US Army Corps
of Engineers ®
San Francisco District

PAJARO RIVER FLOOD RISK MANAGEMENT PROJECT

SANTA CRUZ AND MONTEREY COUNTIES

CALIFORNIA

CLIMATE ASSESSMENT

APPENDIX L OCTOBER 2018

Pajaro River Basin Climate Change Assessment:

Introduction: ECB No. 2016-25 requires USACE planning studies to provide a qualitative description of climate change impacts to inland hydrology. The purpose of this section is to meet the requirements as set forth in the ECB to enhance climate preparedness and resilience by incorporating relevant information on the impacts of climate change to inland Hydrology in designs and projects (USACE 2016). Up to the present time, USACE projects and operations have generally proven to be robust in the face of natural climate variability over their operating life spans. However recent scientific evidence shows, that in some geographic locations and for some impacts relevant to USACE operations, climate change is shifting the climatological baseline about which natural climate variability occurs and the range of the variability may be changing as well. More extreme seasonal conditions of flooding or drought may become more prevalent in some regions especially the Southwestern United States (USACE 2016). This section will describe how climate change could impact the hydrologic runoff processes in the watersheds in the *study* area. The outline of the assessment is given in Figure 1 below.

The purpose of the study is to determine if there is a Federal interest in providing additional flood risk management (FRM) improvements along the Pajaro River and its tributaries. The Pajaro River watershed is located on the central coast of California about 75 miles south of San Francisco. The project area is located within the lower Pajaro River watershed. The Pajaro River basin drains an area of approximately 1,300 square miles Salsipuedes and Corralitos Creeks, which join just north of the Pajaro River in Santa Cruz County, are tributaries of the Pajaro River.

The project delivery team (PDT) evaluated two sets of four flood risk management alternatives –one set of alternatives for the Pajaro River mainstem and the other set for Corralitos and Salsipuedes Creeks tributaries. All eight alternatives considered consist of constructing flood control levees. Mitigation efforts will also be undertaken to include all measures that would avoid, minimize, offset or compensate for potential environmental effects.

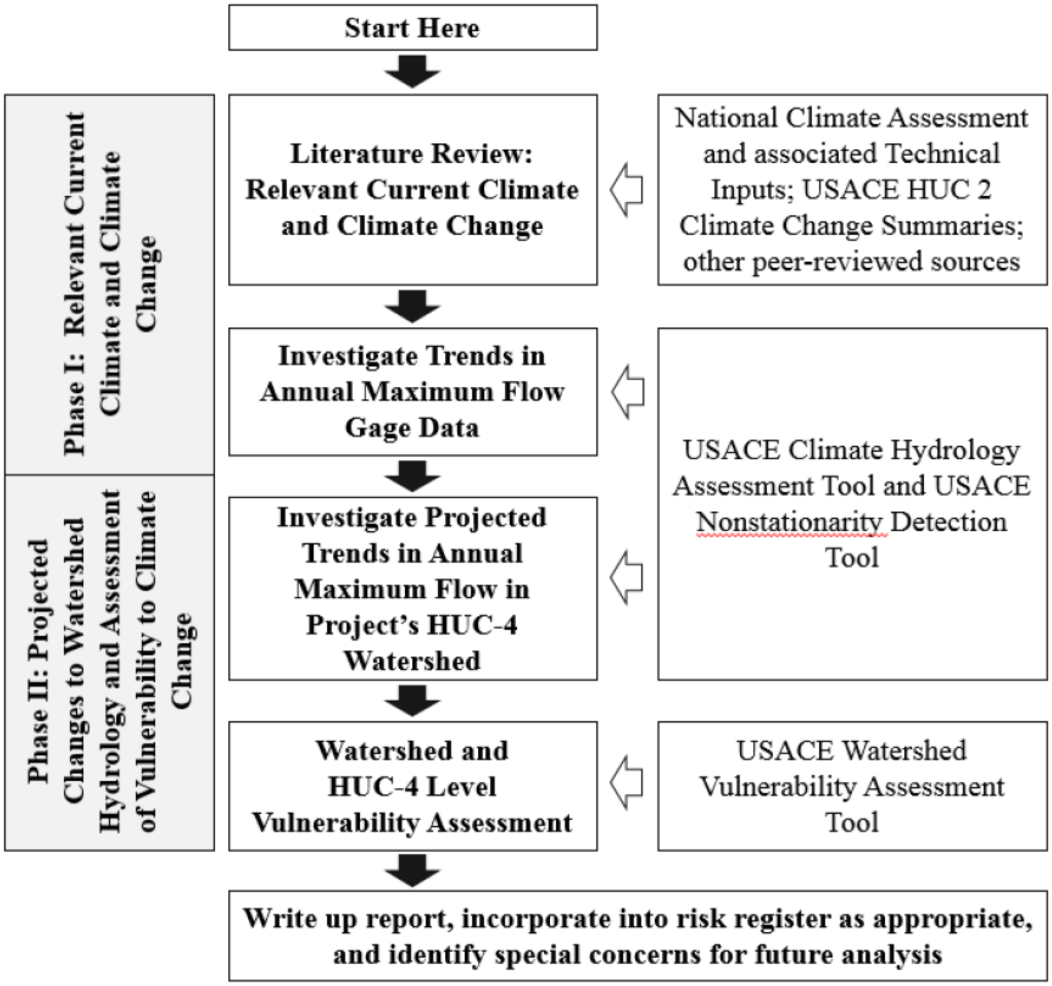

Figure 1 Flow Chart describing the qualitative climate change assessment to be used in Hydrology studies for Corps projects. From ECB 2016-25, Attachment B.

Literature Synthesis:

This section gives a brief description of observed and projected trends in local climate and hydrology as discussed in relevant peer reviewed literature including the USACE Climate Change and Hydrology Literature Synthesis (for HUC2-18 California), 3rd National Climate Assessment (for Southwest United States), California Department of Water Resources (DWR) reports and other sources. New climate projections (CMIP5) are now available which are consistent with the most recent Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5; Taylor et al. 2012) and many of these resources incorporate this updated data resource. Three DWR supported, research studies initiated in 2013 have been completed as of 2017. These include the *Climate Variability Sensitivity Study* (CVSS) completed by California DWR and USACE the Sacramento District in 2015 which evaluated the effects of increasing temperature on flood runoff on selected watersheds in the San Joaquin and Sacramento Valleys. This study used historic storm patterns with observed and projected temperatures to study the effect that warmer temperatures would have on runoff from historic storms.

