARAMETERS

Transform		Loss		Baseflow		
Tc (hr)	R	Initial Loss (in)	Constant Loss (in/hr)	Initial Discharge (cfs/ sq mi)	Recession Constant	Ratio to Peak Coefficient
1.95	2.34	0.25	0.12	3.5	0.3	0.03

6 Original R/Tc ratio under HMR 36 and HMR 49 reported as 1.31 (DSOD, 1981)

PMF inflow and outflow under existing conditions and raised gate configuration

ESA simulated the updated PMF under the existing conditions spillway and the raised sluiced gate condition. Development of the stage-storage-discharge hydraulics for the spillway conditions is described in Chapter 3. Table 3 summarizes a comparison of the inputs and results for the existing and proposed PMP/PMF based on the hydrologic parameters and spillway hydraulics under existing conditions and the raised sluice gate configuration. Freeboard is calculated as the difference between the peak stage to the dam crest of 214 NGVD (Harlan Miller Tait, 1985)[7].

TABLE 3. PMP/ PMF PARAMETERS AND RESULTS FOR THE EXISTING AND PROPOSED SPILLWAY

Source	PMP (inches)	Total Inflow Volume (in)	Tc (hr)	R	Peak Inflow (cfs)	Peak outflow (cfs)	Peak reservoir stage (ft NGVD29)	Freeboard (ft)
1985 design report (existing spillway)8	23.05	17.31	0.43	0.56	12,300	4,150	209	5.0
Existing conditions including 30” outlet pipe (ESA, 2024)	31.28	22.62	1.95	2.55	10,900	5,480	210.8	3.2
Fully raised sluice gate configuration including 30” outlet pipe (ESA, 2024)	31.28	22.62	1.95	2.55	10,900	5,460	211.4	2.6

[7] Survey elevations documented in the 1985 design report were later corrected by +1 ft NGVD based on findings summarized in a 2008 NMWD memo (NMWD, 2008).

[8] PMP rainfall depth, total inflow volume, Tc, R, and peak inflow obtained from (DSOD, 1981). See p. 5-11. Peak outflows and reservoir stage obtained from (Harlan Miller Tait, 1985). See p. 8.

Figure 5 compares the set of inflow/outflow PMF hydrographs using the recalculated subbasin parameters and the inflow/outflow PMF hydrographs presented in the 1985 design report. Tabulated inflow, stage, and outflow under existing conditions and the raised gate conditions are summarized in Appendix A, Table A 2.

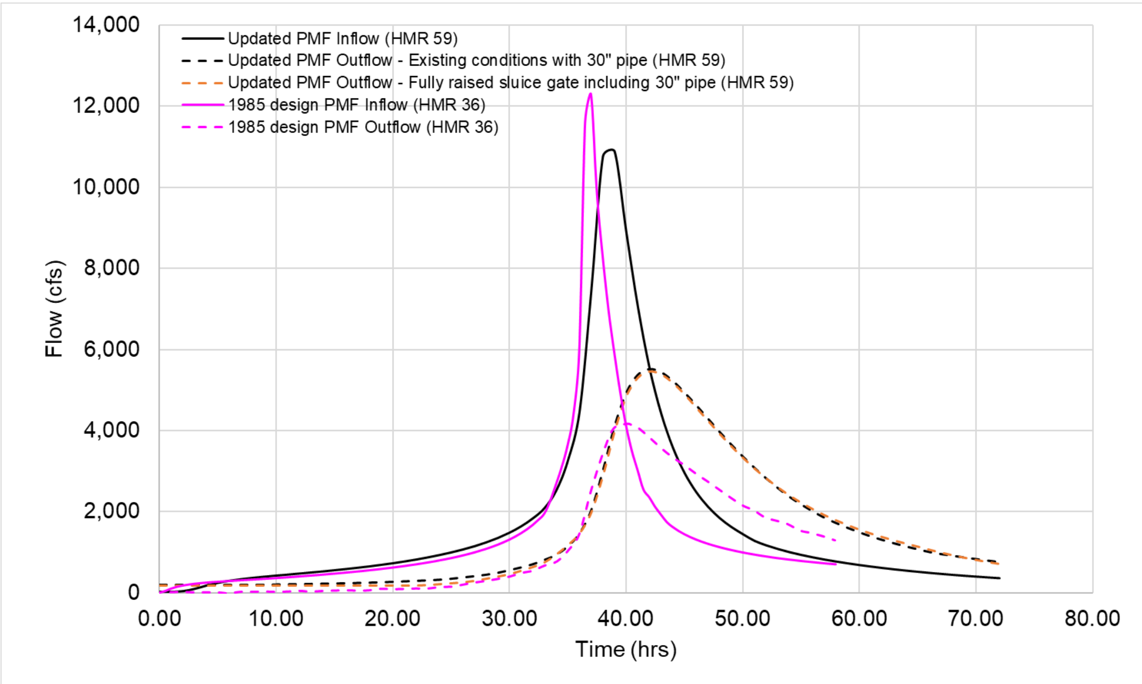


Figure 5. Comparison of inflow/ outflow hydrographs (PMF = 23.05" vs PMF = 31.28")

Though the PMP depth estimated under HMR 59 is greater than the PMP estimated under HMR 36, the updated time of concentration shifts the timing of the peak inflow to the right while the increased storage coefficient lowers the peak inflow to a value of 10,900 cfs and extends the recession limb relative to the HMR 36 PMF hydrograph. However, the larger volume of the inflow hydrograph leads to a larger peak outflow of 5,480 cfs under the existing spillway configuration and 5,460 cfs under the fully raised sluice gate configuration. A tabulated version of the PMP, inflow and outflow hydrographs under current and raised-gate conditions is provided in Appendix A. The model files containing the PMP are included in Digital Appendix B.

ESA submitted a memo to NMWD and subsequently to the California Division of Safety of Dams (DSOD) summarizing the PMP development methodology and results (ESA, 2024). The DSOD reviewed the memorandum and provided comments on September 19, 2024. ESA and NMWD have submitted an updated draft to DSOD on February 10, 2025, and received approval from DSOD on June 3, 2025 accepting the updated PMP methodology and results. The DSOD letter of correspondence is included in Appendix C.

2.2 Recurrence interval events

MCFCD staff conducted flood-frequency analysis for the Novato Creek gage using discharge data through 2012 following Bulletin 17B procedures (Marin County, 2013). Table 4 summarizes the design event flows below:

TABLE 4: SUMMARY OF BULLETIN 17B DESIGN EVENT FLOWS

Design Event	Flow (cfs)
10% (10-year)	2,052
2% (50-year)	3,866
1% (100-year)	4,828
0.5% (200-year)	5,914
0.2% (500-year)	7,558

Review of the HEC-HMS setup and parameters and potential refinements

In the original HEC-HMS model developed by the FCD, the design hydrographs were produced using the Frequency Storm method, which used the NOAA Atlas 14 depth-duration-frequency values to create a nested hyetograph. Upon review from WRECO, a consultant contracted to review the FCD's HEC-HMS model, WRECO updated the methodology using unit precipitation hyetographs based on the 2005 New Year's Eve storm event and scaled the hyetographs to the NOAA Atlas 14 48-hour depth values for the 10-, 50-, and 100-year events to better match the flows in Table 4 (WRECO, 2013).

Though not the primary focus of this study, ESA reviewed the model setup for physical consistency and potential improvements. We noted potential improvements in three model elements (1) loss rates, (2) rainfall gage application for design events and (3) depth-duration-frequency for design rainfall. The following summarizes ESA's findings from the model review.

Loss rates

In reviewing the model we noted that loss parameters (shown in Table 5) vary between design events (i.e. 10-year infiltration is more than 100-year infiltration). While initial loss can vary between events depending on antecedent rainfall, constant loss is a physical property of the land surface and soil with a watershed and should not vary significantly between events. Review of the HEC-HMS model documentation revealed that the constant loss parameters were adjusted based on an optimization trial to calibrate to the Bulletin 17B flows (WRECO, 2013). Given the lack of physical consistency in this approach, the FCD may need to consider revisiting the calibration to find a single set of loss parameters that provide reasonable results for design peak flows.

TABLE 5: SUMMARY OF HEC-HMS LOSS PARAMETERS FOR EACH DESIGN EVENT CONFIGURATION

Subbasin	10-yr:			50-yr			100-yr		
	Initial Loss (in)	Constant Rate (in/hr)	% impervious	Initial Loss (in)	Constant Rate (in/hr)	% impervious	Initial Loss (in)	Constant Rate (in/hr)	% impervious
W900	0.25	0.21	0.2%	0.25	0.15	0.2%	0.25	0.12	0.2%
W810-Leveroni Creek HW	0.25	0.33	0.0%	0.25	0.24	0.0%	0.25	0.18	0.0%
W820-Bowman_canyon	0.25	0.25	0.0%	0.25	0.18	0.0%	0.25	0.14	0.0%
W1780	0.25	0.20	2.0%	0.25	0.14	2.0%	0.25	0.11	2.0%
W920	0.25	0.21	10.1%	0.25	0.15	10.1%	0.25	0.11	10.1%
W930	0.25	0.22	15.6%	0.25	0.15	15.6%	0.25	0.12	15.6%
W1500	0.25	0.19	3.1%	0.25	0.13	3.1%	0.25	0.10	3.1%
W1490	0.25	0.11	34.0%	0.25	0.08	34.0%	0.25	0.06	34.0%
W1560	0.25	0.20	0.2%	0.25	0.15	0.2%	0.25	0.11	0.2%
W1610	0.25	0.17	29.3%	0.25	0.12	29.3%	0.25	0.09	29.3%
W1040-Wilson Creek	0.00	0.37	7.2%	0.25	0.27	7.2%	0.00	0.21	7.2%
W1660	0.00	0.26	23.5%	0.25	0.19	23.5%	0.00	0.15	23.5%
W1020	0.00	0.35	0.6%	0.25	0.25	0.6%	0.00	0.20	0.6%
W1700	0.00	0.28	25.1%	0.25	0.20	25.1%	0.00	0.15	25.1%
W1710	0.00	0.36	0.8%	0.25	0.26	0.8%	0.00	0.20	0.8%
W1030	0.00	0.17	41.4%	0.25	0.12	41.4%	0.00	0.09	41.4%
W1151	0.00	0.12	50.2%	0.00	0.09	50.2%	0.00	0.07	50.2%
W1260	0.00	0.16	28.6%	0.25	0.11	28.6%	0.00	0.09	28.6%
W1370	0.00	0.34	2.3%	0.25	0.25	2.3%	0.00	0.19	2.3%
W1320	0.00	0.31	7.6%	0.25	0.22	7.6%	0.00	0.17	7.6%
W1330-Pacheco_Creek	0.00	0.27	17.2%	0.00	0.19	17.2%	0.00	0.15	17.2%
W1152	0.00	0.12	5.0%	0.00	0.09	5.0%	0.00	0.07	5.0%
W1090	0.00	0.20	5.1%	0.00	0.14	5.1%	0.00	0.11	5.1%
W1310	0.00	0.09	22.6%	0.00	0.06	22.6%	0.00	0.05	22.6%
W1290	0.00	0.07	1.8%	0.00	0.05	1.8%	0.00	0.04	1.8%
W1250	0.00	0.07	10.4%	0.00	0.05	10.4%	0.00	0.04	10.4%
W41	0.00	0.12	2.0%	0.00	0.09	2.0%	0.00	0.07	2.0%
W1462	0.00	0.12	0.2%	0.00	0.09	0.2%	0.00	0.07	0.2%
W141	0.00	0.12	31.2%	0.00	0.09	23.4%	0.00	0.07	23.4%
W1461	0.00	0.12	55.8%	0.00	0.09	30.2%	0.00	0.07	30.2%
W1463	0.00	0.12	2.7%	0.00	0.09	30.6%	0.00	0.07	30.6%
W323	0.00	0.12	23.4%	0.00	0.09	31.2%	0.00	0.07	31.2%
W248	0.00	0.12	30.2%	0.00	0.09	55.8%	0.00	0.07	55.8%
W741	0.00	0.12	30.6%	0.00	0.09	2.7%	0.00	0.07	2.7%

Rainfall gage setup

For the current model, WRECO had developed unit precipitation hyetographs for each subbasin in the model based off the 2005 New Years' Eve event. We found that the unit precipitation hyetographs applied for each subbasin vary across the design events as shown in Table 6. This indicates that different hyetograph distributions were used to calibrate the model to the Bulletin 17B flows. For example, subbasin W1710 applies gage W1710 for the 10-year, gage W1780DESIGN2006 for the 50-year, and gage W930 DESIGN2006 for the 100-year. A graph of the rainfall distribution for these three gages is shown in Figure 6.

TABLE 6. DESIGN METEOROLOGIC MODEL UNIT HYETOGRAPHS FOR DESIGN STORM EVENTS

Subbasin	Unit Hyetograph		
	10-yr	50-yr	100-yr
W1020	W1020	W820 DESIGN2006	W1020
W1030	W1030	W920 DESIGN2006	W1030
W1040-Wilson Creek	W1040	W920 DESIGN2006	W1040
W1090	W1090	W1780DESIGN2006	W1090
W1151	W1150	W810 DESIGN2006	W1150
W1152	W1150	W810 DESIGN2006	W1150
W1250	W1250	W1500 DESIGN2006	W1250
W1260	W1260	W1780DESIGN2006	W1260
W1290	W1290	W1500 DESIGN2006	W1290
W1310	W1310	W930 DESIGN2006	W1310
W1320	W1320	W1490 DESIGN2006	W1320
W1330-Pacheco_Creek	W1330	W1490 DESIGN2006	W1330
W1370	W1370	W930 DESIGN2006	W1370
W141	W1150	W810 DESIGN2006	W1150
W1461	W1150	W810 DESIGN2006	W1150
W1462	W1150	W810 DESIGN2006	W1150
W1463	W1150	W810 DESIGN2006	W1150
W1490	W1490 DESIGN2006	W1490 DESIGN2006	W1490 DESIGN2006
W1500	W1500 DESIGN2006	W1500 DESIGN2006	W1500 DESIGN2006
W1560	W1560 DESIGN2006	W1560 DESIGN2006	W1560 DESIGN2006
W1610	W1610	W1560 DESIGN2006	W1610
W1660	W1660	W1780DESIGN2006	W1660
W1700	W1700	W1780DESIGN2006	W1700
W1710	W1710	W1780DESIGN2006	W930 DESIGN2006
W1780	W1780DESIGN2006	W1780DESIGN2006	W1780DESIGN2006
W248	W1150	W810 DESIGN2006	W1150
W323	W1150	W810 DESIGN2006	W1150
W41	W1150	W810 DESIGN2006	W1150
W741	W1150	W810 DESIGN2006	W1150
W810-Leveroni Creek HW	W810 DESIGN2006	W810 DESIGN2006	W810 DESIGN2006
W820-Bowman_canyon	W820 DESIGN2006	W820 DESIGN2006	W820 DESIGN2006
W900	W900 DESIGN2006	W900 DESIGN2006	W900 DESIGN2006
W920	W920 DESIGN2006	W920 DESIGN2006	W920 DESIGN2006
W930	W930 DESIGN2006	W930 DESIGN2006	W930 DESIGN2006

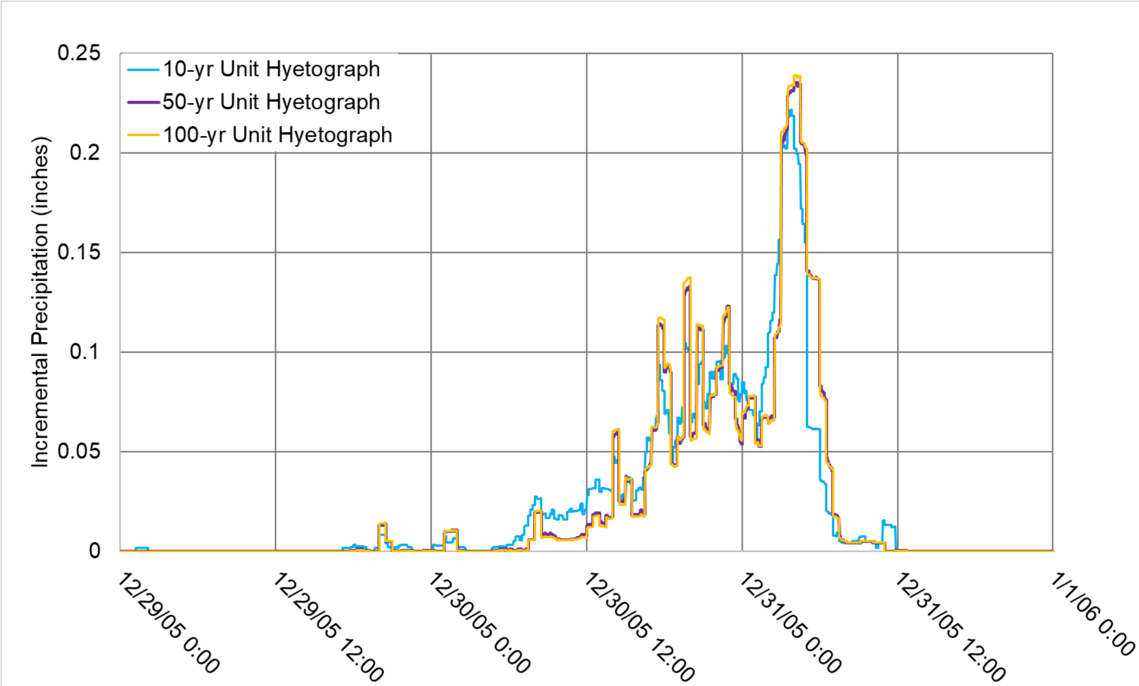


Figure 6. Unit Hyetograph Comparison of 10-, 50, and 100-year design events for Subbasin W1710

Design rainfall depth-duration-frequency

The design event applied in the model has a 48-hour duration with 48-hour depths derived from NOAA Atlas 14 and the temporal distribution derived from New Year's Eve 2005 rainfall gage data. It is typically desirable to match design depths for the full duration of the storm (48-hours in this case) as well as other sub-durations (i.e. 1-hour, 2-hour, 3-hour etc.) which may drive peak flows across various parts of the watershed. ESA compared the 100-year hyetographs in each subbasin to NOAA Atlas 14 data to evaluate whether the design rainfall depth is captured across all durations during the design event. Table 7 summarizes the average, maximum, and minimum difference across all HEC-HMS subbasins between the HMS and NOAA Atlas 14 100-year sub-duration values.

