Carmel River Floodplain Restoration and Environmental Enhancement Project

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Technical Studies that are Bound Separately

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Climate Change Impacts Memo

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BALANCE HYDROLOGICS, Inc.

MEMO

To: Sarah Hargrave, Big Sur Land Trust
From: Kealie Pretzlav, PhD, Shawn Chartrand, PhD
Date: October 1, 2018

Subject: Climate Change Impacts to Flood Recurrence Intervals and Sea-Level Rise in the Carmel River Watershed

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INTRODUCTION

This memo serves as a preliminary climate analysis as part of the Benefit Cost Analysis (BCA) portion of the Hazard Mitigation Grant Sub-Application for the Carmel River Floodplain Restoration and Environmental Enhancement (CRFREE) Project in Monterey County, California. This climate analysis will cover results for the following topics:

1. Overall trends in projected precipitation in the Carmel River watershed;
2. Projected shifts in recurrence interval of the 20- and 100-year flood events in the lower Carmel River; and
3. Potential impacts of sea-level rise to the proposed project.

This is a preliminary analysis that can be used to understand primary impacts of climate change on the CRFREE Project for the purposes of the BCA, which is specifically designed to quantify the expected shifts in flood frequency for smaller, more frequent flood events (e.g. 20-year). The applicability of this analysis is limited to the applicability of the climate change projections to the Carmel River watershed. Additional analysis could further explore climate change impacts as needed.

Projected Climate Change Data

The most recent projections for climate change were released as part of the 5th Coupled Model Intercomparison Project (CMIP5). The CMIP experiments were developed in order to produce climate change projections that could be reasonably compared across different Global Climate Models (GCM). Comparison across the different GCMs is important because each GCM uniquely represents the details of how Earth's climate works. As a result, different physical processes of climate are simulated in different ways, and it is instructive to understand how these differing technical approaches affects the actual climate projections of, for example, air temperature and precipitation.

The CMIP5 data sets[1] were published by late 2012 or early 2013, and later reported within the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). Various groups of climatologists have developed downscaling processes for projecting climate change data to a finer grid. For this analysis, we have selected precipitation projections derived from SimCLIM[2], a climate change software application that produces spatial data and builds databases of climate projections for a variety of parameters. SimCLIM has 55 of the most recent general circulation models (GCMs) with the current generation (CMIP5) of global coupled ocean-atmosphere modules at a 0.5° x 0.5° model resolution. We have selected a proprietary climate software dataset to take advantage of the relatively small grid cell resolution (1km x 1km), which is important for capturing the large variability of annual precipitation in the Carmel River watershed. A similar open-source dataset is available from the State of California (http://caladapt.org/, “Cal-Adapt”).

GCMs are run using four different representative concentration pathways (RCP): 2.6, 4.5, 6.0, and 8.5. Each RCP represents a future greenhouse gas concentration trajectory. It is generally accepted that RCP 2.6 is likely not achievable. RCP 8.5 is used here as the most likely future scenario for climate change analyses given present-day trends of annual global emissions. Last, we follow the guidance offered by the State of California (Cal-Adapt) for climate change planning studies, and use SimCLIM data for the following downscaled model projections:

1. MIROC5.1 – Model for Interdisciplinary Research on Climate Version Five
2. HadGEM2-ES.1 – Hadley Global Environment Model 2 – Earth System;
3. CanESM2.1 – Canadian Earth System Model 2.1;
4. CNRM-CM5.1 - Centre National de Recherches Météorologiques – Cerfacs Model 5.1.