The results from this study indicate that warmer temperatures would reduce the volume of the antecedent snowpack and increase the storm runoff due to more precipitation falling as rain and larger portions of the watersheds contributing runoff (USACE 2015). The other two DWR studies include the 2011 *Climate Change, Atmospheric Rivers, and Floods in California* Study (supported by the UCSD Scripps Institute of Oceanography and the USGS; Detinger 2011) investigating indices and future projections of the major flood-producing atmospheric processes, and the2010 *Hydrologic Response and Watershed Sensitivity Study* (led by UC Davis; Null et al. 2010) investigating the atmospheric and watershed conditions that contribute to the extreme flows on several Central Valley watersheds. The results of these studies are based on downscaled outputs from a subset of the Coupled Model Intercomparison Project – Phase 5 (CMIP5) global climatic models, which DWR has determined are most suitable for modeling climate change on the west coast of California. These analyses rely upon existing, available downscaled climate projections and hydrologic models to represent a range of potential future changes to unregulated flow volumes due to climate change**.** These studies show that annual runoff and event runoff will occur earlier in the season as a result of increasing temperatures and declining snowpack. In general, there is more confidence in temperature change projections than changes in precipitation (USACE 2015, Detinger 2011, Null et al. 2010). In 2017, DWR published quantitative projections of future runoff from watersheds in the Sierra Nevada watersheds which drain into Central Valley of California as part of it's Central Valley Flood Protection Plan (CVFPP). As in prior DWR analyses, this study utilized downscaled projections from a subset of the CMIP5 GCMs which DWR determined were representative of the high natural variability that occurs on the west coast of the United States. An existing condition Variable Infiltration Capacity (VIC) model was calibrated to unregulated flow frequency curves developed in these watersheds. A summary of the some of the important findings were 1) in the Sacramento River watershed, there is more clarity that climate change will result in wetter annual conditions, whereas there are more neutral projections for the San Joaquin River watershed. 2) extreme precipitation which drives rare floods in the Central Valley is likely to intensify, even with projections of overall drier conditions 3) Watershed characteristics strongly influence the hydrologic response to climate change. Since the San Joaquin River watershed has such high mountain ranges, this region will experience the largest increase in runoff due to an increase in precipitation falling as rain in the upper elevations (instead of falling as snow) and more rapid melt of the snowpack.

Observed Temperature Trends. Recent surface observations of temperature in the southwest United States including Northern California indicate a significant warming trend starting about 1970 (NOAA 2013). This recent warming trend is especially noticeable in the minimum temperatures during the interval from 1990 to about 2005. This warming is in addition to more general warming trends from about 1890 to the present. The reasons cited among scientists include natural multi-decadal oscillations, increased greenhouse gases in the atmosphere, land use changes, and urban heat island effects (NOAA 2013, Levi 2008, Barnett et al. 2008, Das et al. 2011).

Projected Temperature Trends. Simulations with global circulation models (GCM) are mostly consistent in predicting that future climate change will cause an increase in air temperatures in California, including during the critical months when the most precipitation falls. It has been projected that air temperatures will increase by over three degrees Fahrenheit by the middle of the current century. November through

March is the period when the most significant and damaging storms hit this region. Climate models suggest the projected temperature signal is strong and temporally-consistent. All projections are consistent in the direction of the temperature change, but vary in terms of magnitude and range (Das et al. 2013, NOAA 2013, CH2MHILL, 2014).

Observed Precipitation Trends. The largest storms that typically impact the west coast of the United States are termed "pineapple express" or more recently "atmospheric rivers" by meteorologists. This type of event occurs when a long plume of saturated air moves northeastward from the low-latitudes of the Pacific Ocean and mixes with cold dense air moving southward from the arctic. The mixing of cold and warm air causes a storm front. As these very moist storms move eastward over the Coastal Mountain ranges, the air is pushed to high elevations where more cooling occurs, thus increasing condensation and precipitation. Historically, the largest and most damaging floods in Northern California are caused by atmospheric rivers (Detinger et al 2013, Detinger et al 2011). However no consistent trend in overall precipitation or streamflow has been identified (USACE 2015, USGCRP, 2014, NOAA 2013)

Projected Precipitation Trends. Annual precipitation projections are not as directionally consistent as temperature trends and multi-decadal variability complicates period analysis. With less certainty than the trends observed in projected temperature, some global circulation models indicate that future conditions may increase the amount of moisture in the storms, since warmer air holds more moisture than cold air. When air cools, condensation occurs which causes precipitation. Given the discussion in this paragraph, it is possible that due to increasing temperatures, atmospheric rivers will have higher precipitation depths in the future because the warmer air can hold more moisture than cooler air, and this will lead to an increase in the size of runoff peaks and volumes (Das et al 2013, Detinger et al 2011 a and b, NOAA 2013).

Observed Trends in Hydrology (Streamflow Response).
USGCRP (2014) indicates a decreasing trend in streamflows in California between 2001 and 2010 however statistical significance of this trend is not provided. USACE (2015) reports that the majority of studies indicate no statistically significant trends have been identified in the streamflow data for the latter half of the 20^{th} century although advances in timing of spring runoff have been observed in many locations in the state.

Projected Trends in Hydrology (Streamflow Response).
USACE (2015) reports that little consensus exists in the literature with regard to projected trends in streamflow and runoff in California. This is due to the high variability and uncertainties of future precipitation trends combined with HUC scale hydrology models that carry their own uncertainties. Projections of future streamflow and runoff are generally consistent with projections of future precipitation in that the northern areas of California may experience increases in precipitation and runoff while the southern areas may see decreases of precipitation and runoff.

USACE (2015) and USGCRP (2014) indicate that a strong consensus in the scientific literature, that air temperature and extreme precipitation events will increase in California over the next century; however little consensus exist supporting overall changes and hydrology in the region. Overall, the literature review indicates that both historic observations and downscaled climate model projections indicate that the climate along the Central California Coast could be warmer than the present one. There is little, if any significant trend in annual precipitation, however the effects of large storms will be amplified by warmer moist air and increased urbanization encroaching on the floodplain. Droughts also would likely be more frequent and prolonged than at present (USGCRP 2014, USACE 2015)

Phase I: Trends in Current Climate Observations:

USACE Climate Hydrology and Nonstationarity tools

For the USACE Climate Hydrology and Nonstationarity Tools two analyses points were selected: USGS gage 11159200 Corralitos Creek at Freedom, CA (Drainage Area (DA): 27.8 sqare miles) and USGS gage 11159000 Pajaro River at Chittenden, CA (DA: 1,186 square miles). These two streamflow gage sites were selected because they have relatively long periods of record (extending from 1940 to the present and 1956 to the present, respectively),are in close proximity to the project location and are where the frequency analyses were performed for this study. The flow at these locations is unregulated and the watershed above both of the gages is primarily rural with no significant changes in land use from 1940 to the present. Annual maximum flows are examined in this study because the project involves modification of and use of levees in flood risk management. Figures 2 and 3 show the period of record of annual maximum flows at both gages, as well as a linear trend assessment for these two sites.