TABLE 7: COMPARISON OF AVERAGE, MAXIMUM, AND MINIMUM NOAA ATLAS 14 100-YEAR SUBDURATION DEPTHS AND HEC-HMS SUBDURATION DEPTHS ACROSS ALL SUBBASINS (HEC-HMS MINUS NOAA ATLAS 14)

Subduration	Average Delta (inches)	Maximum Delta (inches)	Minimum Delta (inches)
48hr	-0.01	0.86	-0.45
24hr	1.59	2.19	0.78
6hr	1.78	2.21	1.56
3hr	0.45	0.85	0.27
2hr	0.31	0.5	0.1
60min	0.05	0.26	-0.05
30min	-0.18	0.05	-0.26
15min	-0.38	0.05	-0.26
5min	-0.22	-0.19	-0.3

While the 48-hour NOAA Atlas 14 and model depths are similar, there are disparities in the sub-48-hour depths. Future work should focus on revisiting the design events calibration to improve fidelity in the design rainfall across multiple durations within each design event.

2.3 Sequential flood risk

Characterization of three sequential event scenarios

Sequential events are classified as large precipitation events, often atmospheric rivers, that occur within a short time span. Atmospheric river clusters can include storms with a range of durations and intensities. Because a watershed's soil is still saturated after an initial storm, the flooding impact of a second storm in short sequence can be amplified relative to a singular storm event. The preceding event's intensity and recency can control the magnitude of the second storm's flooding impact (Bowers et al., 2024). A recent example of sequential events occurred during the 2022-2023 winter season, when California experienced a cluster of nine atmospheric rivers, leading to extreme flooding, landslide, and power outages.

To model hypothetical sequential events at Stafford Lake, ESA scaled up a historical sequential storm event to a 100-year storm peak preceded by a lesser design storm peak. ESA reviewed historical hydrologic data from the Novato Creek USGS discharge gage and Novato OneRain[9] precipitation gages to identify large magnitude events containing consecutive significant storm peaks within 24 to 48 hours of one another. While several Novato Creek annual peak storms were identified as sequential storm events, ESA selected the January 2023 storm due to its intensity and clear separation of two peaks in both the discharge and rainfall data (Figure 7). The observed peak flows during this event of 990 and 1,390 cfs at the USGS Novato gage 11459500 roughly represent a 2-year and 5-year design event, respectively.

[9] https://marin.onerain.com/

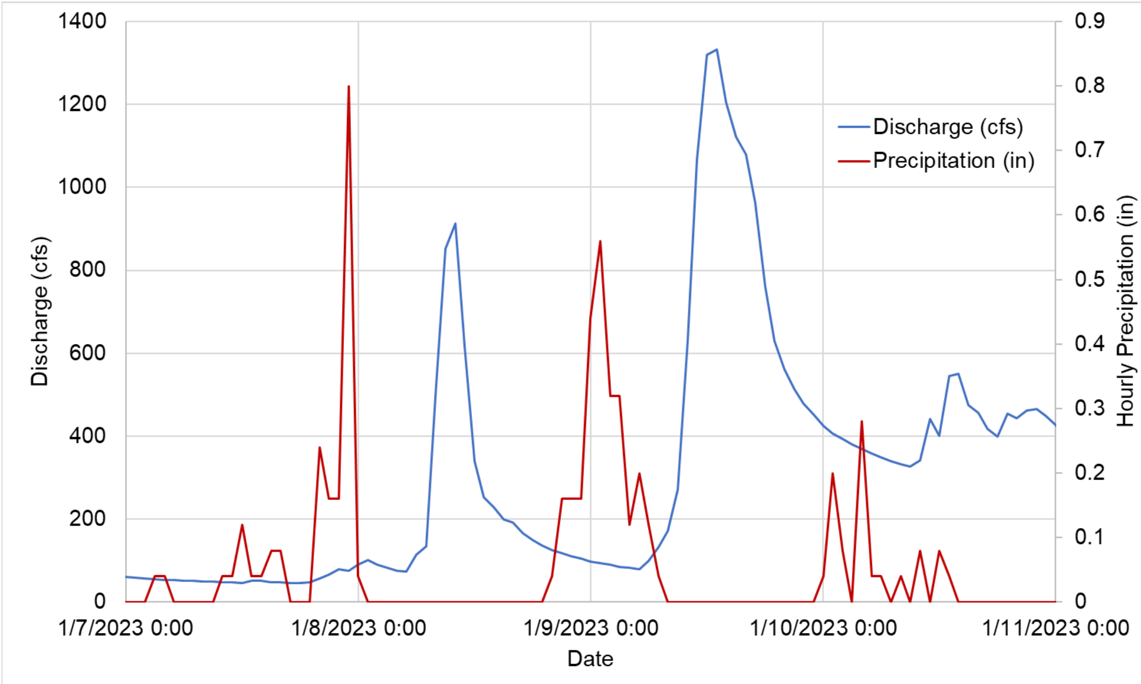


Figure 7. January 2023 sequential event discharge and precipitation gage data

To create three sequential event scenarios, ESA used the precipitation data from this 2023 January storm to simulate a 100-year event preceded by either a 10-, 25-, or 50-year event. These scenarios were modeled to evaluate how large of an effect the preceding events would have on the 100-year inundation. We used the Novato Center Road Tank rainfall gage, the closest gage with rainfall measurements for the January 2023 event, to set the temporal distribution for this event. For the sequential scenarios, the measured rainfall was scaled to match NOAA Atlas 14 depths in the watershed. This produced scaled-up precipitation data for three sequential storm scenarios: (1) a 10-year/100-year storm, (2) a 25-year/100-year storm, and (3) a 50-year/100-year storm.

To run the sequential event scenarios in HEC-HMS, each peak was run separately with the corresponding subbasin model for each recurrence interval. The four subbasin models were based on the previously calibrated subbasin models with infiltration parameters for the 10-, 50-, and 100-year design events (Table 5). The constant loss rates for the 25-year design event basin model were interpolated using the infiltration rates from the HEC-HMS model (Table 8). Because the 100-year storm was used to represent the subsequent peak, initial losses for the 100-year subbasin model were set to zero.

TABLE 8. HEC-HMS ESTIMATED LOSS PARAMETERS FOR 25-YEAR DESIGN EVENT

Subbasin	Initial Loss (in)	Constant Rate (in/hr)	% impervious	Subbasin	Initial Loss (in)	Constant Rate (in/hr)	% impervious
W900	0.250	0.187	0.190	W1260	0.000	0.137	28.600
W810-Leveroni Creek HW	0.250	0.290	0.040	W1370	0.000	0.302	2.300
W820-Bowman_canyon	0.250	0.217	0.030	W1320	0.000	0.270	7.600
W1780	0.250	0.177	2.000	W1330-Pacheco_Creek	0.000	0.239	17.200
W920	0.250	0.181	10.100	W1152	0.000	0.109	5.000
W930	0.250	0.190	15.600	W1090	0.000	0.177	5.100
W1500	0.250	0.164	3.100	W1310	0.000	0.078	22.600
W1490	0.250	0.095	34.000	W1290	0.000	0.061	1.800
W1560	0.250	0.179	0.190	W1250	0.000	0.060	10.400
W1610	0.250	0.150	29.300	W41	0.000	0.109	2.000
W1040-Wilson Creek	0.000	0.328	7.200	W1462	0.000	0.109	0.200
W1660	0.000	0.232	23.500	W141	0.000	0.109	31.200
W1020	0.000	0.310	0.590	W1461	0.000	0.109	55.800
W1700	0.000	0.242	25.100	W1463	0.000	0.109	2.700
W1710	0.000	0.318	0.830	W323	0.000	0.109	23.400
W1030	0.000	0.150	41.400	W248	0.000	0.109	30.200
W1151	0.000	0.109	50.200	W741	0.000	0.109	30.600

To transfer the soil moisture conditions and water levels from the first peak to the second peak, ESA used the “Save States” option within HEC-HMS. Using the “Save States” option, the results at the end of the initial peak (including storage and stage at Stafford Lake) were fed into the starting conditions of the subsequent 100-year event simulation to represent the full sequential storm event. Similarly, HEC-RAS has an option to feed results from the end of the initial peak run into the starting conditions of the subsequent peak run. Using the HEC-HMS results and HEC-RAS’s “Restart File” or “hotstart file” option, the 100-year storm was run with three initial conditions based on results from the 10-year, 25-year and 50-year runs. Results of the hydrologic and hydraulic models for the sequential events are discussed in Section 3.2.

2.4 Future flood risk with climate change

Future climate conditions scenarios representing 2050 – 2100 were analyzed for the 100-year design event and the PMF. Extreme rainfall was quantified using the LOCA2 dataset, which are downscaled climate model projections from the latest release of the Coupled Model Intercomparison Project 6 (CMIP6) global circulation models (GCMs) developed at the Scripps Institute of Oceanography (Pierce et al. 2015). The latest update to LOCA, applied updates to the methodology and increased the spatial resolution for California from 6 kilometers to 3 kilometers (Pierce et al. 2023). Prior screening analysis had been conducted on a large set of CMIP6 models and 15 were identified as the most accurate for simulating California climate (Kranz et al. 2021).

The LOCA2 dataset had data for 13 of these GCMs. Table 9 summarizes the climate models used to characterize future extreme rainfall.

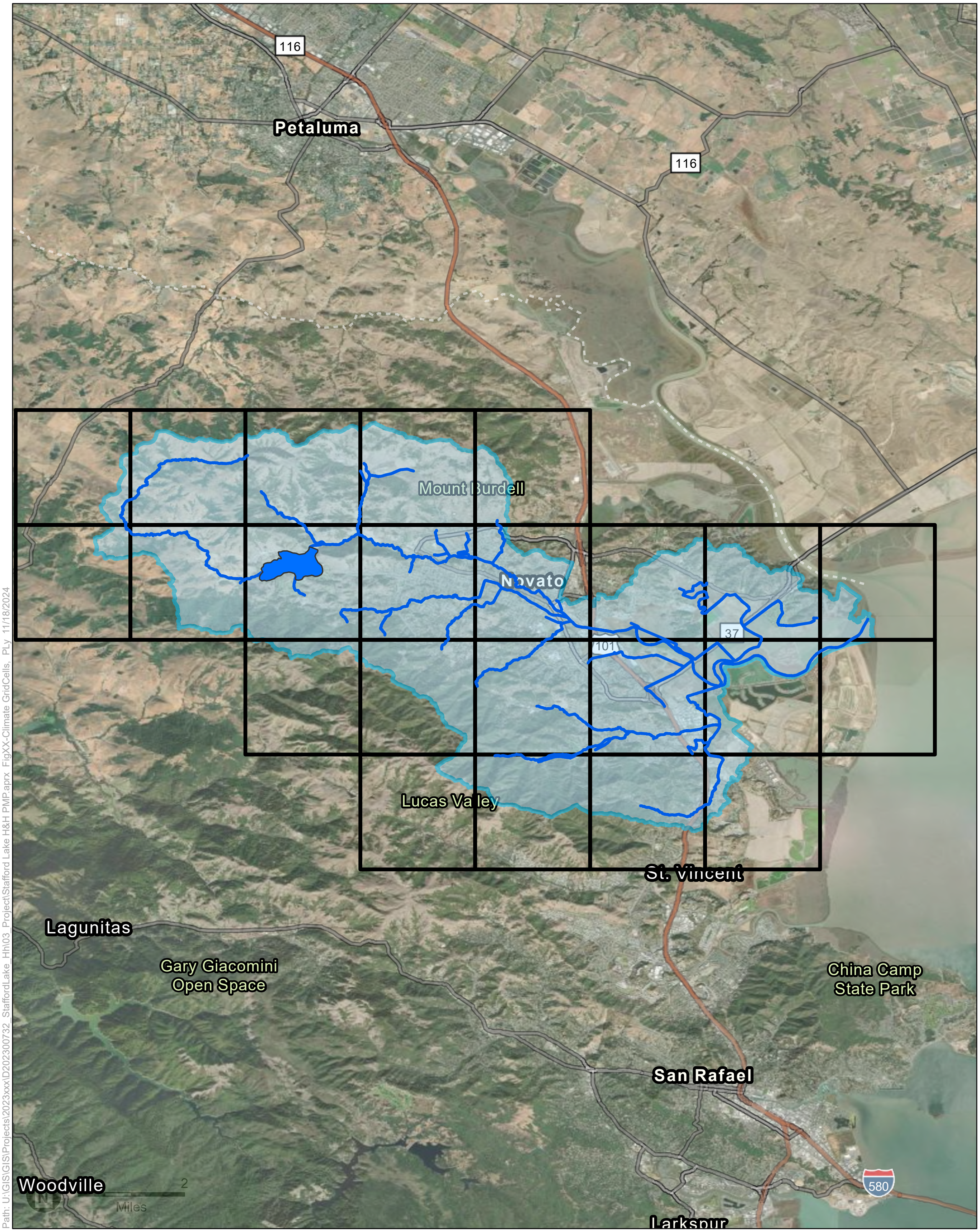
TABLE 9. DOWNSCALED GCMS USED TO CHARACTERIZE EXTREME RAINFALL

Model Name	Model Institution	Spatial Resolution (sq km)
ACCESS-CM2	Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Bureau of Meteorology in Australia	27.8
CNRM-ESM2-1	Centre National de Recherches Météorologiques (CNRM) in France	150
EC-Earth3-Veg	European Consortium for Earth System Modelling	55.6
EC-Earth3	European Consortium for Earth System Modelling	55.6
FGOALS-g3	State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) in China	111
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory (GFDL), part of the National Oceanic and Atmospheric Administration (NOAA) in the United States	111
HadGEM3-GC31-LL	Met Office Hadley Centre for Climate Science and Services in the United Kingdom	124
INM-CM5-0	Institute for Numerical Mathematics (INM) of the Russian Academy of Sciences	222
IPSL-CM6A-LR	Institut Pierre-Simon Laplace of France	208
KACE-1-0-G	Korea Institute of Atmospheric Prediction Systems (KIAPS) in South Korea	27.8
MIROC6	University of Tokyo, the National Institute for Environmental Studies (NIES), and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	122
MPI-ESM1-2-HR	Max Planck Institute for Meteorology (MPI-M) in Germany	111
MRI-ESM2-0	Meteorological Research Institute (MRI) in Japan	111

The downscaled climate data are gridded datasets, with each grid cell containing simulated rainfall and other climate variables at a 3-kilometer resolution. The LOCA2 downscaled climate model grid cells intersecting the Novato Creek Watershed are shown in Figure 8.

ESA used the downscaled projected daily rainfall dataset from 13 of the climate models that most accurately simulated California's observed climate records as previously assessed by (Krantz et al. 2021). Scenarios analyzed include a high emissions scenario[10] reflecting the model mean of the climate model ensemble and a very high emissions scenario (E++) scenario reflecting the upper end of the climate model distribution (model mean plus two standard deviations).