Projected Precipitation Changes, Carmel River Watershed

The CRFREE Project is located at the downstream end of the Carmel River watershed, approximately one mile from its mouth at Carmel Bay. The Carmel River is a relatively large watershed for central coastal California, with a total watershed area of approximately 247 square miles at the United States Geological Survey (USGS gage no. 11143250) streamgage, located at the Via Mallorca Road crossing, approximately 1.4 miles upstream of the east end of the proposed floodplain restoration. Although historically regulated by two dams in its headwaters[3], the river is still subject to very large seasonal and annual variations in total and peak discharge. The USGS gaging station often records no flow during the summer months, whereas exceptionally wet winter periods can see very significant peak discharge values. The peak flow of record at this gage was approximately 16,000 cubic feet per second (cfs) on March 10, 1995, estimated as just larger than a 30-year event. This peak flow is equivalent to 65 cfs per square mile and reflects the high rainfall totals in the mountainous upper reaches of the watershed. The Federal Emergency Management Agency (FEMA) Federal Insurance Study (FIS) estimates the 100-year flood

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[1] Reclamation, 2013. Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs. U.S. Department of the Interior, Bureau of Reclamation, 104 p., available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_ climate.pdf.

[2] CLIMSystems, 2017, SimCLIM Data Manual 4.4, p. 20.

[3] San Clemente Dam was removed in 2015.

event to be 22,700 cfs. Interpolation of the flood recurrence intervals reported in the FIS using a logarithmic function results in an estimated 20-year event flow to be 13,268 cfs.

Figure 1 illustrates the comparison between projected precipitation values averaged between the four priority models (HadGEM2-ES, CNRM-CM5, CanESM2 and MIROC5) and the historical baseline precipitation data[4]. Although there is considerable variability in the projected precipitation values, the average projected precipitation suggests an increase in January precipitation of approximately 2.5 inches. Projections also suggest slightly less precipitation in the spring and fall months. These results are consistent with the academic literature which indicates that winter storms will likely increase in magnitude and frequency in wet months[5].

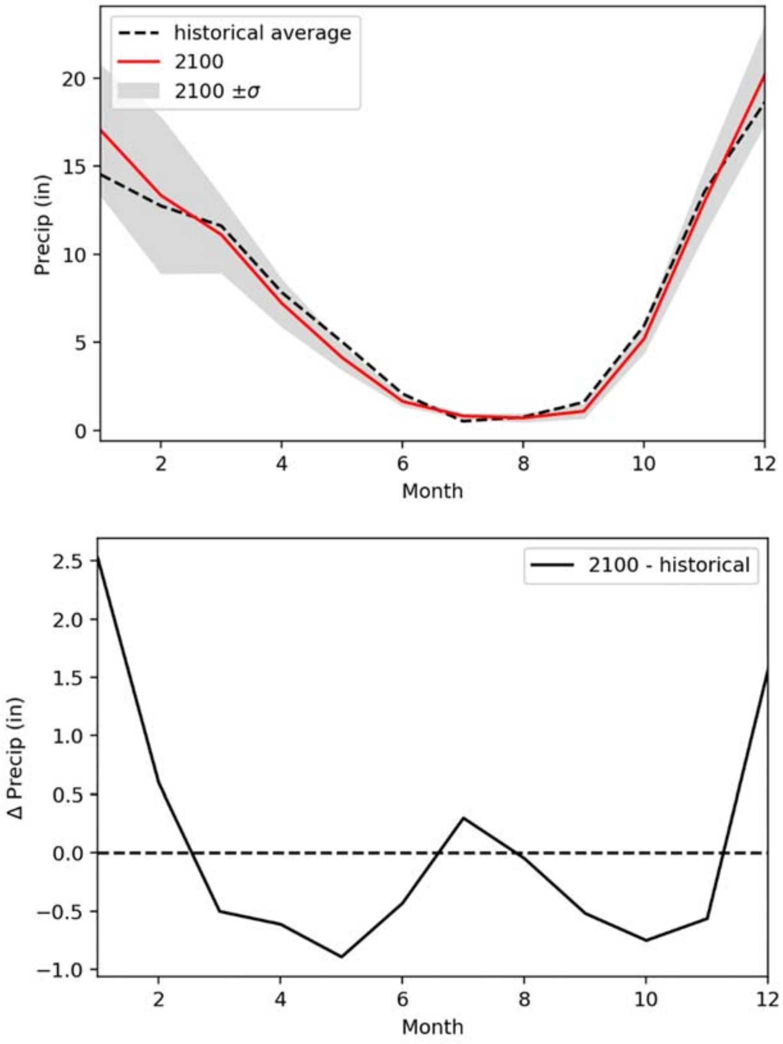

Figure 1. Comparison of historical average monthly precipitation and projected precipitation in 2100.