There are six reservoirs that are considered major, reservoirs in the Pajaro River basin. Table 1 lists them along with their storage capacity and the year they were constructed. Refer to Plate 1 of the Hydrology Appendix for their location. Except for College Lake, the reservoirs were mainly constructed for the purpose of water supply and are not expected to have a significant impact on flood flows in the lower portion of the basin during major flood events.

Table 1: Major Reservoirs in the Pajaro River Basin

Name	Capacity (ac.ft.)	Year Constructed
Hernandez	18,000	1962
Uvas	10,350	1958
Chesbro	7,630	1955
North Fork	6,150	1939
Paicines	4,500	1912
College Lake	500	natural

College Lake, which is a natural reservoir, intercepts runoff from 19.6 square miles of the Salsipuedes Creek watershed and has a major influence on discharges downstream of its confluence with Corralitos Creek. Because the bottom of the lake is approximately five feet below the channel elevation at the junction of the two creeks, reverse flow from Corralitos Creek can occur. Considerable attenuation of peak flows on Salsipuedes Creek is common during storm events because of the natural lake however, this lake does not impact peak flows on either Corralitas Creek at Freedom CA or the main stem of the Pajaro River at Chittenden.

The USACE Climate Hydrology Assessment Tool is used to examine trends in recorded annual instantaneous peak streamflow data at a USGS gages of interest. This web based tool can be accessed at: http://corpsmapu.usace.army.mil/cm_apex/f?p=313.

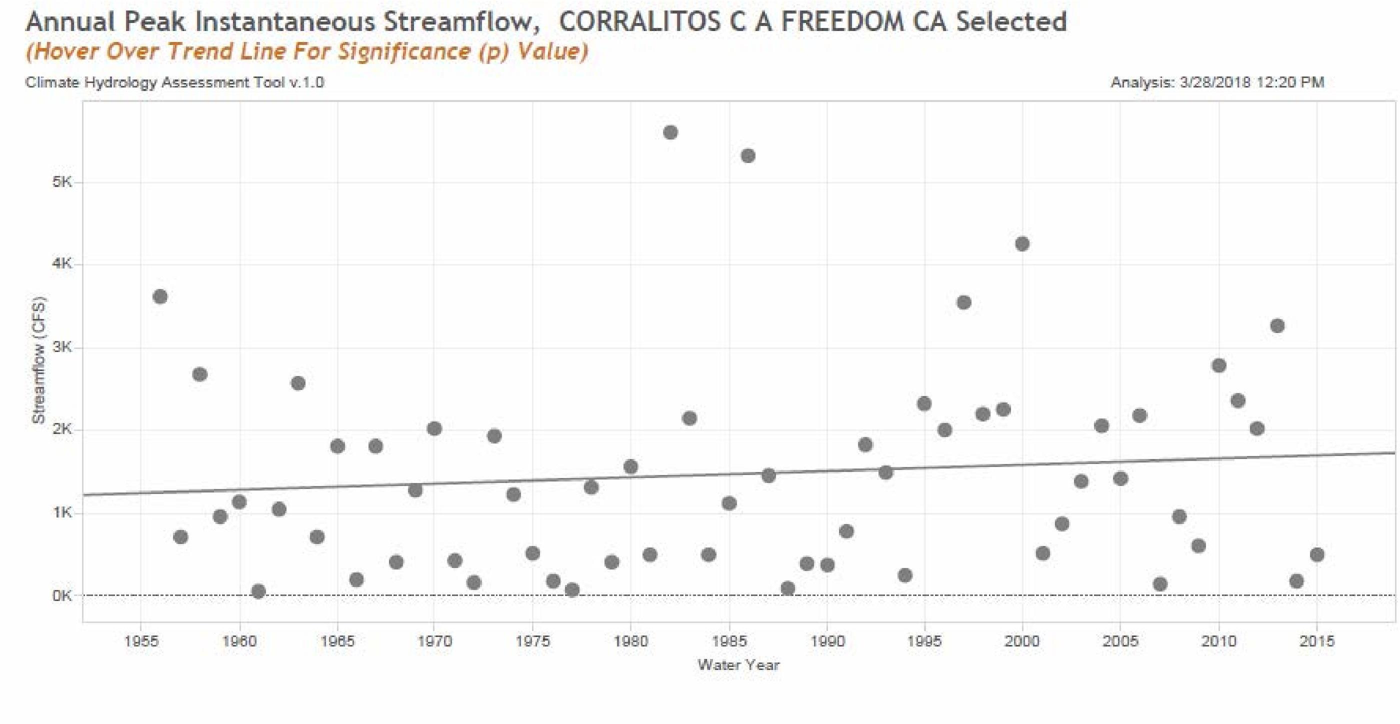

Figure 2 Annual Maximum Flows at Corralitos Creek at Freedom CA.