[10] Shared Socioeconomic Pathway and Representative Concentration Pathway 4.5 (SSP2-4.5) from the IPCC's sixth assessment report (IPCC 2021)



SOURCE: ESA, 2022

D202300732.00 - Stafford Lake Hydrology and Hydraulics

Figure 8
Novato Creek Watershed LOCA2 Climate Grid Cells

ESA

Characterization of the 100-year design event under climate change

To estimate the increase in the 100-year rainfall depth by end of century, ESA conducted a frequency analysis to estimate increases in extreme rainfall for a medium emissions climate trajectory (Shared Socioeconomic Pathway [SSP] 2-4.5) and a high emissions trajectory (SSP 5-8.5). The former climate change scenario pathway represents an increase of 4.5 watts per meter squared of warming and moderate population growth relative to historic conditions, while the latter represents an increase of 8.5 watts per meter squared of warming relative to historic conditions and primarily fossil-fueled development. The SSP climate scenarios reflect the latest frameworks for analyzing climate change under varying assumptions of development and are used in the latest Coupled Model Intercomparison Project (CMIP) global climate models analyzed in the latest Intergovernmental Panel on Climate Change (IPCC) report. For each projected daily rainfall timeseries at each of the grid cells that intersected the Novato Creek watershed, ESA extracted the annual maxima rainfall series and, following the rainfall frequency methodology from NOAA's Atlas 14 (NOAA, 2018), fit generalized extreme value (GEV) distribution curves for historical and future periods from each downscaled climate model under climate scenarios SSP 2-4.5 and 5-8.5. The change in extreme rainfall for each grid cell is calculated using the following formula where $P_{100,future}$ and $P_{100,historical}$ are the 100-year, 24-hour future and historical rainfall depths, respectively:

$$\%\ change = \frac{P_{100,future} - P_{100,historical}}{P_{100,historical}}$$

Percent change scalars for the 100-year, 24-hour event under the High Emissions scenario is the mean percent change from the 13 the climate models. Percent change scalars for the 100-year, 24-hour event under the E++ scenario were calculated by estimating the standard deviation of the distribution of percent changes from the 13 climate models, multiplying the standard deviation by two, and adding that value to the model mean for each grid cell (i.e. model mean plus two times the standard deviation). Figure 9 plots the model distribution of percent change in 100-year rainfall for SSP2-4.5 averaged over the watershed. The mean percent increase from the 13 climate models shown in Figure 8 as the yellow vertical line represents the High Emissions scenario, whereas the mean percent increase plus two standard deviations shown in Figure 8 as the black vertical line represents the E++ scenario.

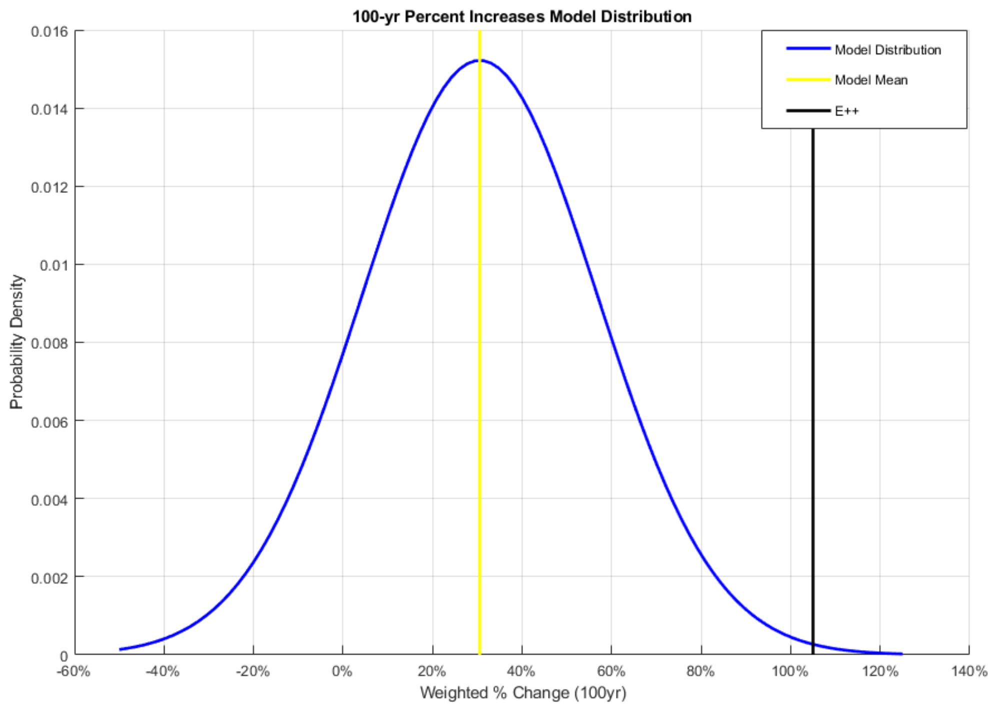


Figure 9. Model distribution of percent change of 100-year rainfall over the Novato Creek watershed (SSP 2-4.5)

The final percent change scalars for the high emissions and E++ scenarios are ensemble-average, watershed-weighted values. The percentage scalars are then multiplied by the baseline design rainfall hyetograph depths in the HEC-HMS model to estimate future runoff.

The time window over which annual maxima are extracted and used for GEV fitting was found to play a significant role in defining estimates of future extreme rainfall. For the historical period, annual maxima were extracted from 1950-2014 which provides 65 years of rainfall. For future periods, it is typical to use time windows of at least 30-years to provide sufficient accuracy for the 1/100 annual chance (or 100-year) event. However, we found that when fitting the annual maxima using only 30 years of data, the midcentury increase was found to be higher than the end-of-century increase across the recurrence intervals analyzed. This result appeared unintuitive, given that extreme precipitation generally scales with the increase in temperatures projected to the end of century.[11]

[11] "The Clausius–Clapeyron (CC) equation states that the moisture-holding capacity in the atmosphere increases at a rate of ~ 7 % °C−1 (Trenberth et al. 2003). According to this equation, it is expected that the heavy rainfall events should scale with temperature when a constant relative humidity is assumed (Trenberth 2011; O'Gorman 2015). Recent studies on heavy rainfall events indicated that higher-percentile precipitation intensities mostly increase with temperature (Lenderink and Meijgaard 2008, 2010; Lenderink et al. 2011; Muller 2013; Berg et al. 2013; Nayak and Dairaku 2016; Taylor et al. 2017; Nayak et al. 2018; Nayak 2018; Nayak and Takemi 2019a)." (Nayak and Takemi, 2020).

Figure 10 shows that when fitting 30 years of annual maxima rainfall, outliers in the midcentury deflect the fitted frequency curve upwards, resulting in increased extreme rainfall estimates compared to the end-of-century. To address this issue, ESA extended the window to fit 50 years of projected annual maxima rainfall data from 2050-2099, which incorporates both midcentury and end-of-century rainfall peaks into the final percent scalars. Given the uncertainty in the rainfall projections, this is sufficiently accurate for characterizing future changes over the next 50-75 years.

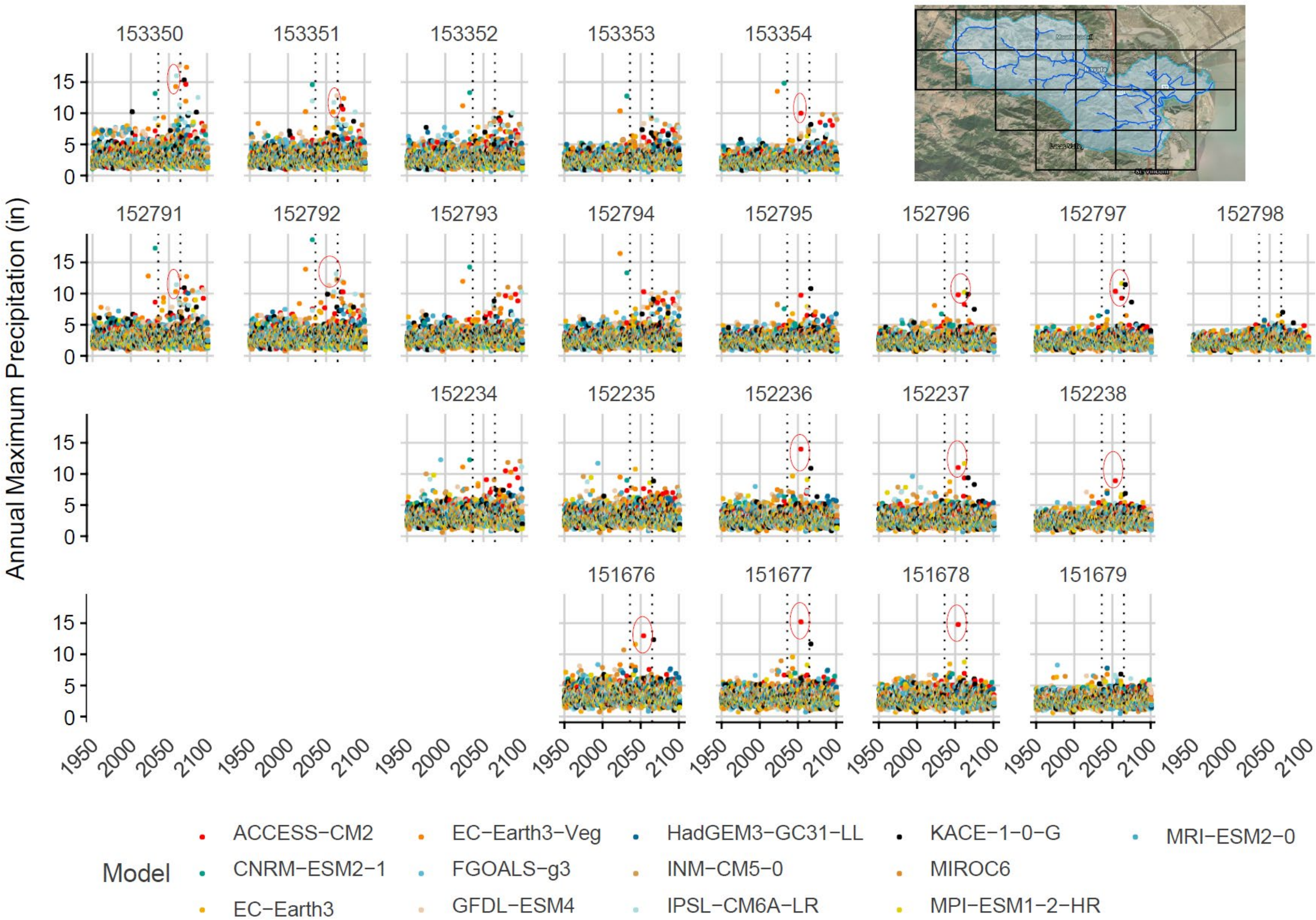


Figure 10. LOCA2 projected annual maxima rainfall by climate model and mid-century outliers under SSP 2-4.5

The same unit hyetograph method used to model the present-day design flows was used to simulate the 100-year future hydrographs. Percent scalars for the high emissions and E++ scenario were calculated under SSP2-4.5 and SSP 5-8.5, and the higher percent change scalars from SSP 2-4.5 were used. The percent scalars in Table 10 were applied to the NOAA Atlas 14 48-hour 100-year depths for all used to scale the 2005 New Year's Eve unit hyetographs. Scalars were applied to rainfall inputs for all subbasins in the HMS model.

TABLE 10. FUTURE ESTIMATED PERCENT CHANGE IN 100-YEAR RAINFALL (SSP 2-4.5)

Scenario	Design Event	Weighted Increase High Emissions model mean)	Weighted Increase E++ (model mean + 2SD)
Future	100-yr	31%	105%

Characterization of the PMP under climate change

Because the PMP is currently defined as a deterministic estimate of the theoretical maximum precipitation depth that can occur over a specified area, estimates for future PMP depth could not be estimated using frequency analysis. ESA used the same downscaled climate dataset but instead estimated the change in the existing and future 72-hour PMP using the Hershfield equation. The Hershfield equation is a statistical method that relies on the annual maxima rainfall series for estimating the PMP and is one of the recommended approaches by the World Meteorological Organization (WMO, 2009). Resulting PMP estimates are found to be closely comparable to estimates under physical approaches for the United States when sufficiently long precipitation records are available (Sarkar and Maity, 2020). The PMP is computed using the mean of the annual maxima rainfall series (X_n), the standard deviation of the annual rainfall series, and statistical variable (K_m):

$$PMP = X_n + K_m \sigma_n$$

The statistical variable represents the maximum value of the observed rainfall series and is computed using the maximum of the annual maxima rainfall series (X_m), and the mean value and standard deviation computing excluding the largest rainfall observation in the annual maxima rainfall series (X_{n-1} and σ_{n-1}, respectively):

$$K_m = \frac{X_m - X_{n-1}}{\sigma_{n-1}}$$

ESA estimated the existing PMP under WYs 1950-2014 and the future PMP under WYs 2050-2100. The PMP hyetograph shown in Figure 3 was scaled by the percent scalars in Table 11 to simulate the future PMF hydrographs.

TABLE 11. FUTURE ESTIMATED PERCENT CHANGE IN PMP

Year	Scenario	Event	Weighted Increase (model mean)
1950-2100	SSP245	PMP	15%

2.5 Summary of Flows

For each of the hydrologic scenarios analyzed, the HMS model was used to derive flows into Stafford Lake and out of Stafford Dam and for watersheds draining downstream of the Lake which were routed directly in the RAS model. Peak flows at the lake and the USGS gage on Novato Creek are summarized in Table 12.

TABLE 12. SUMMARY OF HEC-HMS PEAK INFLOWS AT STAFFORD LAKE AND PEAK FLOWS AT NOVATO CREEK USGS GAGE 1149500

Hydrologic Scenario	Spillway Configuration[1]	Climate Condition	Peak Inflow at Stafford Lake (cfs)	Peak Outflow at Stafford Lake (cfs)	Peak Flow at USGS Gage 11459500 (cfs)
PMF	Gate lowered	Present Day	10,900	5,480	14,290
PMF	Fully raised sluice gate	Present Day	10,900	5,460	14,240
10-year	Gate lowered	Present Day	1,320	320	2,050
50-year	Gate lowered	Present Day	2,410	990	3,870
100-year	Gate lowered	Present Day	2,940	1,380	4,830
10-year/ 100-year	Gate lowered	Present Day	2,780	1,470	5,220
25-year/ 100-year	Gate lowered	Present Day	2,780	1,530	5,340
50-year/ 100-year	Gate lowered	Present Day	2,790	1,580	5,430
PMF	Gate lowered	Late Century (High emissions - model mean)	12,580	6,610	16,910
100-yr	Gate lowered	Late Century (High emissions - model mean)	4,020	2,140	6,890
100-yr	Gate lowered	Late-century (E++ - model mean + 2SD)	6,670	4,080	12,120

[1]Gate lowered refers to the existing spillway configuration consisting of the lower control crest and upper emergency spillway. Fully raised sluice gate refers to the proposed adjustable gate in the fully raised position covering the entirety of the lower control crest.

2.6 Future Updates to the PMP Framework

The science community and federal scientific agencies have begun a process to revise the definition and methodologies for estimating PMP, after acknowledging that there is no first-principles physics-based rationale for its current definition as the greatest depth of precipitation meteorologically possible for a given duration and watershed. The National Academies of Sciences, Engineering, and Medicine has authored a report that lays out a regulatory and procedural roadmap to modernizing PMP estimates (National Academies, 2024). The report envisions a PMP that is redefined as "the depth of precipitation for a particular duration, location, and areal extent, such as a drainage basin, with an extremely low annual probability of being exceeded, for a specified climate period". The methodology associates PMP to recurrence interval for extremely unlikely events on the order of 10^{-4} to 10^{-7} annual chance of exceedance. For comparison, the updated PMP estimate from ESA for this study of 31.3 inches exceeds the NOAA Atlas 14 upper 95th percentile confidence interval estimate for the 10^{-3} annual chance event (NOAA, 2011). One advantage to the redefined framework is that the proposed methodological updates will lend themselves to integrating data from future climate projections enabling estimates for projected PMP under climate change.

The NAS committee has laid out a multi-year roadmap for updating PMP and full guidance is not anticipated until 2030 at the earliest. Thus, no imminent actions are recommended for NMWD. However, for long-range planning, we recommend NMWD monitor updates to this process and implications for future PMP estimates. In the interim, ESA's analysis is a proactive approach for NMWD's benefit, updating their PMP to the latest statewide standards and leveraging the latest climate science and data to evaluate climate resilience for the dam.

