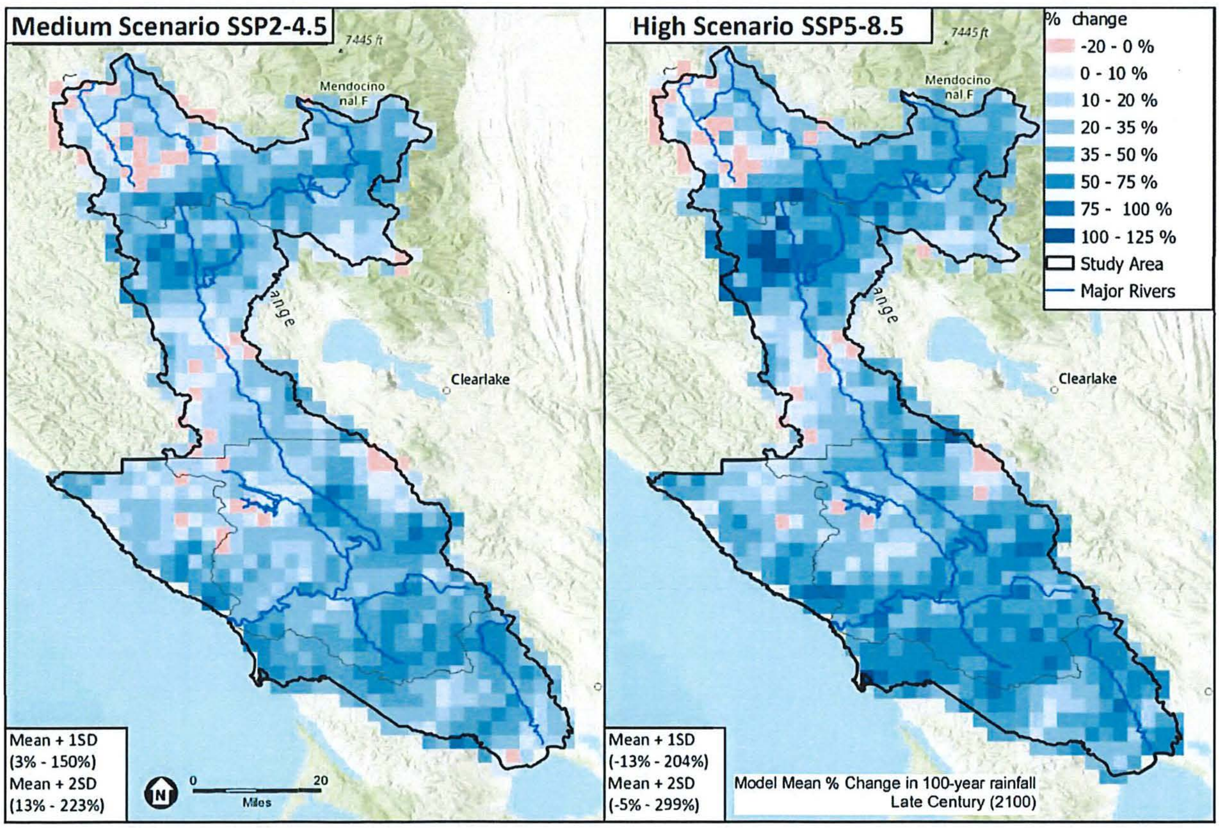
SONOMA WATER FUTURE RAINFALL DATABASE

Technical methods and results report

Prepared for
Sonoma Water

April, 2024

ESA



SONOMA WATER FUTURE RAINFALL DATABASE

Technical methods and results report

Prepared for
Sonoma Water

April, 2024

Services provided pursuant to this Agreement are intended solely for the use and benefit of Sonoma Water.

No other person or entity shall be entitled to rely on the services, opinions, recommendations, plans or specifications provided pursuant to this agreement without the express written consent of ESA, 575 Market Street, San Francisco CA 94105.

180 Grand Avenue
Suite 1050
Oakland, CA 94612
510.839.5066
esassoc.com

ESA

Atlanta
Bend
Irvine
Los Angeles
Mobile
Oakland
Orlando
Palm Beach County
Pasadena
Pensacola
Petaluma
Portland
Rancho Cucamonga
Sacramento
San Diego
San Francisco
San Jose
Sarasota
Seattle
Tampa
Thousand Oaks