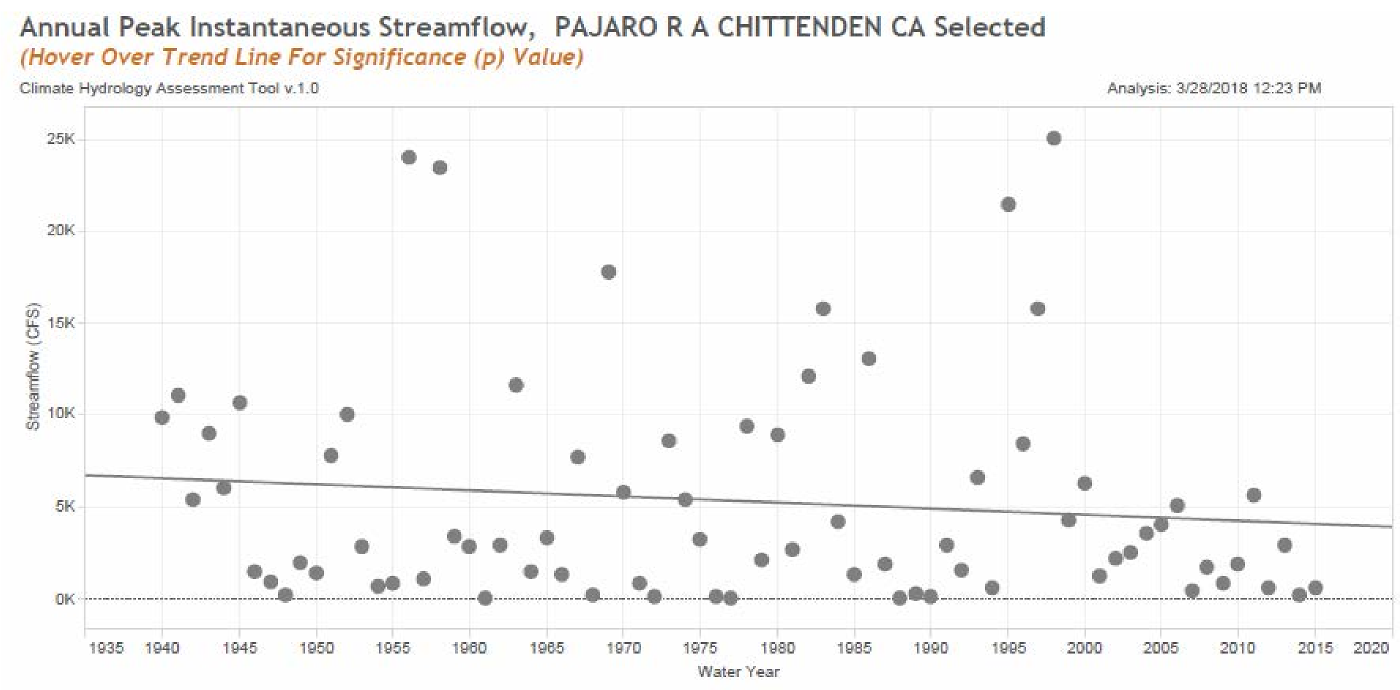

Figure 3 Annual Maximum Flows at Pajaro River at Chittenden CA.

Neither Corralitos Creek, nor the Pajaro River show a significant trend in peak flows over time. The significance of the trends is determined by the p-values computed for the stations: 0.300 for the Pajaro River at Chittenden and 0.420 for Corralitos Creek at Freedom. Smaller p-value values indicate greater statistical significance of trends. In practice, a p-value of 0.05 is often used as a threshold for significance. A p-value of 0.05 indicates that there is a 5% chance of type I errors or false positives (USACE, 2016 b).

The analysis of trends in observed data continues with an assessment of non-stationarities in annual peak streamflow data carried out in accordance to ETL 1100-2-3 (*Guidance for Detection of Nonstationarities in Annual Maximum Discharges,* USACE 2017) using the USACE Nonstationarity Detection Tool (USACE 2016 c)(http://corpsmapu.usace.army.mil/cm_apex/f?p=257:10:0::NO). This web based tool uses a series of statistical tests to detect changes in the trends (mean, variation and distribution) of the recorded, USGS annual instantaneous peak flow data at each gage. The tests include the Lombard model which identifies breaks in the mean and / or variance; the energy based divisive (ecp) method, a nonparametric test that detects multiple change points in the distribution; and other statistical tests. The levels of significance for each test can be controlled by the user- default setting were applied for this analysis. The same analyses points were selected, as were used for the Climate Hydrology Assessment Tool: USGS gage 11159200 Corralitos Creek at Freedom, CA (Period of Record 1956-2014) and USGS 11159000 Pajaro River at Chittenden, CA (Period of Record 1940-2014). Strong Nonstationarities were not detected at either location (see figures 4 and 5). Additionally monotonic trend analyses were performed on each of the datasets to check for increasing or decreasing trends in the flow data: no trends were detected using the Mann-Kendall or Spearman tests applied by the tool.

At the Corralitos USGS gage two statistically significant nonstationarities are identified in 1986 and 1994. Both represent a detected trend in the overall statistical distribution. However these nonstationarities are not carried forward in the analysis because in order for a nonstationarity (change point) to be considered strong or robust, a minimum of three methods targeting changes in mean, distributional characteristics or variance are required to detect a nonstationarity during a five year period (at minimum two tests indicating a change in the same statistical property and an additional test indicating a change in a different statistical property). Magnitude of the change is also an indicator of a strong nonstationarity if the difference between the component means and variances before and after the change point is significant (USACE 2017). No nonstationarities were detected at the Pajaro River at Chittenden gage.