CHAPTER 3
Hydrologic and hydraulic modeling

The MCFCD provided an existing HEC-HMS hydrologic model of the Novato Creek watershed, and ESA updated the model to produce flow hydrographs for the PMF, design events, sequential events scenarios, and PMF design flood events under future climate conditions. The flow hydrographs were applied as boundary conditions into a combined one-dimensional/two-dimensional (1D/2D) hydraulic model that was previously developed by updating the MCFCD's existing conditions HEC-RAS model geometry. The model spans from downstream of the Stafford Lake reservoir to the San Pablo Bay. Additional information on the HEC-RAS model development and data sources can be found in the Deer Island Tidal Restoration hydraulic report (ESA, 2023). The below sections describe key updates to the HEC-HMS and HEC-RAS models and summarize model results for the extreme hydrology scenarios.

3.1 HEC-HMS and HEC-RAS Model Updates

Stage-discharge with and without sluice gate

ESA developed an updated stage-storage-discharge relationship for Stafford Lake and implemented it in the updated HEC-HMS model to reflect outflow under existing conditions and the raised sluice gate configuration. The storage-discharge curves in the original 2013 model provided to ESA come from the 1985 design report for the spillway reconstruction project. This storage-discharge curve did not account for the low flow contribution of a 30" pipe located in an intake tower at the northeast corner of the reservoir. ESA incorporated the low flow 30" pipe into the spillway storage-discharge curve and added it into the 2024 HMS model for existing conditions and the raised gate configuration.

The flow contribution from the 30" low flow pipe was calculated using data provided in the 1981 inspection report. The 1981 inspection report stated that the outlet pipe could release 140 cubic feet per second (cfs) at elevation 180' and 100 cfs at elevation 165' (DSOD, 1981). Using the as-built outlet pipe invert elevation of 145 feet NGVD29 (NMWD, 1951), we used the standard orifice equation presented below to back-calculate the pipe's discharge coefficient (C_0) corresponding to these flows and elevations. The orifice equation relates discharge (Q, cubic feet per second) to C_0, head (H, feet) measured from the pipe centerline, and pipe area (A_g, square feet). We estimated an average C_0 of 0.63 which is in the typical range for pipe flow (Lindell *et. al.* 2018).

$$Q = C_0 A_g \sqrt{2gH}$$

NMWD provided updated invert elevations of the outlet tower surveyed in 2007 (Creegan + D'Angelo, 2007). Using the updated invert elevation, ESA added the flow contribution at each corresponding stage from the outlet pipe to the 2013 HMS stage-discharge curve to represent existing conditions. The stage-storage curve for current spillway conditions with the addition of low flows from the intake tower is presented in Figure 11.

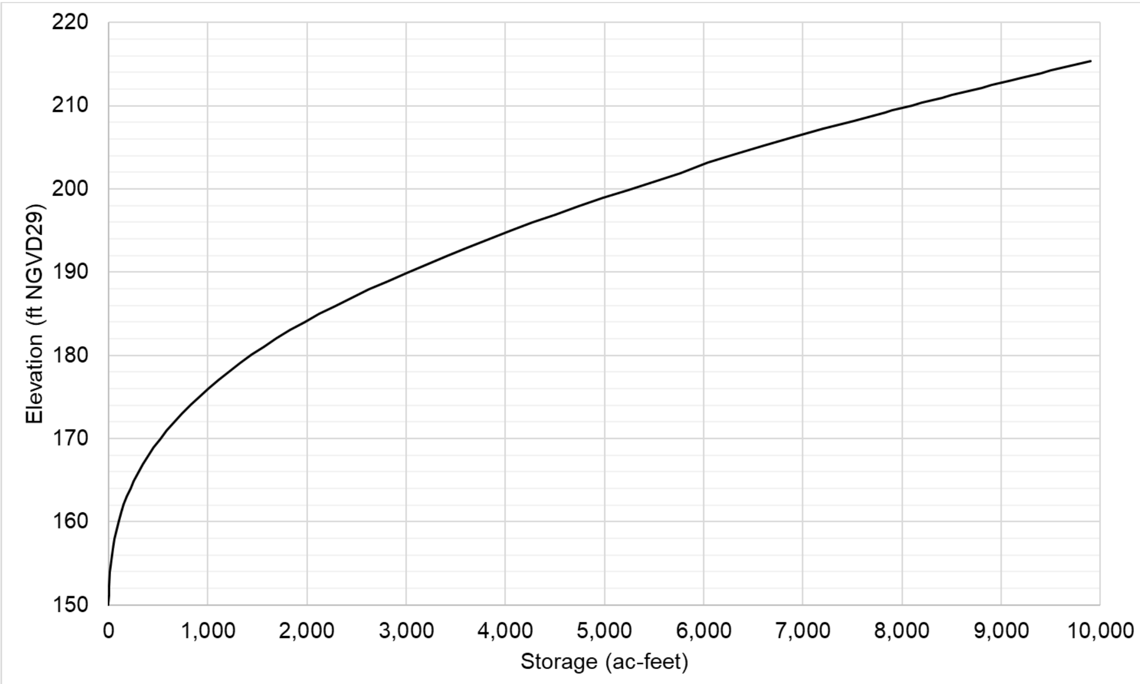


Figure 11. Stage-storage curve for existing spillway conditions

To develop the spillway rating curve under the proposed project's fully raised sluice gate configuration, ESA used the same US Bureau of Reclamation Design of Small Dams procedure (USBR, 1987) that was used to develop the 1985 stage-discharge curve. The raised gate configuration would cover the control crest in the spillway (10-ft wide x 3-ft high) when fully raised. From the Design of Small Dams procedure, stage and discharge are related using the following equation relating flow (Q, cubic feet per second) over the spillway as a function of effective head (H_e, feet), discharge coefficient (C_d), and effective spillway length (L_e, feet):

$$Q = C_d L_e H_e^{1.5}$$

The effective spillway width decreases as a function of the effective head and abutment contraction coefficient (K_a) based on the following equation:

$$L_e = L' - 2K_a H_e$$

When the gate is fully raised, the total spillway width is 32 feet. For rounded abutments with headwalls perpendicular to the direction of flow, the abutment contraction coefficient is 0.10 (USBR 1987), which was the value applied in the 1985 design study. Starting at the elevation of the emergency crest (199 feet NGVD29), ESA calculated the flow over the spillway using the above equations and added the flow contribution from the 30-inch outlet pipe.

Figure 12 compares the stage-discharge curves of the existing spillway (last modified in 1985) and the proposed spillway with the sluice gate fully raised including the contributing flow from the 30-inch outlet pipe.

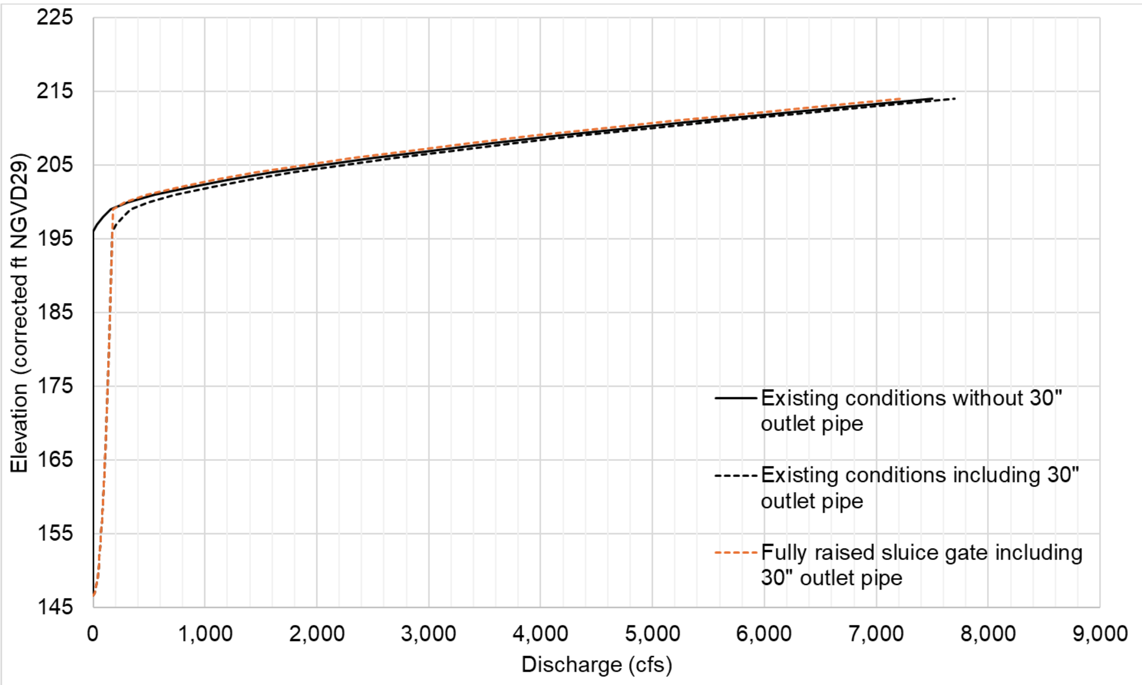


Figure 12. Elevation-discharge curves for existing and proposed spillway

The latest stage-storage curves provided by NMWD (provided to ESA in July 2023) for elevations from 150 ft NGVD to 202 ft NGVD29 was used to update the storage-discharge curves. Corresponding storage values for stages above 202 ft NGVD29 were calculated using the 2019 Marin County LiDAR dataset (QSI, 2019). As shown in this figure, the proposed sluice gate project, when raised in place, reduces flows by 160 cfs at 199 ft NGDVD29 (spillway crest) and 500 cfs at 214 ft NGVD29 (Stafford Lake crest) compared to existing conditions. Using the combined stage-storage curves, ESA developed storage-discharge curves (Figure 13) and entered these into the HEC-HMS model for the reservoir outflow computations.

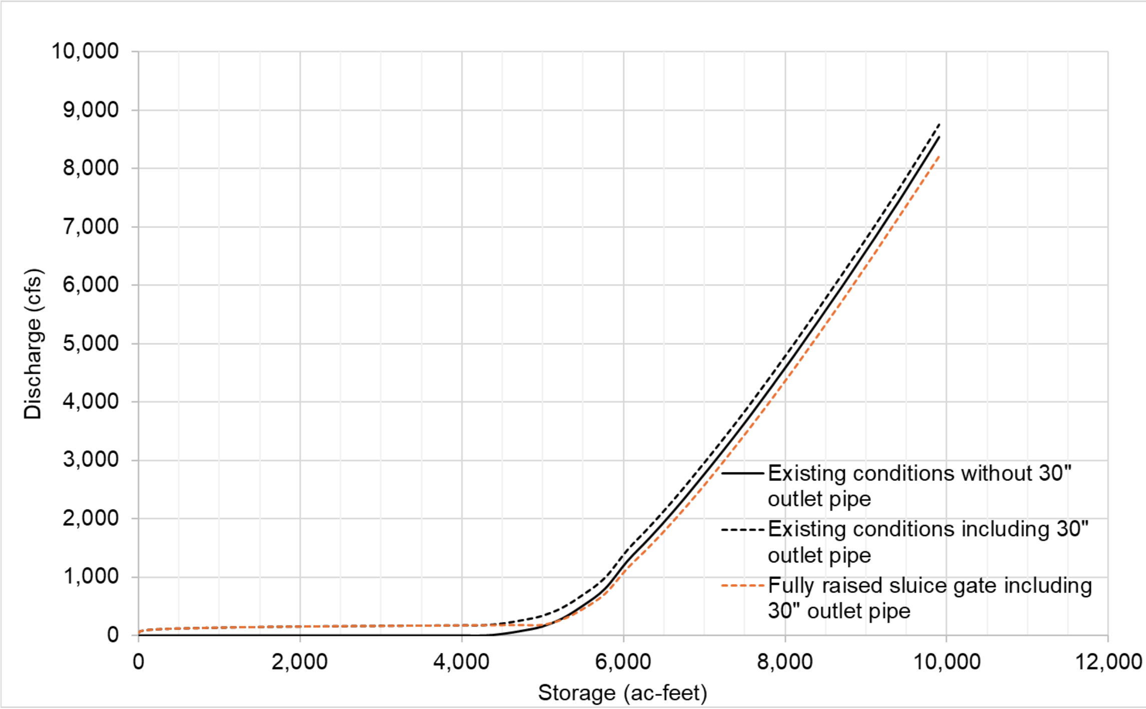
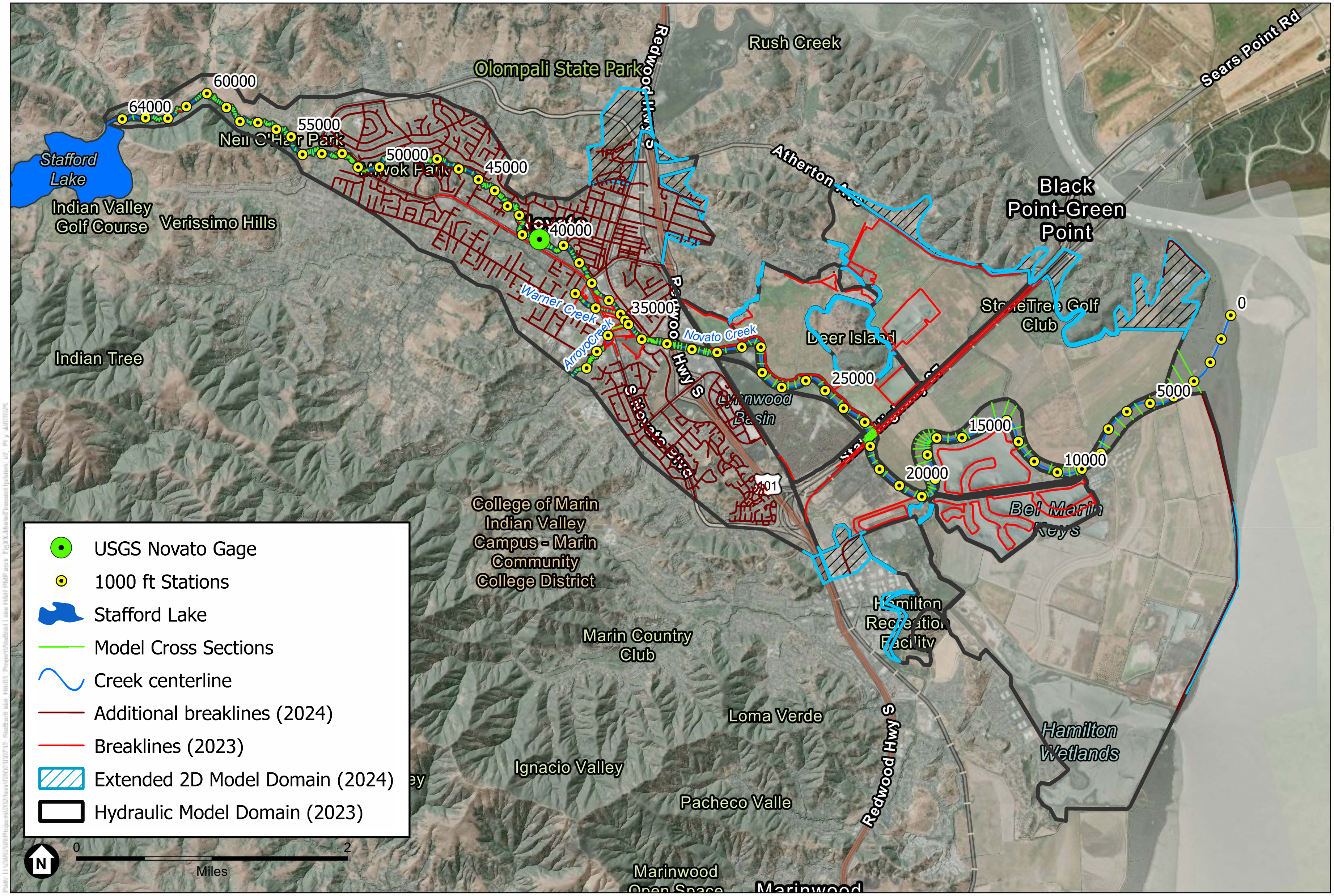


Figure 13. Storage-discharge curves for existing and proposed spillway

HEC-RAS Model Domain Updates

Minor adjustments were made to the HEC-RAS model domain to ensure accuracy when modeling the PMF. Initial PMF simulations showed areas of the 2D computational domain that required extension, as the initial PMP flood extents were "glasswalled" against the original 2D computational domain's perimeter. Areas where the 2D computational domain were extended include Olompali State Historic Park west of Highway 101, Green Point north of Atherton Avenue, and Day Island. Additionally, the Marin County roads GIS shapefile was applied as breaklines to enforce road crest elevations within the computation domain. Figure 14 summarizes the updates to the HEC-RAS geometry.