Shifts in Flood Recurrence Intervals

Expected shifts in the timing and magnitude of winter storm events will likely have an impact on the recurrence intervals of major flood events. The basis for damages used in the BCA uses the 20- and 100-year flood events as benchmarks for moderate and extreme flood events in the lower Carmel River.

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[4] Historical baseline data accompanies each GCM and is calculated as average precipitation from 1986 – 2005, centered around 1995.

[5] e.g. Milly et al., 2002, Pelletier et al., 2015, Hagos et al., 2016

Historical watershed-averaged total annual precipitation was calculated using PRISM data[6], which is a spatially interpolated dataset based on publicly available climate station data. Grid cells are 4 km x 4km and the Carmel River watershed is comprised of 46 of the PRISM grid cells. Comparison between watershed-averaged total annual precipitation and historical peak flows from the USGS Via Mallorca gage reveal a power law function (R^2=0.71, p=3.94×10^{-15}) such that:

$$\boldsymbol{p = 0.014 {Q_{max}}^{3.53}}$$

where p is total annual precipitation in inches and $\boldsymbol{Q_{max}}$ is instantaneous annual peak flow in cubic feet per second (***Figure 2***). It is notable that the two largest precipitation events are not described by the power law function, but our objective here is to provide a preliminary understanding of general trends in potential climate change impacts.

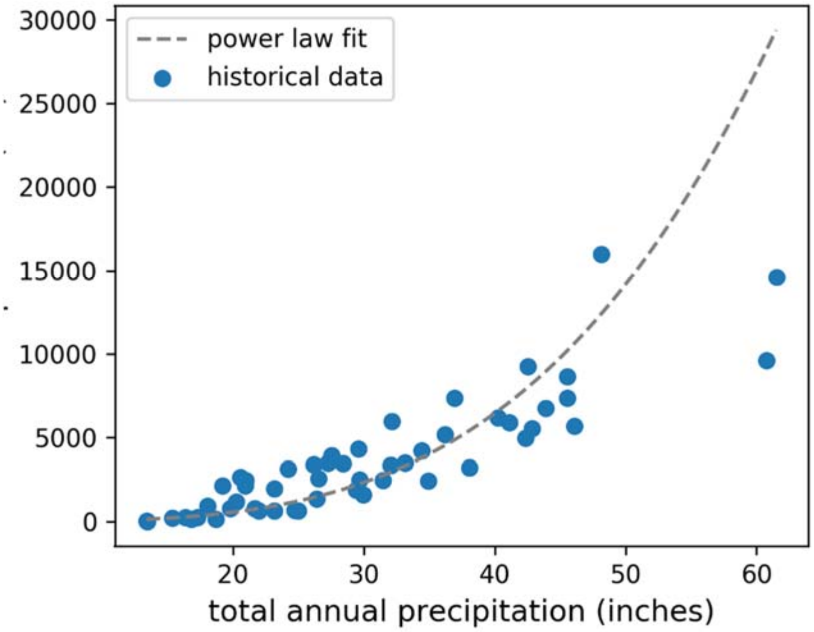

Figure 2. Statistically significant relationship between watershed averaged total annual precipitation and annual peak flow.