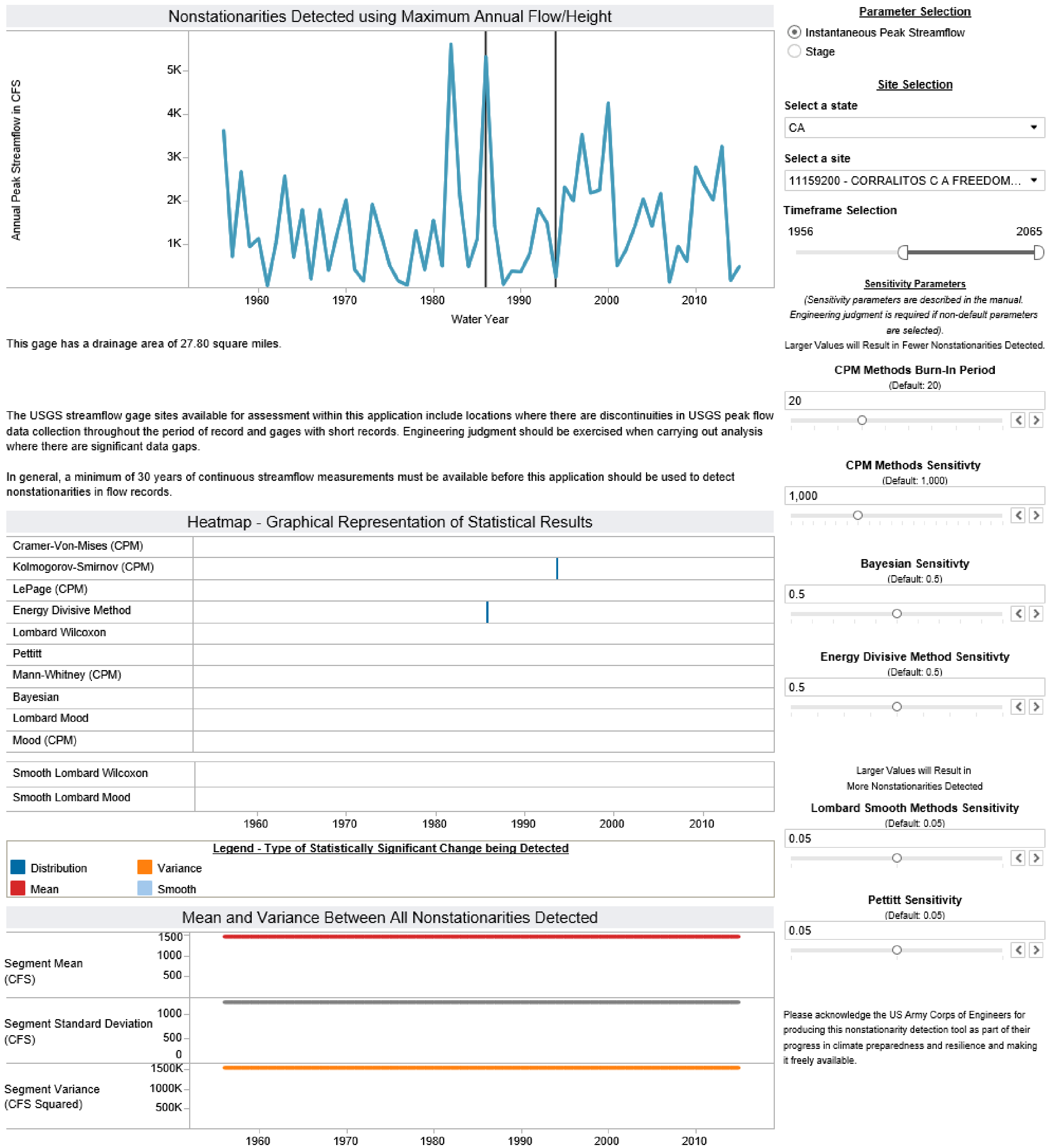

Figure 4 Corralitos Cr at Freedom, CA (USGS 11159200) Nonstationarity Detection. Note nonstationarities are detected in the overall statistical distribution of the data however the nonstationarities are not large in magnitude and are only detected by one test.

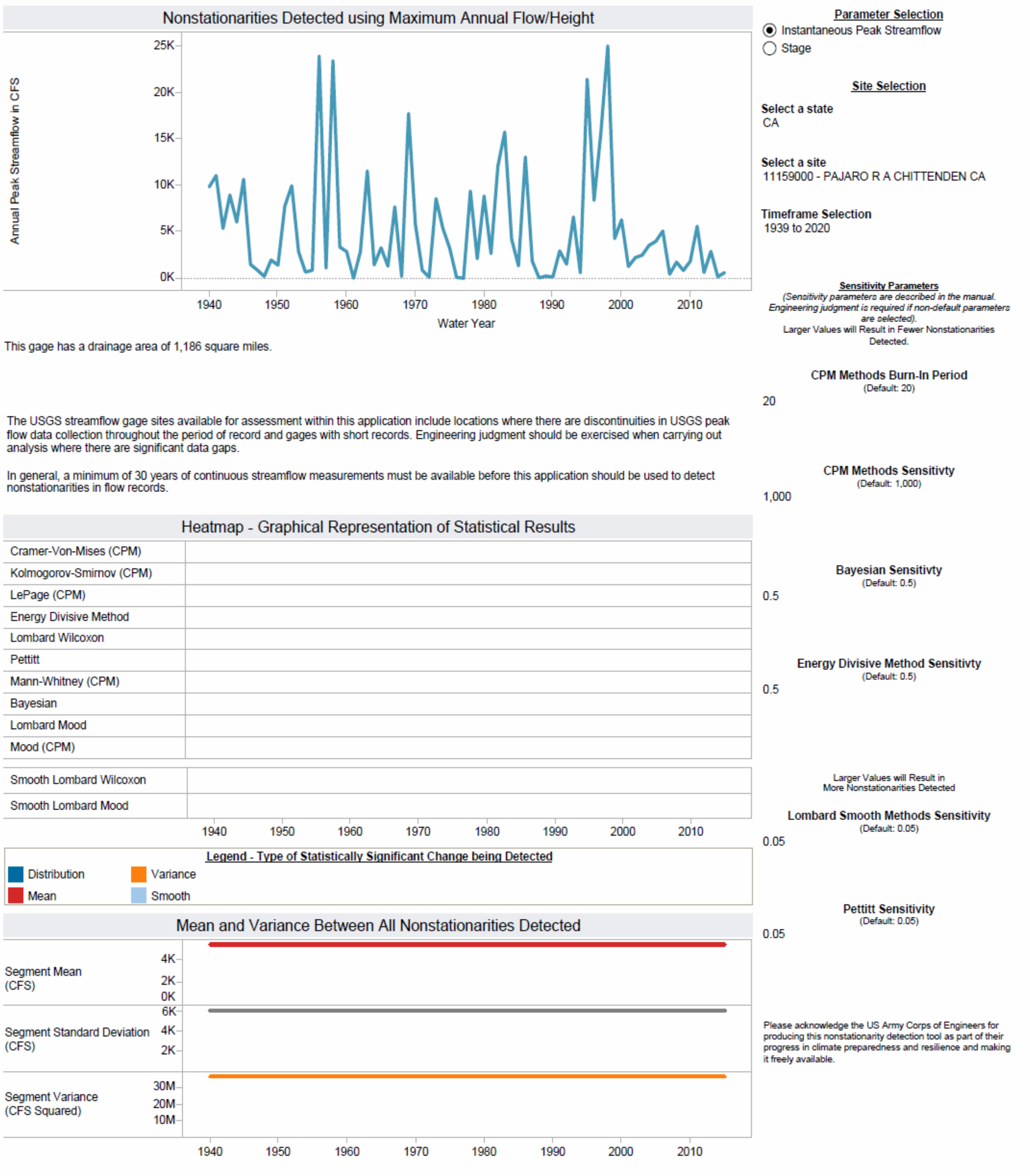

Figure 5 Pajaro River at Chittenden, CA (USGS 11159000) Nonstationarity Detection Results. No nonstationarities were detected.

Phase II Future Climate Scenarios:

Projected changes in future climate contain significant uncertainties. Uncertainties exist with respect to understanding and modeling of the earth systems, uncertainties with respect to future development and greenhouse gas emission pathways, and uncertainties with respect to simulating changes at the local scale.

The Climate Hydrology Assessment Tool is used to look at trends in projected, annual maximum monthly streamflow over the HUC-4 watershed area. Figure 6 shows annual maximum monthly flow trends computed using 93 different combinations of Global Circulation Model outputs run for different concentration pathways of greenhouse gas emissions (RCPs) and translated into a hydrologic response using the U.S Bureau of Reclamation's Unregulated, Variable Infiltration Capacity Hydrology model. Data is analyzed at a HUC-4 watershed scale for the Central California Coast region (HUC-1806). The mean projected annual maximum monthly trendline (blue line) does not show much change in discharge over time, but the range (deviation) of projections indicates increasing variability in global circulation model outputs as time progresses. This increase in the range of outputs being produced by the global circulation models (yellow area) is indicative of the uncertainty associated with projected, climate changed hydrology. Note that this uncertainty appears to increase with time.