SOURCE: ESA HEC-RAS Modeling

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Figure 14
HEC-RAS Model Domain Updates

ESA

3.2 Hydraulic Model results

PMF under present and future climate

The flood hydrographs produced for the PMP derived from the HEC-HMS model were used as the boundary conditions for the HEC-RAS model. For future climate, under the high emissions scenario, the peak modeled inflow and outflow at Stafford Lake are 12,580 cfs and 6,600 cfs respectively. The corresponding peak stage at Stafford Lake is 212.5 ft NGVD29 with a freeboard of 1.5 feet. The flow hydrographs produced in HEC-HMS were applied as boundary conditions into the HEC-RAS model. A summary of rainfall, peak inflow and outflow, and freeboard is provided in Table 13.

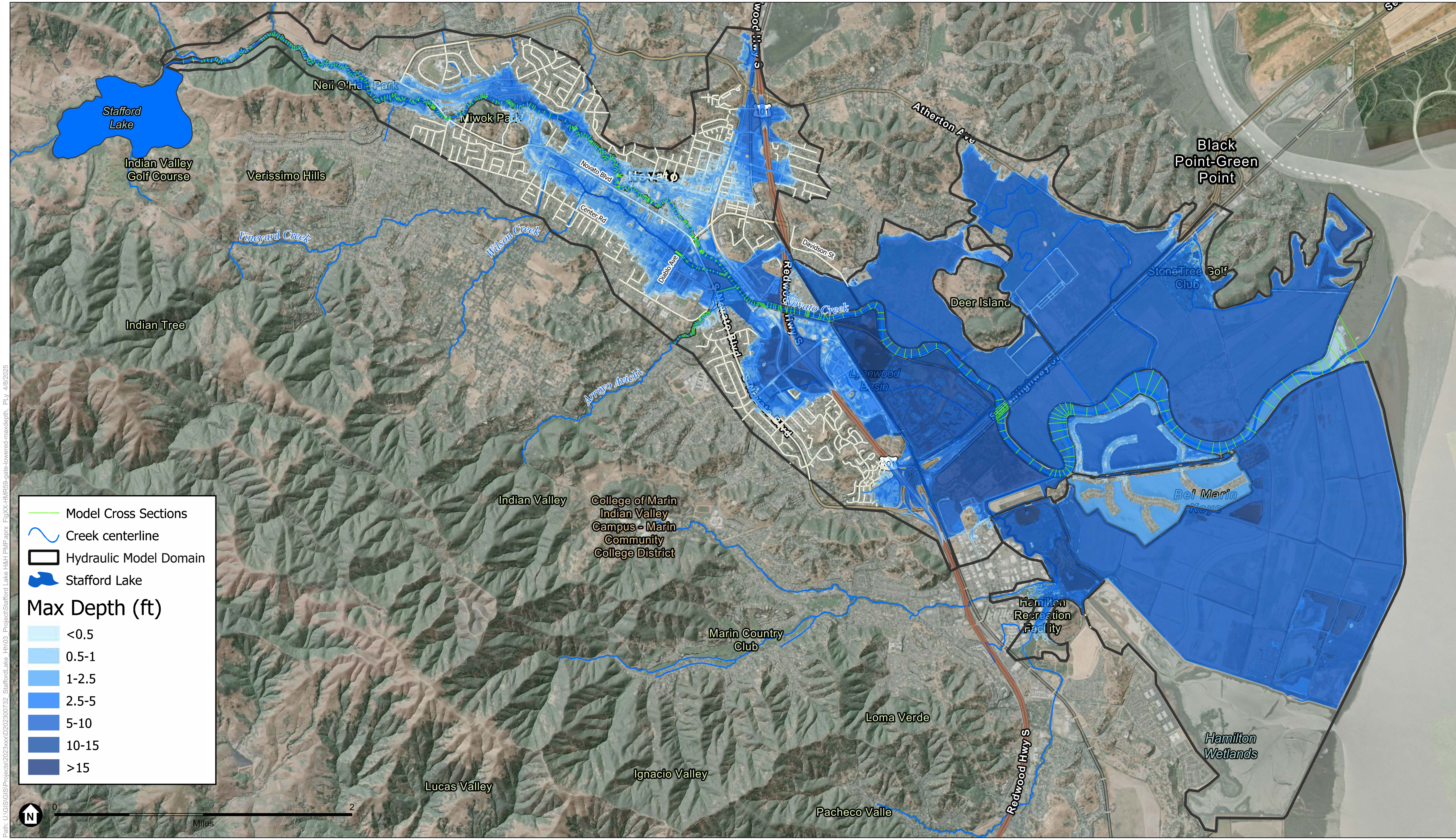
TABLE 13. PMF SUMMARY OF MODELED FLOWS

Spillway Configuration	Climate Condition	PMP (inches)	Peak Inflow at Stafford Lake (cfs)	Peak Outflow at Stafford Lake (cfs)	Peak Stage at Stafford Lake (ft NGVD29)	Freeboard (ft)	Peak Flow at USGS Gage 11459500 (cfs)[12]
Gate lowered	Present Day	31.28	10,900	5,480	210.8	3.2	14,440
Fully raised sluice gate		31.28	10,900	5,460	211.4	2.6	14,410
Gate lowered	Late century (High emissions - model mean)	35.83	12,580	6,610	212.5	1.5	16,990

As shown in this table, under present climate, the dam attenuates the PMF from 10,900 cfs to 5,480 cfs with the sluice gate lowered, and 5,460 cfs with the gate raised. Downstream of the dam, tributaries add additional inflow, raising the flow on Novato Creek to 14,440 cfs at the USGS gage. For these scenarios, the PMP rainfall was applied as input for all subbasins in the HMS model, including basins downstream of the dam.

The floodplain inundation extents for the PMP under the existing (no gate or gate lowered under proposed project) spillway configuration and the fully raised sluice gate configuration are shown in Figure 15 and Figure 16 respectively. As the difference in the PMF for these scenarios is negligible (20 cfs at the dam), the inundation extents are nearly identical. The inundation extent of the PMF under the high emissions scenario is shown in Figure 17. This scenario shows additional flooding depth and extent.

[12] Modeled HEC-RAS flows at USGS Gage 11459500 vary from flows presented in Table 12 due to overtopping and attenuation effects captured in the hydraulic model.



SOURCE: ESA HEC-RAS Modeling

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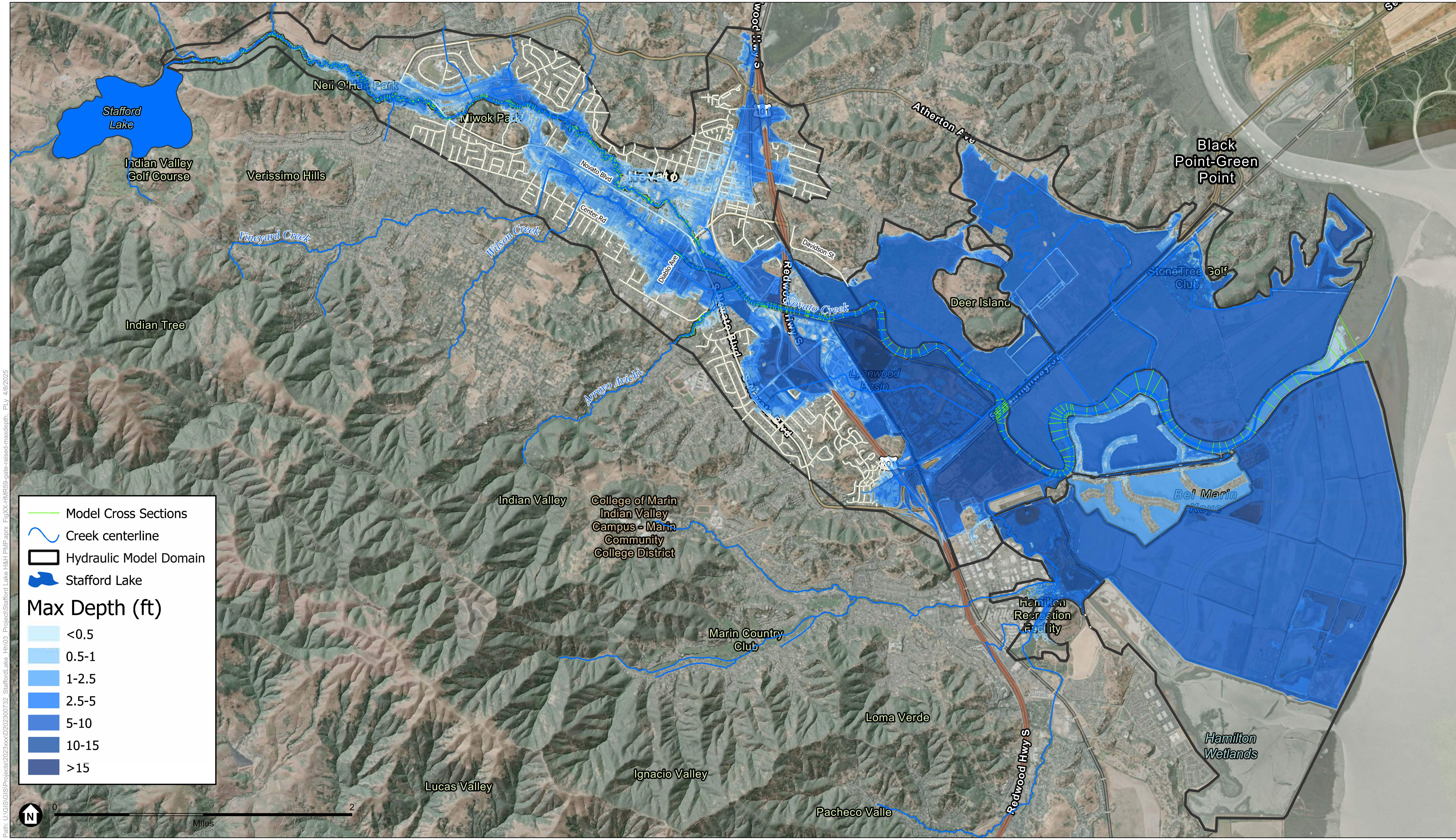
Figure 15
HMR59 PMF (Present Day - Gate Lowered) Maximum Depth



SOURCE: ESA HEC-RAS Modeling

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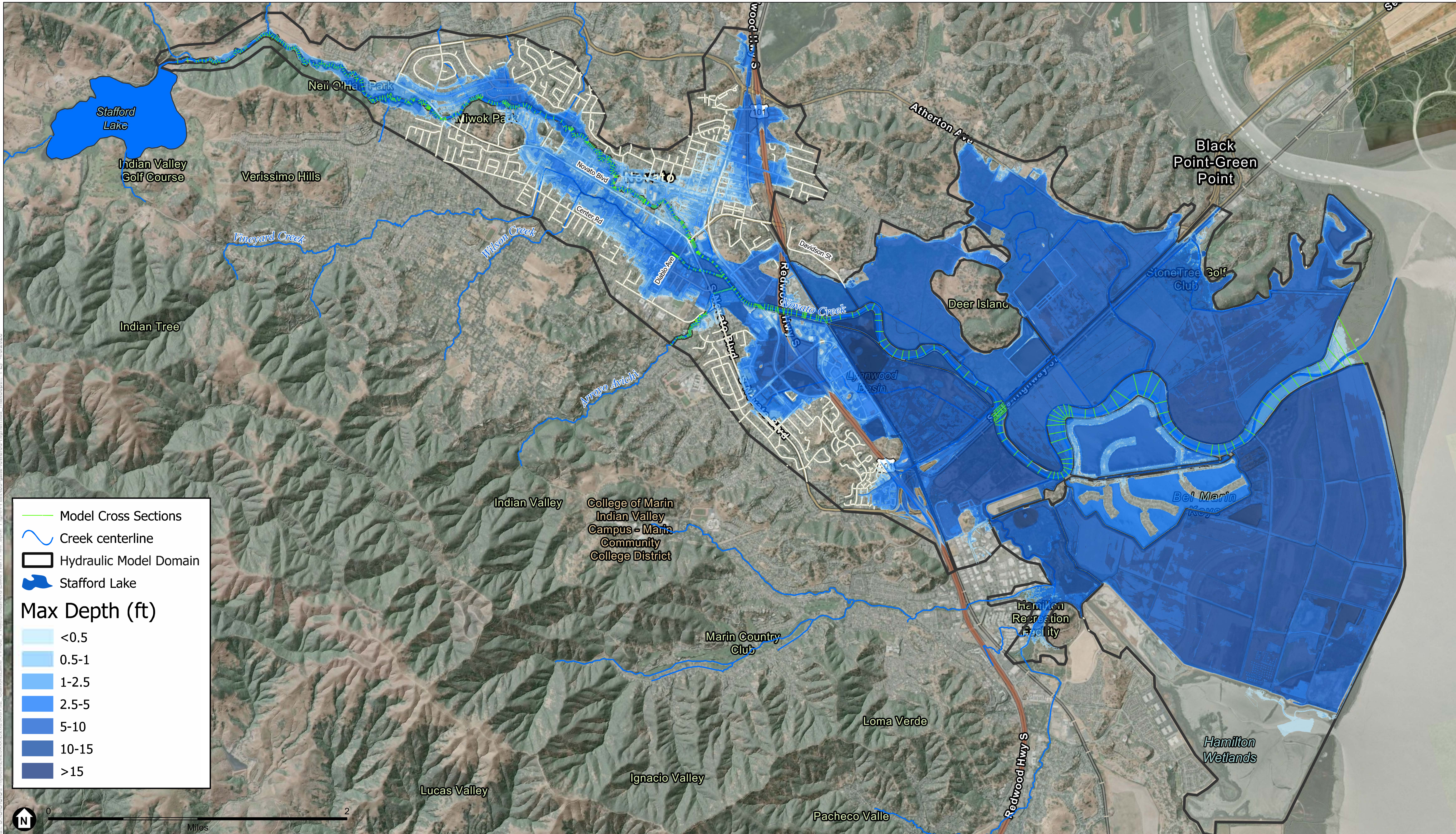
Figure 16
HMR59 PMF (Present Day - Fully raised sluice gate configuration) Maximum Depth

ESA



SOURCE: ESA HEC-RAS Modeling

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Figure 17
HMR59 PMF (2050-2100 [High Emissions - model mean]- Gate Lowered) Maximum Depth

ESA

Design Storms under present and future climate

For present climate, the 10-year and 50-year floodplain inundation extents are mapped in Figure 18 and 19. For the 100-year event, floodplain inundation extents for present-day and the late century High Emissions and E++ scenarios are mapped in Figure 20. Table 14 summarizes the peak inflows and outflows at the dam and at the USGS for the 10-year, 50-year, and 100-year events under present-day and future climate conditions.