Projected total annual precipitation is calculated for one 10-year period, 2091 – 2100. Even though four priority models have been vetted and recommended by the State of California, there is a relatively large amount of variability for any given month within the projection period of the four chosen models. To deal with this uncertainty, we constructed 500 realizations of projected precipitation by sampling from the ten-year period for each month. We then sum each of the 500 precipitation time series over the projected ten year period to produce associated time series of total annual precipitation. The end result includes 500 randomly constructed annual precipitation records for the period 2091-2100. The power law relationship in *Figure 2* is then applied to projected total annual precipitation to estimate annual peak flow and calculate flood recurrence intervals (*Table 1*). Interestingly,

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[6] PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 26 September 2018.

historical 10- and 20-year flood flows become considerably more frequent, with flows from those events changing to a 5.4 and 13.9 recurrence interval, respectively (

Table 2). However, the larger flood events, such as the historical 100-year event, become rarer occurrences.

Table 1. Comparison of historical and projected peak flows, and projected maximum flows.

% Exceedance *(percent)*	**Recurrence Interval** *(years)*	**Historical Flows** *(cfs, 1963-2008)*	**Projected Flows** *(cfs, 2091-2100)*	**Maximum Projected Flows** *(cfs, 2091-2100)*
0.1	10	9,464	12,066 ± 458	13,168
0.05	20	13,268	14,490 ± 570	15,852
0.02	50	18,470	16,918 ± 719	18,366
0.01	100	22,630	18,366 ± 960	21,497
0.002	500	32,470	22,263 ± 1,820	27,261

Table 2. Projected Recurrence Interval

Historical Flows *(cfs, 1963-2008)*	**Historical Recurrence Interval** *(years)*	**Projected Recurrence Interval** *(year, 2091-2100)*
9,464	10	5.4
13,268	20	13.9
18,470	50	102.9
22,630	100	>500
32,470	500	>500

These results are focused on quantifying projected changes in flood frequency for the more frequent flood events (e.g. 20-year) in the lower Carmel River, with intended application for the BCA analysis. For these more frequent flood events, results are consistent with other studies in the Monterey area[7].

However, the preliminary methodology presented here, when applied to larger flood events (e.g. 100-year) has some major limitations. One clear limitation is that we use a regression to represent the relationship between total annual rainfall and instantaneous peak annual flood at the Via Mallorca station. Use of a regression will not capture the relatively large flood events, which will be dependent on the departure of measured instantaneous peak floods from the regression trend. Figure 1 shows that the two largest floods do not constrain the upper part of the regression equation, so our approach introduces

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[7] AghaKouchak, A., Ragno, E., Love, C., Moftakhari, H., 2018, Projected changes in California's precipitation intensity-duration-frequency curves, prepared for California's Fourth Climate Change Assessment.

uncertainty in this respect. Second, it is possible that the watershed-averaged projections used do not adequately capture the west-east gradient of precipitation in the watershed. Mean annual precipitation can differ by approximately 20 inches between the west and east portions of the watershed, and relatively large historical floods generally have significantly higher precipitation within the east side of the watershed. Our use of spatial precipitation averages may therefore introduce bias in the projection of relatively large instantaneous peak flows, such that the projections are systematically lower for these large events.

The majority of the body of literature suggest that the historical 100-year event will occur more frequently, and larger events will become the new 100-year event. Additional analysis specifically designed to address larger flood events can be conducted in the future to quantify these expected shifts in flood frequency.

Sea-level Rise Impacts

Along with changes in expected precipitation, climate change is also projected to increase sea level on the California Coast. ***Figure 3*** shows expected sea level rise averaged over the four priority GCMs. As a conservative estimate of sea level rise, we recommend using the “High” sensitivity projections of sea level rise. There is also some recent evidence that sea level rise projections may under-estimate the mechanism and speed by which supraglacial water can be delivered to the base of an ice sheet, perhaps via moulins, and as a result may under-estimate the magnitude of sea level rise due to ice cap mass loss. Sea level is expected to increase by approximately 3 feet (1 meter) in the Carmel Bay by the year 2100.