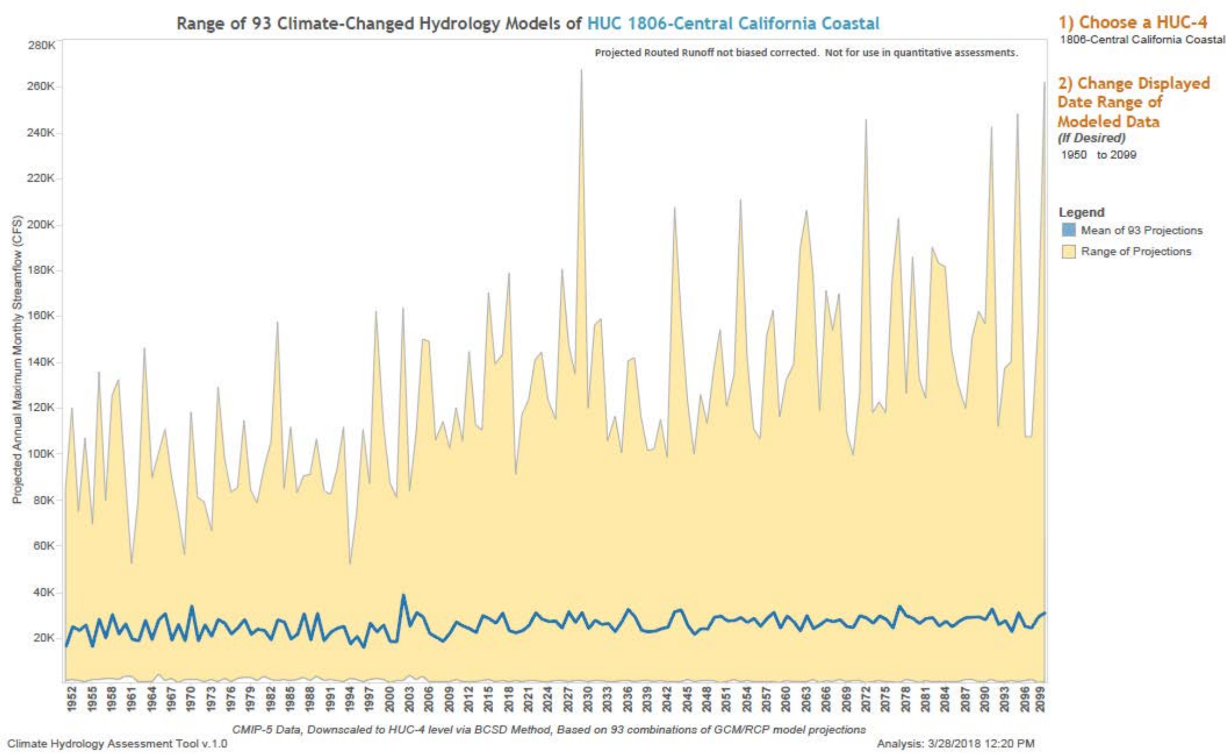

Figure 6 Mean and range of 93 Climate changed Hydrology projections for the Central California Coast Region.

Figure 7 shows a trend assessment of the mean annual maximum monthly runoff over the Central California Coast Region for the present conditions (1950-2014) based on Global Circulation Model outputs translated into a hydrologic response using the VIC model.The significance values (p-values) of the trendlines displayed are 0.379 for the 1950-2014 period and 0.114 for the future conditions. Significance levels (p-value) of 0.05 or less indicate statistically significant trends in the data, so because the p-values associated with the data are significantly higher than 0.05 it can be assumed that there is no statistically significant trend in the data for either the period of record from 1950-2014 or 2017 to 2100.