TABLE 14. DESIGN STORMS SUMMARY OF MODELED FLOWS

Design Event	Spillway Configuration	Climate Condition	Peak Inflow at Stafford Lake (cfs)	Peak Outflow at Stafford Lake (cfs)	Peak Stage at Stafford Lake (ft NGVD29)	Freeboard (ft)	Peak Flow at USGS Gage 11459500 (cfs)
10-year	Gate lowered	Present Day	1,320	320	200.0	14.0	2,190
50-year			2,410	990	202.4	11.6	3,840
100-year			2,940	1,380	203.5	10.5	4,800
100-year		Late-century (High emissions - model mean)	4,020	2,140	205.2	8.8	6,830
100-year		Late-century (E++ - model mean + 2SD)	6,660	4,080	208.9	5.1	11,950

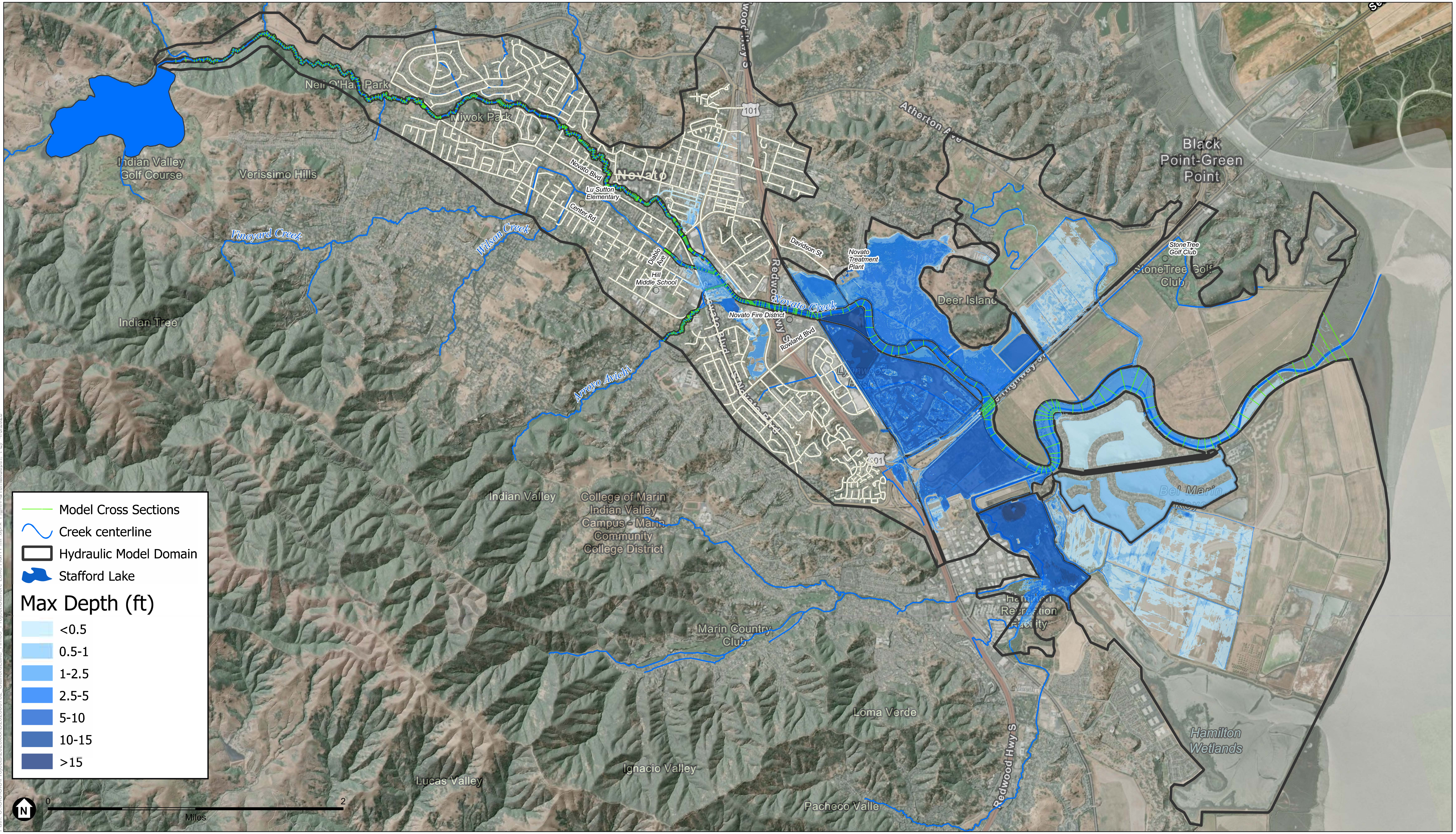
For the 100-year event, outflows from Stafford Lake are approximately one-third of the peak flows at the USGS gage under present-day and late-century climate scenarios, with tributaries downstream of the dam contributing the remainder of the peak inflow at the USGS gage. Under the high emissions 100-year scenario, the inundation area increases by 24% compared to the present-day 100-year event, extending past Novato Boulevard along Novato Creek, increasing the flooding onto Center Road and surrounding neighborhoods and extending into assets such as the Novato Fire Protection District located on Rowland Way.

Under the 100-year E++ scenario, an additional 50% increase in inundated acreage relative to present day is estimated. Near the confluence of Vineyard Creek and Wilson Creek, inundation extends further along Center Road, flooding Lu Sutton Elementary School and surrounding residential neighborhoods as well as Hill Middle School on Diablo Avenue. Further downstream, flooding encroaches onto the parking lots and other assets of the Novato Treatment Plant on Davidson Street and extends into the Stone Tree Golf Club southeast of Highway 37. Total inundated area for each event under the present and future climate conditions is summarized in Table 15.

Although lower recurrence intervals for future conditions were not simulated in the hydraulic model, frequency analysis of the downscaled rainfall data suggests that the present-day 50-year storm event is projected to occur with a frequency equivalent to a 10- to 25-year storm in the future. Similarly, the current 10-year storm precipitation depth is expected to correspond to a frequency between a 5- and 10-year storm.

TABLE 15. DESIGN STORM INUNDATION ACREAGE

Hydrologic Scenario	Climate Condition	Inundated Area (acres)
10-year	Present	2,090
50-year		3,700
100-year		4,290
100-year	Late-century (High emissions - model mean)	5,300
100-year	Late-century (E++ - model mean + 2SD)	6,290



SOURCE: ESA HEC-RAS Modeling

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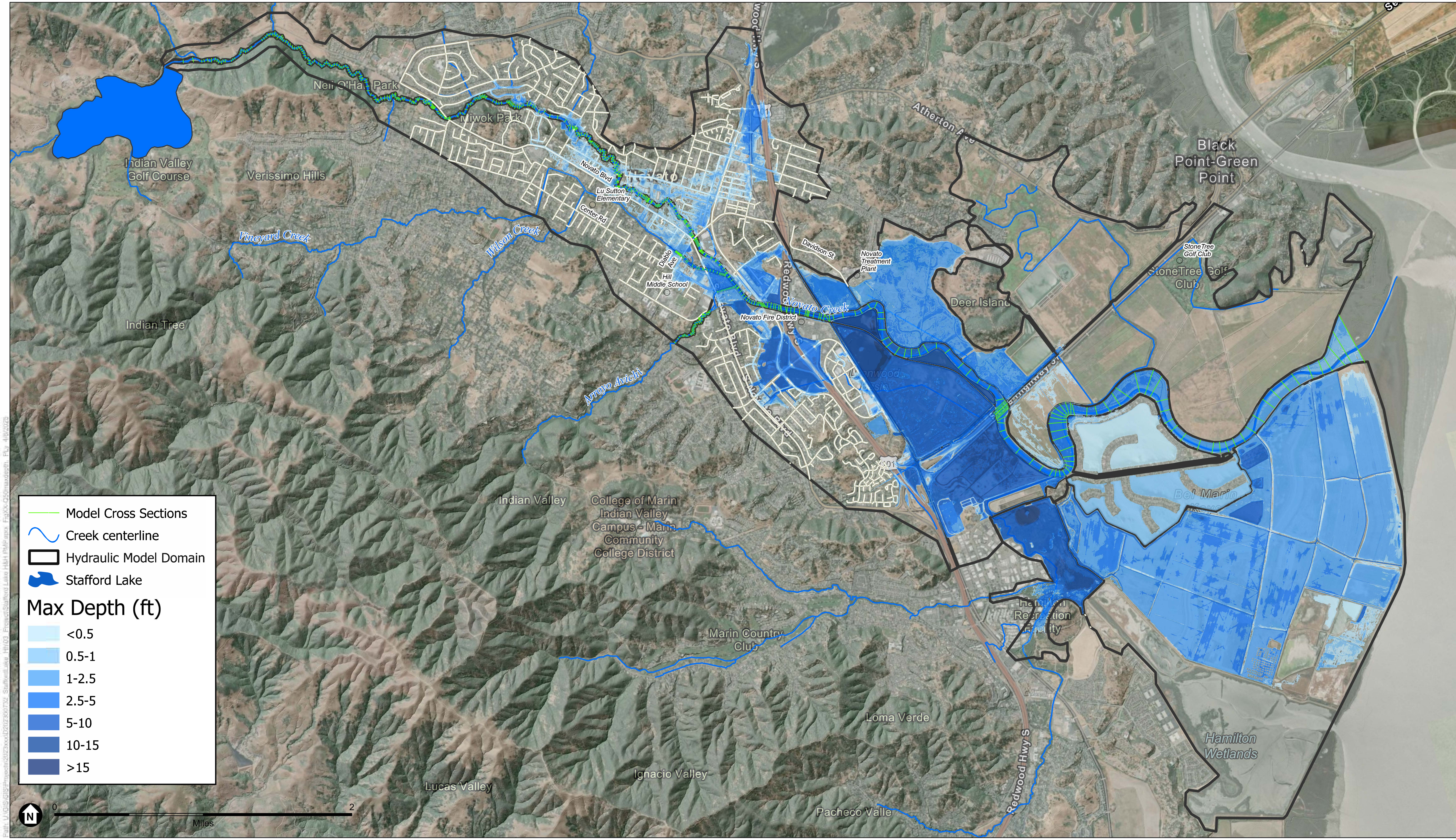
Figure 18
10-year Design Event (Present Day) Maximum Depth

ESA



SOURCE: ESA HEC-RAS Modeling

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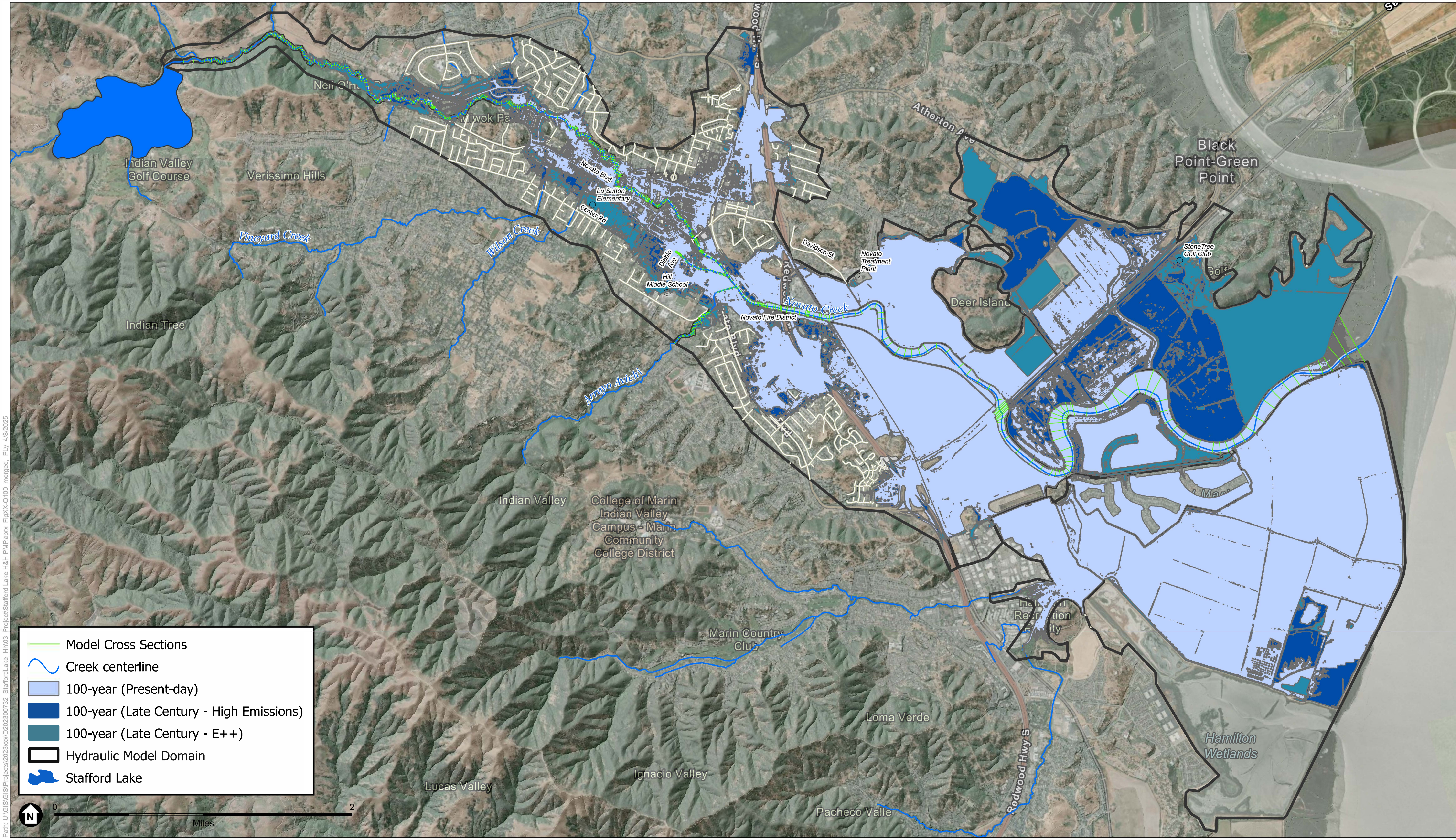
Figure 19
50-year Design Event (Present Day) Maximum Depth

ESA



SOURCE: ESA HEC-RAS Modeling

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Figure 20
100-year Design Event (Present Day) Maximum Depth

ESA

Sequential Event Scenarios

Results from the hydraulic model show that the peak flow and flooding impact increase for each sequential event scenario. Hydrographs for each scenario at the USGS stream gage location are shown in Figure 21. The 10-year, 25-year, and 50-year initial peaks each raise the subsequent 100-year peak slightly higher. In comparison to the singular 100-year design event, the subsequent peak of each sequential event scenario is higher due to the prior event's impact on soil moisture and lake storage conditions. The USGS observed discharge hydrograph, compared to the modeled results of the original, non-scaled precipitation data, confirms that the hydrologic and hydraulic models produce similar timing and magnitude of the observed peak flows.

The intensity of the rainfall for the two atmospheric river events plays a significant role in downstream flow. The first storm (on 1/8) had more intense rainfall which, when used to scale the 50-year rainfall, generates a peak that is close to that generated by the 100-year rainfall applied to the less intense second storm (on 1/9).