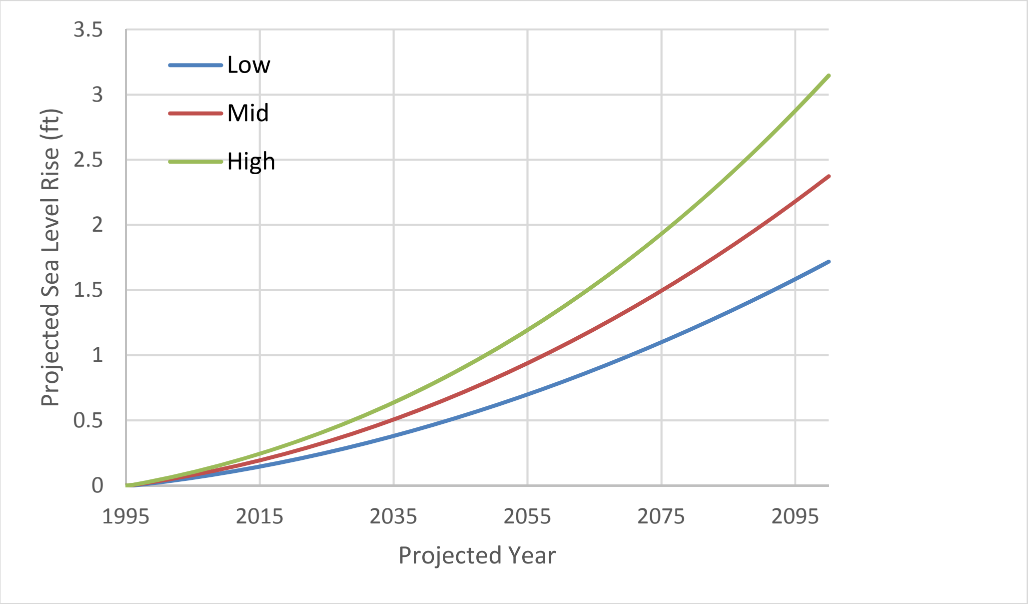

Figure 3. Projected sea level rise in Carmel Bay, low, mid, and high sensitivities.

The Causeway portion of the proposed CRFREE Project is located approximately 3,500 feet upstream from the Carmel River lagoon and beach. In most years, the lagoon typically builds up a natural sand beach barrier which closes the lagoon from ocean inflows and allows the water-surface elevation of the lagoon to remain elevated. Lagoon inflow rates of 200 and 100 cfs will maintain an open lagoon mouth

100 percent and 90 percent of the time, respectively[8]. However, with increased development along the Carmel Lagoon floodplain, the lagoon water-surface elevation is actively managed and manually breached when deemed necessary, typically several times per year[9].

The lagoon and beach also serve as the primary control for the Carmel River tailwater. Tailwater conditions previously modeled for floodplain restoration design use tailwater elevation of 14.6 feet NAVD 88[10]. Mean higher high water in Monterey Bay is 5.48 feet NAVD88[11]. The main controls on the tailwater elevation in large storm events on the Carmel River are therefore most likely a combination of the lagoon and beach elevation, geometry of breach channels through the sand bar deposits, and existing bedrock sill topographic constraints. Projected sea level rise may affect the beach and lagoon elevation as increasing tides have the potential to deposit higher elevation sand deposits. This may have significant impacts on the management of the lagoon water-surface elevation, but because the lagoon is actively managed for flood risk mitigation, will likely not have an impact on the tailwater controls at the Causeway portion of the project site approximately 3,500 feet upstream.

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[8] James, G., 2005, Surface water dynamics at the Carmel River lagoon water years 1991 through 2005, Technical memorandum 05-01, prepared by the Monterey Peninsula Water Management District.

[9] Ballman, E. D., Senter, A. E., 2014, The geomorphic role of riverine processes in Carmel Lagoon water surface elevation and sand bar breaching dynamics for the Carmel River-Lagoon biological assessment report, prepared by Balance Hydrologics for Monterey County Resource Management Agency.

[10] Ballman, E. D., Nazarov, A., Chartrand, S., 2015, Carmel River floodplain restoration and environmental enhancement project – 35 % design basis report, prepared by Balance Hydrologics for Big Sur Land Trust.

[11] NOAA tide buoy data for 9413450, Monterey, California