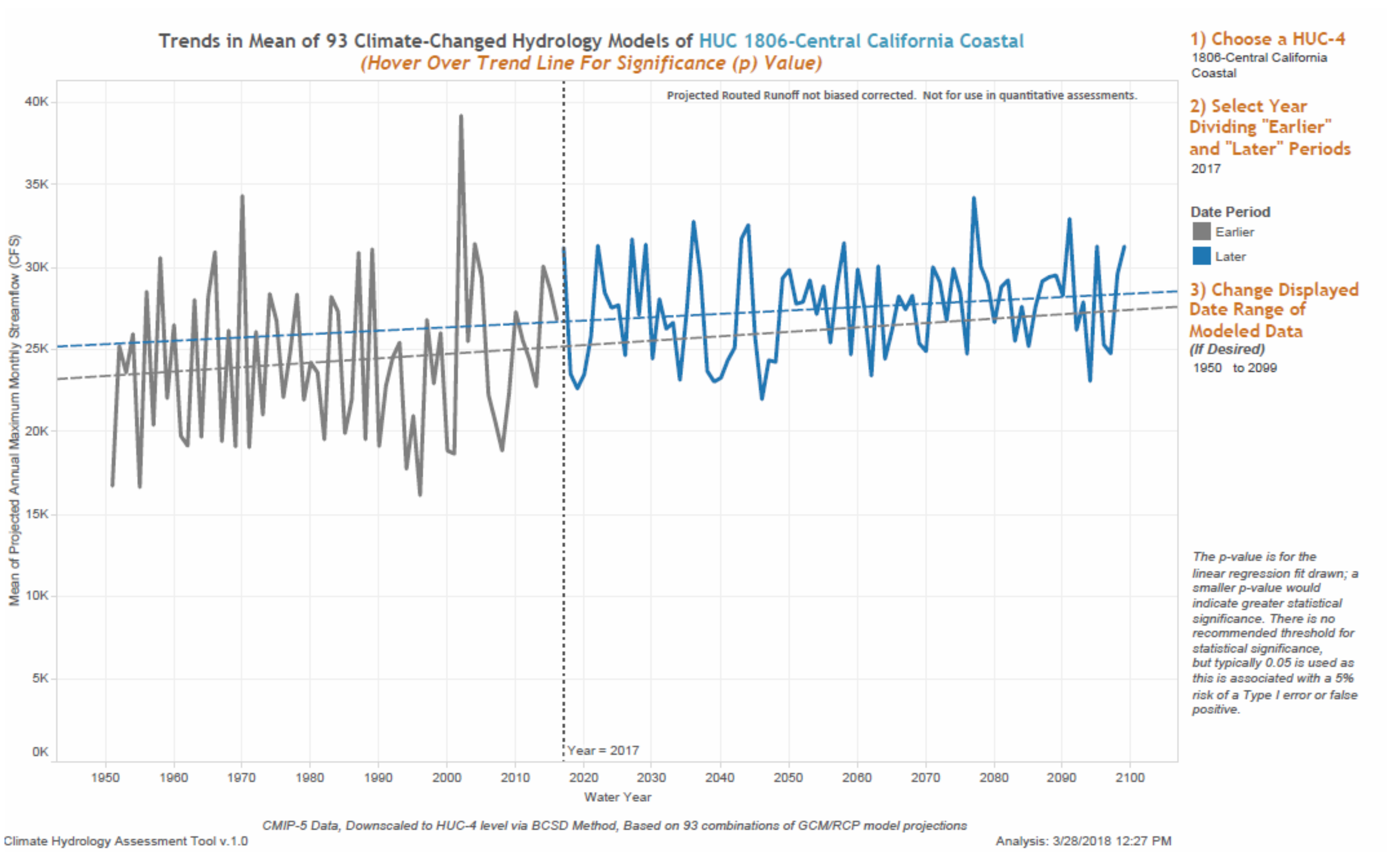

Figure 7. Trends in mean of 93 projections of Climate Changed Hydrology for the Central California Coast Region.

The above results are qualitative because this tool uses climate data projected by global circulation models (GCM) and translated into a hydrologic response using a Variable Infiltration Capacity (VIC) model developed for the entire United States. For the majority of the HUC04 watersheds in the United States, the VIC model is not specifically calibrated to historical values and thus it does not replicate exact historic streamflow within a high degree of accuracy and this adds to the uncertainty associated with the projected, climate changed hydrology.

USACE Vulnerability Assessment tool:

The USACE (2016 d) Watershed Vulnerability Assessment Tool, (https://maps.crrel.usace.army.mil/apex/f?p=170) is used to examine the vulnerability of the project area to future flood risk. This tool provides a screening level assessment of the vulnerability of a given HUC-4 watershed to climate change impacts for a specific USACE business line relative to the other 201

HUC-4 watersheds in the Continental United States (CONUS). Like the Climate Hydrology Assessment Tool, this tool uses climate data projected by Global Circulation Models (GCM) translated into runoff using the Bureau of Reclamation's nationwide VIC hydrology model. This vulnerability assessment uses 27 different indicator variables and eight USACE business lines to develop vulnerability scores specific to each of the 202 HUC-4 watersheds in the United States for each of the business lines. The business lines are the prisms for the evaluation of vulnerability in a given watershed.

The main business line that is applicable to this project is flood risk reduction. The project is located in the Central California Coast HUC-4 watershed (HUC 1806) and based on the results of the vulnerability tool for flood risk reduction, this watershed is considered to be vulnerable to the effects of climate change relative to the other 201 HUC-4 watersheds in the CONUS. The vulnerability assessment is run for two time epochs centered on the years 2050 and 2085 and two subsets of GCM model based projected, climate changed hydrology: 1) a Dry subset of traces which is based on the driest 50% of downscaled CMIP 5 projections and a Wet subset of traces which is based on the Wettest 50% of model projections. Results from the Wet and Dry subsets of traces, as well as the two epochs of time are displayed in order to reveal some of the uncertainties associated with how projected, climate changed variables are computed. The scenarios are derived by comparing 100 different combinations of CMIP 5 GCM projections of temperature and precipitation generated using various greenhouse gas emission scenarios translated into a hydrologic response (when necessary for a given indicator variable) using the U.S Bureau of Reclamation's VIC model. The Wet scenario includes the projections that are above the median value for the given epoch and the Dry scenario includes only those projections that are less than the median for that epoch (USACE 2016 d).

For flood risk reduction, the indicator variables used to compute vulnerability scores at a HUC-4 scale are:

- Indicator #590: Urban area in the 0.2% annual exceedence probability (500 year) floodplain
- Indicator#568C&L: Cumulative and local flood magnification. This is the ratio of monthly runoff exceeded 10% of the time during the given epoch to the monthly runoff exceeded 10% of the time during the base period (1950 – 2000).
- Indicator #175C: Annual covariance of runoff (ratio of standard deviation to the mean including upstream local flows)
- Indicator 277: Runoff from precipitation (median of the standard deviation of runoff times the mean monthly runoff divided by the standard deviation of precipitation times the monthly mean of precipitation.)

Vulnerability scores are computed based on indicator variable values using a weighted ordered weighted average (WOWA) approach. WOWA scores for the primary business line (flood risk reduction) range from 0-100 and are a relative measure of the vulnerability of the given business line in the local watershed relative to scores produced at a HUC-04 scale for the same business line in the entire CONUS. The HUC04 watersheds with the top 20% of vulnerability scores relative to those computed for all the HUC04 watersheds in the CONUS are flagged as being vulnerable to climate change impacts across a given business line.

In Table 2, the flood risk management business line indicator variables and respective component WOWA contributions are displayed. The total WOWA score for flood risk management is also included in Table 2 for both epochs and the Wet and Dry subsets of traces. The total flood risk management WOWA vulnerability scores for the Central California Coast range from 58 for the base period and the Dry subsets for both epochs to 69 during the 2050 epoch Wet scenario and 72 during the 2085 epoch Wet scenario. For the Dry subset of traces, indicator 590, urban area in the 0.2% ACE floodplain is the dominant indicator variable; it accounts for nearly half of that score at 47% as shown in table 2 and figure 8. For the Wet subset of traces, indicator 568C, cumulative flood magnification, is the dominant indicator variable-accounting for 47% of the total WOWA score. Local flood magnification, indicator 568L, takes on a larger percentage of the score during the Wet 2085 scenario thus driving down the influence of the urban floodplain area indicator (590) in the total score. To determine vulnerability these scores are compared relatively to the scores generated for the other 201 HUC-4 watersheds in the nation.

These vulnerability assessment indicates that the region is relatively vulnerable to the effects of climate variability and change relative to the other watersheds in CONUS for flood risk reduction and that this vulnerability may increase slightly with time for both the WWet and DDry subsets of traces. A graphical representation of these results is shown in Figure 8.