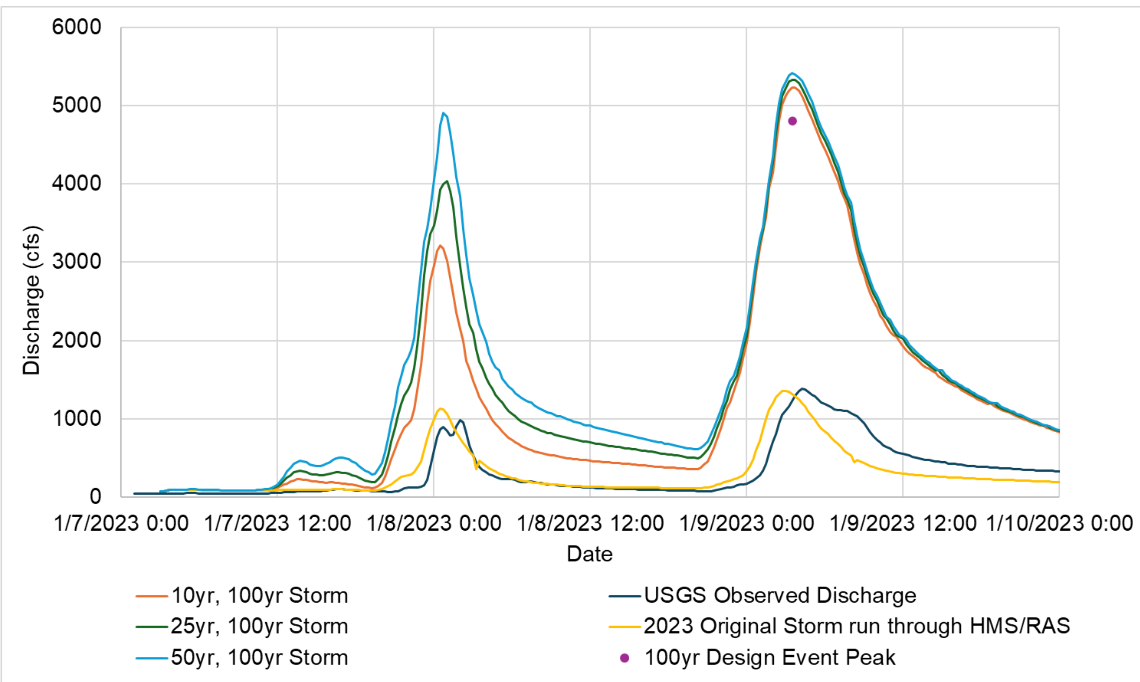
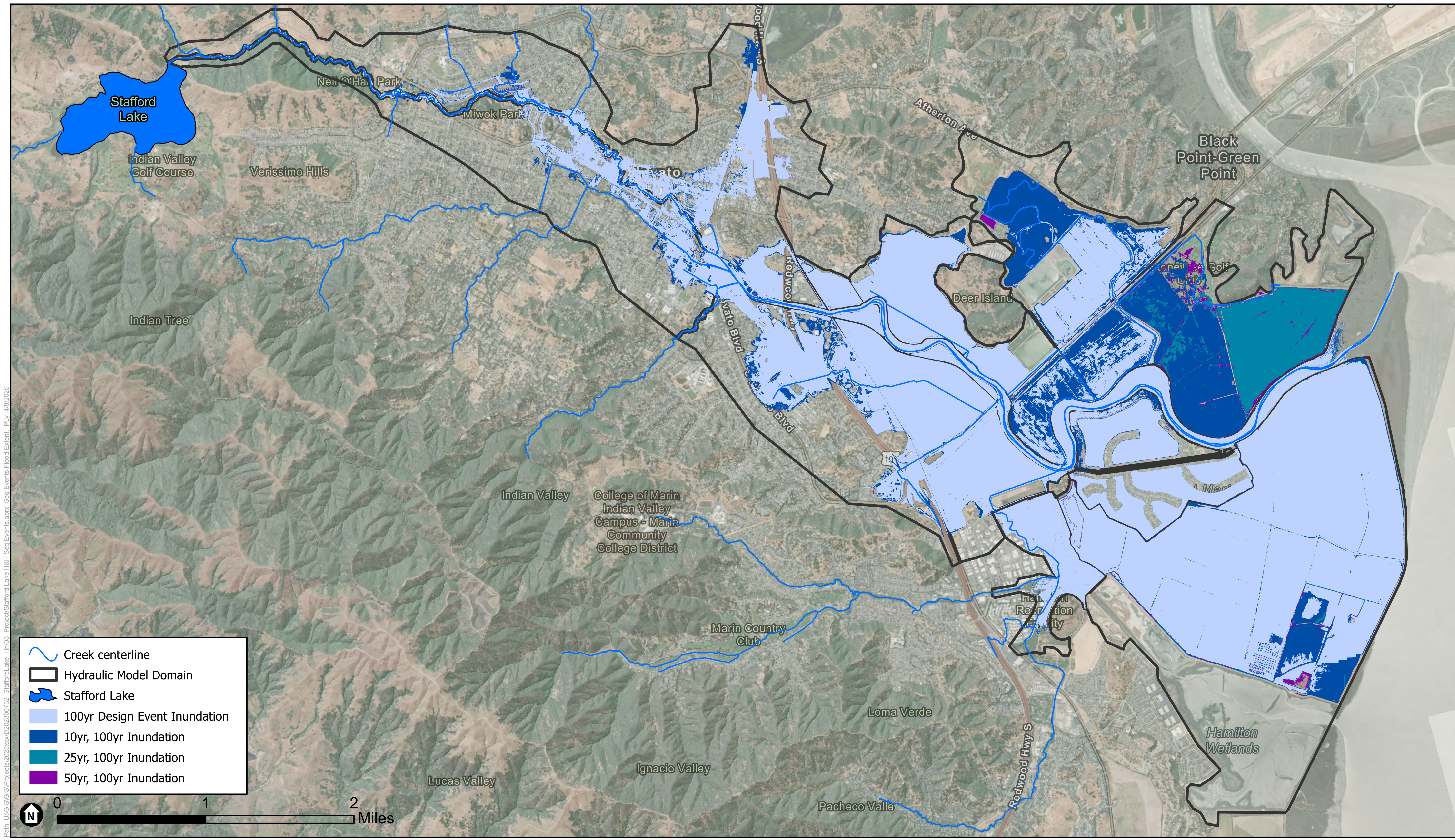


Figure 21. HEC-RAS hydrograph results at USGS Novato discharge gage 11459500

Inundation extents were estimated for the 100-year design event and each sequential event scenario (Table 16). Figure 23 maps the inundation extents for each sequential event scenario compared to a singular 100-year design storm.



SOURCE: ESRI Aerial Imagery (2024), ESA HEC-RAS Modeling (2024)

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Figure 22
Sequential Events Inundation Extent

ESA

TABLE 16. COMPARISON OF FLOODPLAIN INUNDATION EXTENTS UNDER EACH SEQUENTIAL EVENT SCENARIO

Storm Scenario	Inundated Area (acres)	Increase from 100yr (acres)	Increase from 100yr (%)
100yr Design Event	4,290	---	---
10yr, 100yr	5,160	870	17%
25yr, 100yr	5,490	1,200	22%
50yr, 100yr	5,550	1,260	23%

Histograms of the floodplain depths for each sequential event scenario were generated in ArcGIS Pro as shown in Figure 23. Depths are only shown for the overbank area to highlight the effect of each scenario on flooding in developed areas. The histograms show that floodplain depths under the sequential events scenario are greater than the singular 100-year design event. Additionally, the histograms show that the stronger the previous storm in the sequential event, the deeper the flooding area. Under the singular 100-year design event, the most frequent floodplain depth is 1-3 feet. When an initial 10-year peak occurs prior to the 100-year, the most frequently observed floodplain depths range from 3-5 feet. As the initial peak increases to a 50-year peak, the most frequently observed floodplain depths are 5-7 feet.

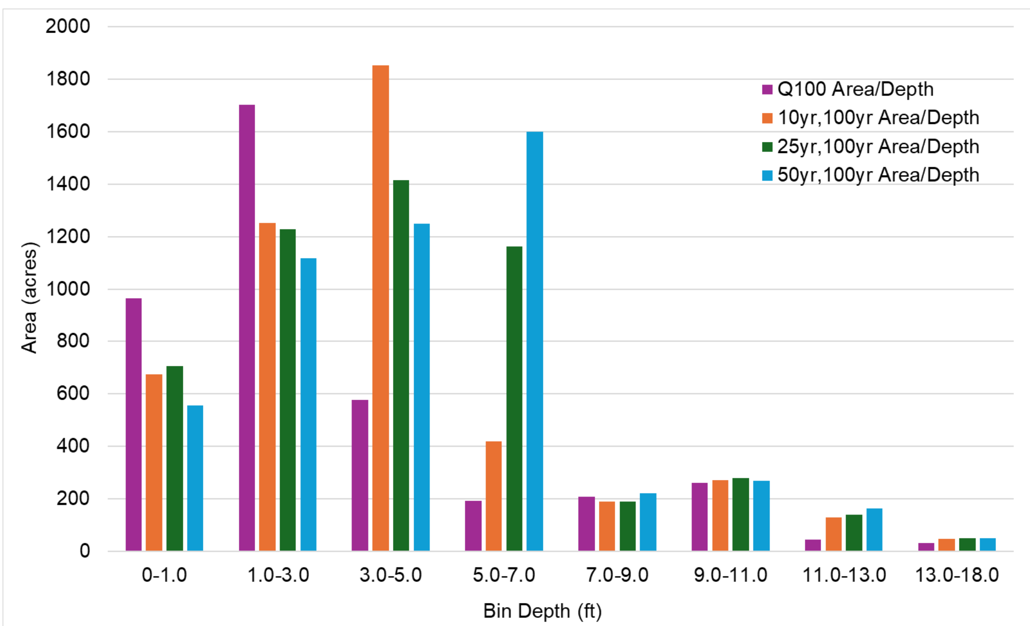

Figure 23. Frequency of floodplain inundation depths under sequential event scenarios

Comparing the inundation extents between sequential event scenarios, it is noticeable that the flooding impact only varies slightly despite the difference in the first peak's storm size. This is due to attenuation in Stafford Lake (Figures 25-27). Given the lag between the two atmospheric rivers in the January 2023 events, the dam has sufficient time to attenuate the first storm. However, events more closely spaced in time would likely generate a larger flood impact. Further evaluation may be warranted to evaluate the likelihood of more tightly spaced events and test the effect of the temporal spacing on downstream flood impact.

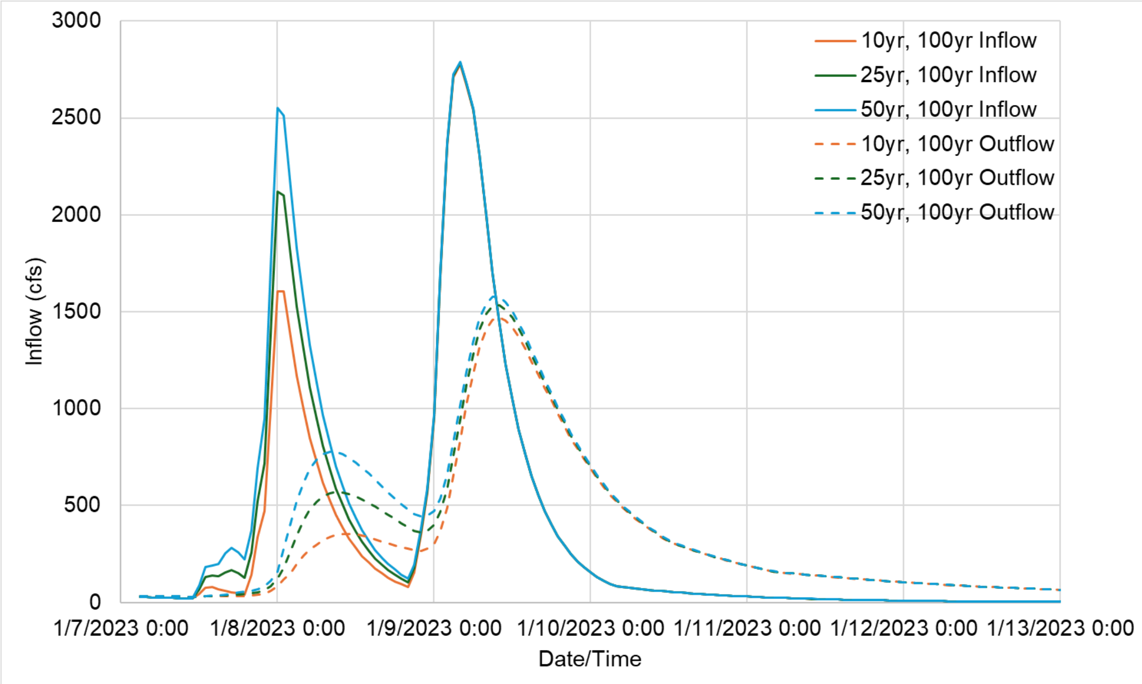

Figure 24. Stafford Lake inflow/outflow hydrographs under sequential events scenarios

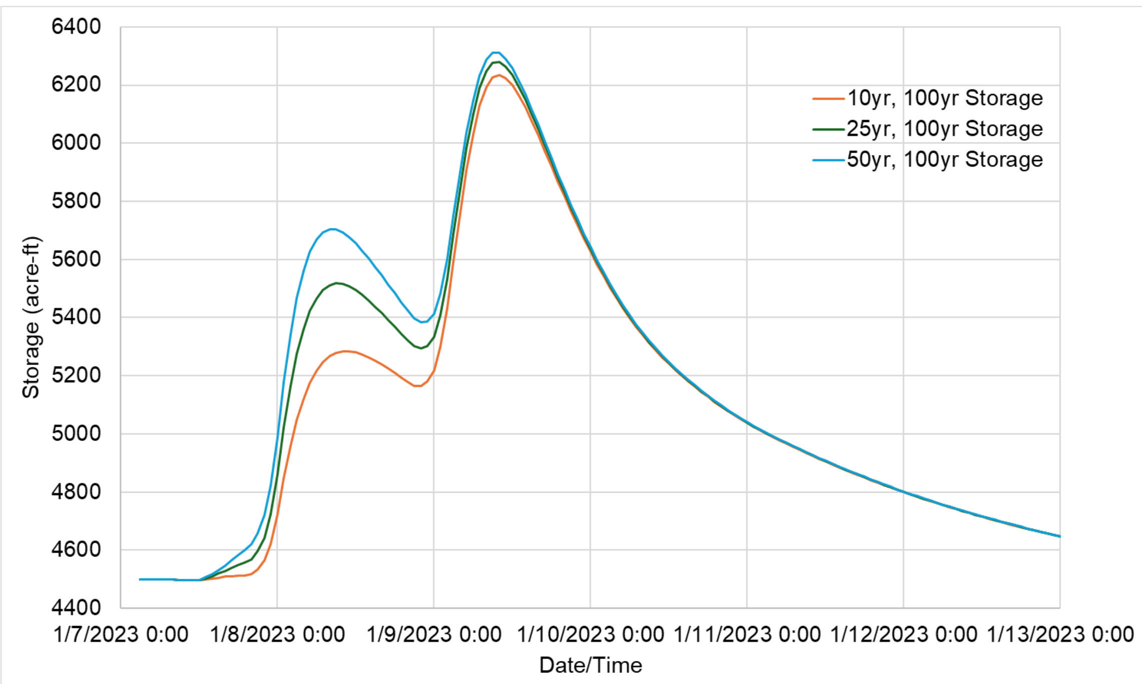

Figure 25. Stafford Lake storage under sequential event scenarios

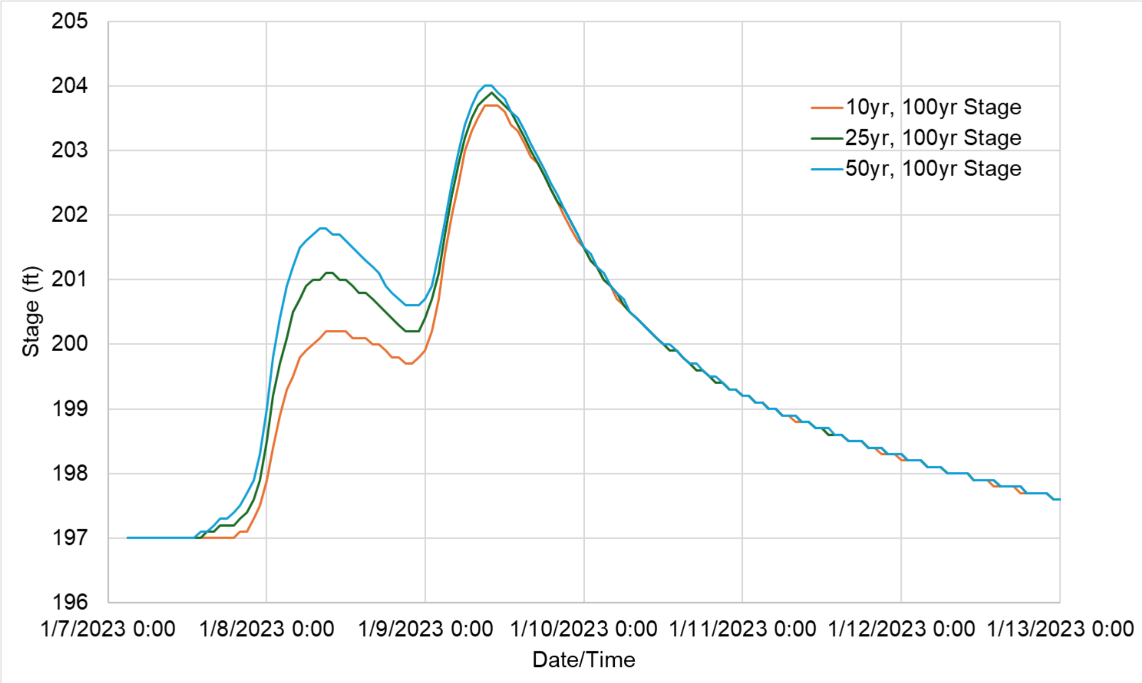

Figure 26. Stafford Lake stage under sequential event scenarios

CHAPTER 4
Conclusions and recommendations

ESA evaluated extreme hydrology scenarios for Stafford Lake and Novato Creek through detailed hydrologic and hydraulic modeling. Key findings include updates to the Probable Maximum Flood (PMF), characterization of sequential storm events, and analysis of climate change impacts on extreme events. ESA evaluated scenarios under the current configuration of the spillway as well as under the proposed sluice gate project.

The updated PMF analysis using HMR 59 methodology indicates a 72-hour PMP of 31.28 inches, an increase from the previous estimate of 23.05 inches used in the 1985 design basis. This increase reflects improved understanding of orographic effects in the Marin Headlands region. Despite the higher PMP, updates to the time of concentration and storage coefficient parameters result in a lower peak inflow of 10,900 cfs compared to the 1985 design value of 12,305 cfs, though with a longer duration that increases the total volume. Under both existing conditions and the proposed raised gate configuration, the PMF produces peak outflows of approximately 5,460-5,480 cfs while maintaining a freeboard above 2 feet. We recommend adopting the updated PMP/PMF developed in this study as the design standard for Stafford Dam.

Analysis of sequential storm events based on the January 2023 atmospheric river pattern demonstrates that Stafford Dam provides significant attenuation of flood peaks. While antecedent storms increase downstream flooding impacts, the reservoir's storage capacity generally attenuates these effects when the peaks are temporally spread out as they were during this observed event. For the scenarios analyzed, when a 100-year event is preceded by a 10-year event, floodplain inundation increases by 17% compared to a singular 100-year event. This increases to 23% when preceded by a 50-year event. However, the temporal spacing between events plays a critical role—the 26-hour gap between peaks in the January 2023 sequence allows for significant attenuation. Future studies led under MCFCD could evaluate the sensitivity of downstream flooding to more closely spaced sequential events.