Table 2
WOWA Scores and Contributions for HUC-4 Watershed 1806 Central California Coast

Business Line	**Flood Risk Reduction**									
Epoch and Scenario	**Base Period**		**Dry 2050**		**Wet 2050**		**Dry 2085**		**Wet 2085**	
Indicator	Raw WOWA	% WOWA	Raw WOWA	% WOWA	Raw WOWA	% WOWA	Raw WOWA	% WOWA	Raw WOWA	% WOWA
175C_ANNUAL_COV	15.548	26.9%	15.806	27.3%	6.683	9.7%	16.252	27.9%	6.869	9.6%
277_RUNOFF_PRECIP	4.593	7.9%	4.846	8.4%	2.983	4.3%	4.820	8.3%	3.070	4.3%
568C_FLOOD_MAGNIFICATION	8.457	14.6%	7.878	13.6%	31.998	46.6%	7.646	13.1%	33.834	47.1%
568L_FLOOD_MAGNIFICATION	2.776	4.8%	2.586	4.5%	10.504	15.3%	2.510	4.3%	17.096	23.8%
590_URBAN_500YRFLOODPLAIN_AREA	26.446	45.7%	26.826	46.3%	16.552	24.1%	26.921	46.3%	11.008	15.3%
Total WOWA Score	57.821	100.0%	57.942	100.0%	68.720	100.0%	58.149	100.0%	71.877	100.0%

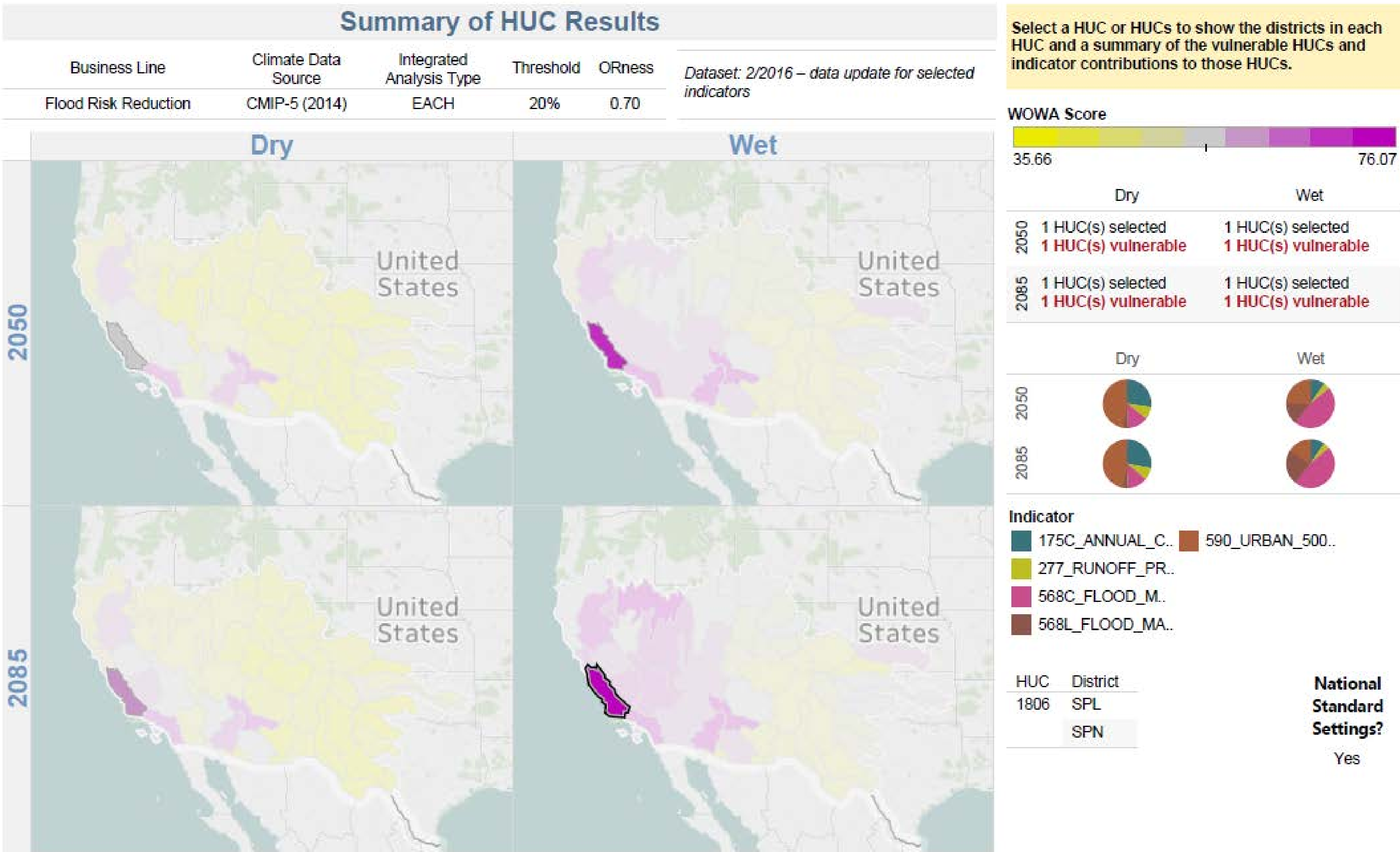

Figure 8 Summary of Vulnerability Assessment tool results for HUC 1806 Central California Coastal Region. This area is relatively vulnerable to increased flood risks due to increases in urban area in the 500 year floodplain and changes in the magnitude of floods as shown in the pie charts on the right of the figure. This area is also subject to higher variability of runoff. The WOWA scores range from approximately 58 to 70.

Conclusions: The literature synthesis summarizing trends in observed and projected meteorology and climate changed hydrology indicate that future conditions will be warmer and possibly wetter then present conditions. This lends itself to a possible increased likelihood of large runoff events due to increases in the moisture content of storms. However, the impact that this will have on flooding in the Pajaro River Basin is uncertain. At this point, the USACE Nonstationarity Detection Tool is not identifying any significant nonstationarities in either of the datasets analyzed as part of this study, and the Climate Hydrology Assessment Tool is not detecting any trends in the recorded peak flow data at either gage location assessed. Additionally, no increasing trends are identified in the projected, climate changed annual maximum monthly streamflow values projected for the HUC 1806 Central California Coastal Region as part of this analysis. The vulnerability assessment conducted as part of this study indicates that the main indicators of vulnerability in terms of flood damage reduction are flood magnification (ratio of the annual runoff exceeded 10% of the time during the given epoch to the same during the base period) and the urban development in the 0.2% exceedance floodplain. The Central California Coastal Region is identified as being relatively vulnerable to increased flood risk due to climate change across all subsets of traces and epochs of time analyzed.

The results of the climate assessment provides further justification that the additional flood protection being proposed as part of this study within the Pajaro River Basin is warranted. The project delivery team and the local study sponsor should consider and evaluate whether there are any other actions that can be taken in the context of the current study or as part of future studies/decision making processes to make the community more resilient to higher, future flows. Such actions might include flood proofing or acquiring structures currently located in or bordering the existing floodplain, developing evacuation plans, land use planning, changes to levees and levee alignment and adjusting elevation or spacing of mechanical features, among other actions. Climate change risks should be detailed in the project risk register.

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