Climate change analysis using the LOCA2 dataset projects substantial increases in extreme rainfall by 2050-2100. Under a high emissions scenario, the 100-year rainfall depth increases by 31%, resulting in a peak discharge increase from 4,830 cfs to 6,890 cfs at the USGS gage. Some of the climate models analyzed project greater future increase. At the upper end of the climate model distribution (E++ scenario), 100-year rainfall is estimated to increase by 105% with corresponding peak flows at the USGS gage of 12,120 cfs. The PMF is projected to increase by 15% under high emissions (model mean), reducing freeboard at Stafford Lake to 1.5 feet under gate-lowered conditions. These projections highlight the importance of incorporating climate change considerations into long-term infrastructure planning and operation.

Recommendations for future work include:

- Evaluate the sensitivity of sequential event impacts to storm spacing and timing.
- Review and consider updating the design storm parameters in the HEC-HMS model to improve consistency in loss rates and temporal rainfall distributions across events.
- Consider additional analysis of very high emissions scenarios if needed for long-term flood risk management planning.
- For long-range planning, monitor developments in PMP estimation methodology, particularly the forthcoming framework in development by the National Academies.

CHAPTER 5
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CHAPTER 6
List of preparers

- James Gregory, P.E.
- Phong Ly, P.E.
- Ruby Telfer, E.I.T.

APPENDIX A

Tabulated stage-storage-discharge relationships and inflow-outflow under existing conditions and raised sluice gate configuration

TABLE A 1. TABULATED STAGE-STORAGE-DISCHARGE CURVES UNDER EXISTING CONDITIONS AND RAISED SLUICE GATE CONFIGURATION

Storage (ac-ft)	Elevation (ft NGVD29)	Discharge (cfs)		
		Existing conditions without 30" outlet pipe	Existing conditions with 30" outlet pipe	Gate raised with 30" outlet pipe
0.0	150.0	0.0	45.1	45.0
0.1	150.2	0.0	46.3	46.3
0.9	151.2	0.0	52.5	52.5
3.7	152.3	0.0	58.6	58.6
12.5	154.0	0.0	66.9	66.9
23.5	155.3	0.0	72.6	72.6
39.2	156.7	0.0	78.3	78.3
58.5	158.0	0.0	83.3	83.2
79.1	159.1	0.0	87.2	87.2
101.0	160.1	0.0	90.6	90.6
128.6	161.2	0.0	94.3	94.3
154.2	162.1	0.0	97.2	97.2
186.6	163.1	0.0	100.3	100.3
219.0	164.0	0.0	103.0	103.0
255.0	164.9	0.0	105.6	105.6
298.6	165.9	0.0	108.5	108.5
346.2	166.9	0.0	110.9	110.9
398.3	167.9	0.0	113.4	113.4
455.3	168.9	0.0	115.8	115.8
517.3	169.9	0.0	118.2	118.2
584.3	170.9	0.0	120.6	120.6
663.5	172.0	0.0	123.3	123.3
741.0	173.0	0.0	125.7	125.7
823.5	174.0	0.0	128.1	128.1
911.5	175.0	0.0	130.5	130.5
1015.4	176.1	0.0	133.2	133.2

Storage (ac-ft)	Elevation (ft NGVD29)	Discharge (cfs)		
		Existing conditions without 30" outlet pipe	Existing conditions with 30" outlet pipe	Gate raised with 30" outlet pipe
1115.5	177.1	0.0	135.6	135.6
1220.5	178.1	0.0	138.0	138.0
1330.5	179.1	0.0	140.4	140.4
1445.7	180.1	0.0	142.8	142.8
1568.1	181.1	0.0	145.2	145.2
1699.4	182.1	0.0	147.1	147.1
1824.5	183.0	0.0	148.8	148.8
1972.0	184.0	0.0	150.7	150.7
2128.5	185.0	0.0	152.7	152.5
2276.6	185.9	0.0	154.4	154.2
2447.8	186.9	0.0	156.3	156.1
2626.1	187.9	0.0	158.2	158.0
2810.5	188.9	0.0	160.2	159.9
3000.5	189.9	0.0	162.1	161.8
3195.9	190.9	0.0	164.0	163.7
3397.3	191.9	0.0	165.9	165.6
3604.7	192.9	0.0	167.9	167.5
3818.1	193.9	0.0	169.8	169.4
4037.5	194.9	0.0	171.7	171.3
4263.8	195.9	0.0	173.6	173.2
4286.5	196.0	0.0	173.8	173.3
4310.0	196.1	3.1	177.1	173.5
4356.9	196.3	9.3	183.6	173.9
4403.8	196.5	15.5	190.2	174.3
4450.7	196.7	21.7	196.7	174.7
4497.6	196.9	27.9	203.3	175.0
4545.2	197.1	36.6	212.3	175.4
4593.6	197.3	47.8	223.9	175.8
4642.0	197.5	59.0	235.4	176.2
4690.4	197.7	70.2	247.0	176.6
4738.8	197.9	81.4	258.5	176.9
4788.0	198.1	94.0	271.5	177.3
4837.9	198.3	108.0	285.8	177.7
4887.8	198.5	122.0	300.2	178.1
4937.7	198.7	136.0	314.5	178.4
4976.3	198.9	150.0	328.8	178.8
5038.2	199.1	172.5	351.7	189.5
5089.6	199.3	203.5	383.0	210.4
5141.0	199.5	234.5	414.4	231.3

Storage (ac-ft)	Elevation (ft NGVD29)	Discharge (cfs)		
		Existing conditions without 30" outlet pipe	Existing conditions with 30" outlet pipe	Gate raised with 30" outlet pipe
5192.4	199.7	265.5	445.7	252.2
5243.8	199.9	296.5	477.1	273.1
5295.9	200.1	335.7	516.6	303.5
5348.7	200.3	383.1	564.3	343.4
5401.5	200.5	430.5	612.1	383.3
5454.3	200.7	477.9	659.8	423.1
5507.1	200.9	525.3	707.5	463.0
5560.6	201.1	578.5	761.1	509.6
5614.7	201.3	637.5	820.4	562.9
5668.8	201.5	696.5	879.7	616.2
5722.9	201.7	755.5	939.1	669.6
5777.0	201.9	814.5	998.4	722.9
5812.8	202.1	878.8	1063.0	781.7
5830.5	202.3	948.4	1133.0	846.0
5848.1	202.5	1018.0	1202.9	910.3
5902.9	202.7	1087.6	1272.8	974.6
5957.7	202.9	1157.2	1342.8	1038.9
6012.8	203.1	1232.0	1417.9	1108.5
6068.4	203.3	1312.0	1498.2	1183.2
6123.9	203.5	1392.0	1578.6	1258.0
6180.2	203.7	1472.0	1658.9	1332.8
6236.4	203.9	1552.0	1739.2	1407.6
6293.1	204.1	1635.4	1822.9	1486.9
6350.1	204.3	1722.2	1910.1	1570.7
6407.0	204.5	1809.0	1997.2	1654.5
6464.7	204.7	1895.8	2084.3	1738.3
6522.4	204.9	1982.6	2171.4	1822.1
6580.4	205.1	2074.5	2263.7	1910.0
6638.8	205.3	2171.5	2361.0	2001.8
6697.1	205.5	2268.5	2458.3	2093.6
6756.1	205.7	2365.5	2555.6	2185.5
6815.2	205.9	2462.5	2653.0	2277.3
6874.5	206.1	2562.1	2752.9	2373.6
6934.2	206.3	2664.3	2855.4	2474.2
6993.9	206.5	2766.5	2957.9	2574.9
7054.2	206.7	2868.7	3060.4	2675.5
7114.6	206.9	2970.9	3163.0	2776.2
7175.3	207.1	3076.1	3268.5	2880.1
7236.3	207.3	3184.3	3377.0	2987.4

Storage (ac-ft)	Elevation (ft NGVD29)	Discharge (cfs)		
		Existing conditions without 30" outlet pipe	Existing conditions with 30" outlet pipe	Gate raised with 30" outlet pipe
7297.4	207.5	3292.5	3485.5	3094.7
7359.1	207.7	3400.7	3594.0	3201.9
7420.8	207.9	3508.9	3702.6	3309.2
7482.9	208.1	3621.5	3815.5	3419.6
7545.2	208.3	3738.5	3932.8	3533.1
7607.6	208.5	3855.5	4050.1	3646.7
7670.7	208.7	3972.5	4167.4	3760.2
7733.7	208.9	4089.5	4284.7	3873.7
7797.1	209.1	4209.0	4404.5	3990.5
7860.8	209.3	4331.0	4526.8	4110.4
7924.5	209.5	4453.0	4649.2	4230.4
7988.9	209.7	4575.0	4771.5	4350.3
8053.2	209.9	4697.0	4893.8	4470.3
8117.8	210.1	4822.7	5019.8	4593.7
8182.8	210.3	4952.1	5149.5	4720.6
8247.7	210.5	5081.5	5279.2	4847.5
8313.2	210.7	5210.9	5408.9	4974.3
8378.7	210.9	5340.3	5538.6	5101.2
8444.6	211.1	5471.6	5670.2	5230.1
8510.7	211.3	5604.8	5803.8	5360.9
8576.8	211.5	5738.0	5937.3	5491.7
8643.5	211.7	5871.2	6070.8	5622.6
8710.2	211.9	6004.4	6204.3	5753.4
8777.2	212.1	6140.9	6341.1	5887.6
8844.6	212.3	6280.7	6481.2	6025.1
8911.9	212.5	6420.5	6621.3	6162.7
8979.9	212.7	6560.3	6761.4	6300.2
9047.9	212.9	6700.1	6901.5	6437.8
9116.3	213.1	6842.7	7044.4	6578.4
9184.9	213.3	6988.1	7190.1	6722.1
9253.6	213.5	7133.5	7335.8	6865.7
9323.0	213.7	7278.9	7481.5	7009.4
9392.4	213.9	7424.3	7627.2	7153.1
9427.1	214.0	7497.0	7700.1	7224.9

TABLE A 2. TABULATED INFLOW, RESERVOIR STAGE, AND OUTFLOW UNDER EXISTING CONDITIONS AND RAISED GATE CONFIGURATION

Simulation Time (hrs)	Inflow (cfs)	Outflow (cfs)		Stage (ft NGVD29)	
		Existing conditions (cfs)	Raised gate configuration (cfs)	Existing conditions (cfs)	Raised gate configuration (cfs)
0	29	203.7	175.1	196.9	196.9
1	27.8	201.8	175	196.8	196.9
2	43.6	200	174.9	196.8	196.8
3	99.8	198.6	174.8	196.7	196.8
4	179.9	198	174.8	196.7	196.8
5	249.1	198.1	174.8	196.7	196.8
6	300.2	199	174.9	196.8	196.8
7	339.8	200.3	175	196.8	196.9
8	372.4	201.9	175.1	196.8	196.9
9	400.9	204	175.2	196.9	197
10	427.2	208	175.4	197	197.1
11	452.5	212.3	175.6	197.1	197.2
12	477.8	217.1	175.7	197.2	197.3
13	503.7	222.3	176	197.3	197.4
14	530.9	227.8	176.2	197.4	197.5
15	559.5	233.8	176.4	197.5	197.6
16	589.4	240.2	176.7	197.6	197.8
17	621.2	247.1	176.9	197.7	197.9
18	655.4	254.5	177.2	197.8	198.1
19	692.4	263.5	177.6	198	198.2
20	732.5	274.4	177.9	198.1	198.4
21	776.2	286	178.3	198.3	198.6
22	824	298.4	178.7	198.5	198.8
23	876.6	311.7	190.8	198.7	199.1
24	934.8	326.1	211.9	198.9	199.3
25	999.3	350.8	234.1	199.1	199.5
26	1071.2	381.8	257.6	199.3	199.7
27	1152.8	414.8	294.4	199.5	200.1
28	1247	450.4	346.2	199.7	200.3
29	1356.9	497.3	400.8	200	200.6
30	1487.1	561.3	460.2	200.3	200.9
31	1645	630.9	544.2	200.6	201.2
32	1841.8	709.8	635.2	200.9	201.6
33	2095.5	816.5	751.7	201.3	202
34	2526.7	943.2	942.7	201.7	202.6
35	3269	1153.7	1177.5	202.4	203.3
36	4476	1473.2	1464.8	203.4	204
37	7444.7	2043.4	1980.1	204.6	205.3
38	10774.4	3021.6	2884.5	206.5	207.1

Simulation Time (hrs)	Inflow (cfs)	Outflow (cfs)		Stage (ft NGVD29)	
		Existing conditions (cfs)	Raised gate configuration (cfs)	Existing conditions (cfs)	Raised gate configuration (cfs)
39	10899.6	4117.4	3977.1	208.4	209.1
40	8915.1	4935.8	4838.5	209.9	210.5
41	7055.4	5384.2	5308.1	210.6	211.2
42	5546.6	5521.2	5457.9	210.8	211.4
43	4420.7	5440.5	5386.4	210.7	211.3
44	3583.4	5226.8	5177.5	210.4	211
45	2958.4	4940.7	4894.2	209.9	210.6
46	2487.9	4628.2	4570.4	209.4	210.1
47	2129.1	4299.4	4244.8	208.8	209.5
48	1849.6	3972.8	3923.4	208.3	209
49	1629	3659.1	3617.4	207.8	208.4
50	1449.1	3361.7	3331	207.2	207.9
51	1283.8	3083.4	3064.6	206.7	207.4
52	1174.2	2824.3	2820	206.3	207
53	1083	2585.9	2599	205.8	206.5
54	1005.7	2369.1	2397.3	205.4	206.1
55	937.7	2180.3	2221.9	205	205.8
56	877.1	2009.6	2060.1	204.7	205.4
57	822.6	1854	1913.7	204.3	205.1
58	773.2	1722.5	1784.9	204	204.8
59	728.1	1602.5	1665.5	203.7	204.5
60	686.8	1492	1555	203.5	204.3
61	648.7	1390.4	1458.3	203.2	204
62	613.1	1302.5	1370.1	202.9	203.8
63	580	1220.9	1287.6	202.6	203.6
64	549.3	1145	1210.5	202.4	203.4
65	520.7	1074.5	1137.5	202.1	203.2
66	493.9	1008.9	1060.3	201.9	203
67	468.7	958.1	989.4	201.7	202.7
68	445.1	915.6	924.1	201.6	202.5
69	422.7	874.7	864.1	201.5	202.4
70	401.6	835.5	808.7	201.3	202.2
71	381.5	797.9	757.6	201.2	202
72	362.5	761.8	710.9	201.1	201.9

APPENDIX B
Digital Model Files

APPENDIX C

DSOD Approval Letter of PMP Methodology and Results

STATE OF CALIFORNIA – CALIFORNIA NATURAL RESOURCES AGENCY GAVIN NEWSOM, *Governor*

DEPARTMENT OF WATER RESOURCES
P.O. BOX 942836
SACRAMENTO, CA 94236-0001
(916) 653-5791

June 3, 2025

Mr. Anthony Williams, General Manager
North Marin County Water District
Post Office Box 146
Novato, California 94948

Attention: Eric Miller, P.E.
Chief Engineer

Novato Creek Dam, No. 88
Marin County

Dear Mr. Williams:

This is in reply to a submittal of a technical memorandum (TM) dated February 10, 2025, from Mr. James Gregory of Environmental Science Associates (ESA) to the Division of Safety of Dams (DSOD), on behalf of the North Marin County Water District, submitting an updated hydrological evaluation for Novato Creek Dam. The TM establishes the inflow hydrograph for the proposed spillway modifications. North Marin County Water District requested DSOD's review of the hydrology methodology and inflow hydrograph presented.

DSOD has completed its independent evaluation of the hydrology for the proposed spillway modifications and accepts the results presented in the TM. The center-loaded inflow hydrograph produced by ESA results in a peak inflow of 10,900 cubic feet per second and a volume of 10,013 acre-feet into the reservoir. This design inflow and runoff volume is acceptable for the design of the proposed spillway modifications. If any changes are made to this inflow hydrograph or related design criteria, it will need to be resubmitted for our review and acceptance.

If you have any questions or need additional information, please contact Design Engineer Jennilynn Janolo at (916) 639-3980 or Project Engineer Christopher Dorsey at (916) 820-7786.

Sincerely,

Shawn Jones

Shawn O. Jones, P.E.
Acting Division Manager
Division of Safety of Dams