TABLE OF CONTENTS

Figures

Tables

1. INTRODUCTION AND BACKGROUND

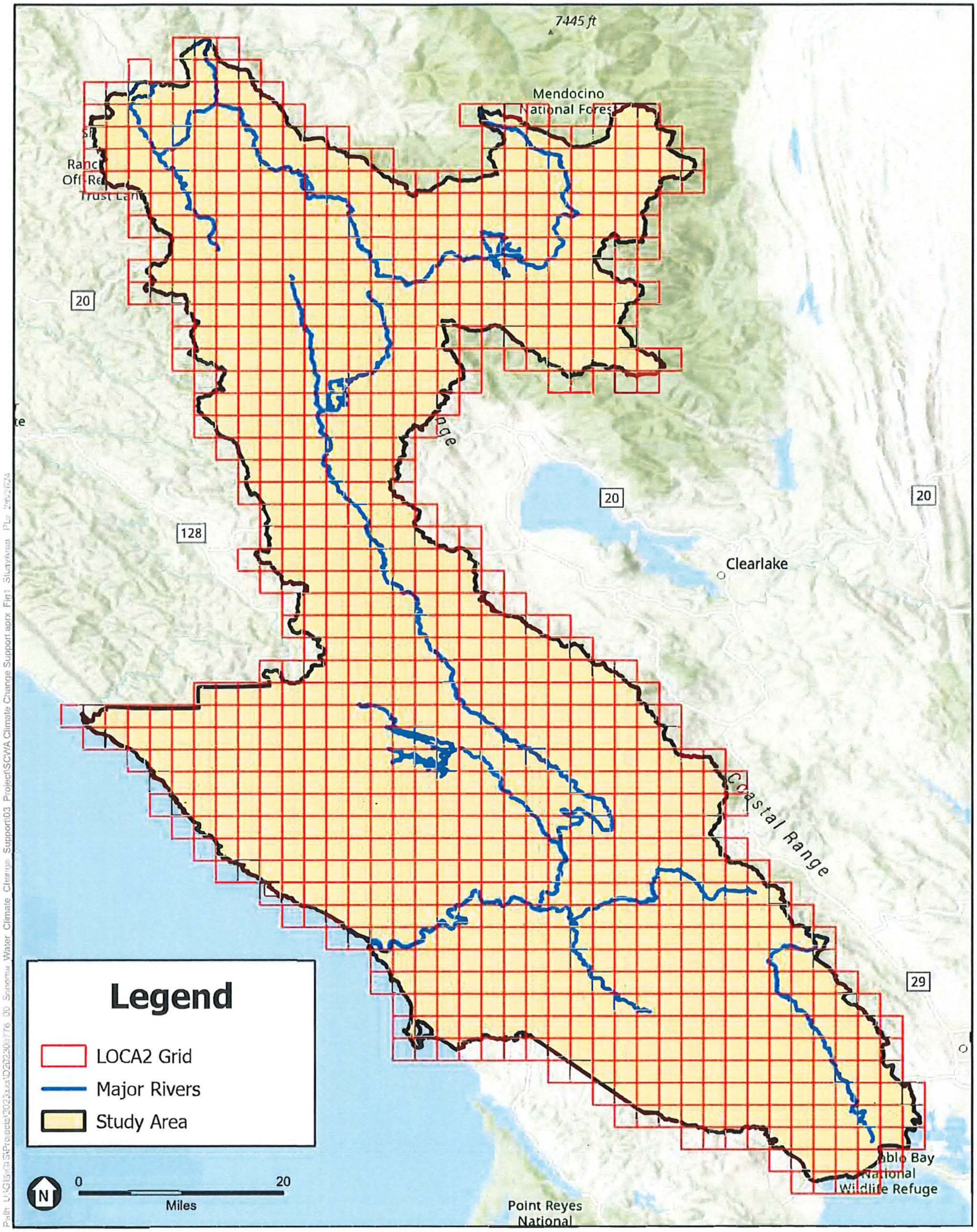
Sonoma Water is a regional leader in water resource management and climate resilience assessment and planning. To support Sonoma Water with understanding, planning for, and addressing future climate impacts, ESA developed a database of future rainfall estimates for a range of key variables commonly used in water resource management applications. The database domain covers Sonoma County, the Russian River watershed, and the Upper Eel River watershed as shown in Figure 1. The database contains spatial and time-series data reflecting estimates of projected rainfall for specific time horizons, emissions scenarios, and climate model ensemble statistics. This report documents the data, methods, results, and assumptions used to develop the database. Guidance on how to use the database in water resource management for Sonoma Water will be provided in a separate report.

The database was derived from a downscaled climate dataset covering California (California LOCA2 (Pierce *et. al.* 2023) described further in Section 2) which contains daily climate model data downscaled to a three-kilometer grid. It contains two primary components (1) geospatial rasters of projected rainfall variables and (2) daily time series spreadsheets extracted from all climate models for every grid cell in the database (928 total at 3km resolution). The data was processed by ESA to produce estimates of design rainfall for three future periods (early-, mid-, and late century) and two emission scenarios (medium-high and high). Geospatial data, including scalars, reflecting percent change in each variable relative to a historic period (WY 1950-2014), and future design rainfall depths, were developed for the 24-hour storm for a range of recurrence intervals including the 1-, 2-, 5-, 10-, 25-, 50-, 100-, and 500-year events. Geospatial data were also developed for scalars of future mean annual precipitation (MAP). Estimates were also developed for 85th percentile rainfall but it was found that climate model data did not produce reliable estimates for this metric, so it was not included (see Section 3.4 for discussion). To capture variability in the ensemble of climate models, ensemble mean as well as mean plus one and two standard deviations (+1SD and +2SD) is provided for each of these scenarios and variables. A summary of the geospatial data contained in the database is provided in Table 1.

TABLE 1. FUTURE RAINFALL GEOSPATIAL DATA

Time Period	Emissions scenario	Variable	Climate model ensemble statistic
Early century (2016-2045 basis, 2030 midpoint)	Medium-high (SSP2-4.5) High (SSP5-8.5)	Return Periods 1-, 2-, 5-, 10-, 25-, 50-, 100-, and 500-year Mean Annual Precipitation	Mean Mean + 1SD Mean + 2SD
Mid century (2046-2075 basis, 2060 midpoint)	Medium-high (SSP2-4.5) High (SSP5-8.5)	Return Periods 1-, 2-, 5-, 10-, 25-, 50-, 100-, and 500-year Mean Annual Precipitation	Mean Mean + 1SD Mean + 2SD
Late century (2070-2099 basis, 2085 midpoint)	Medium-high (SSP2-4.5) High (SSP5-8.5)	Return Periods 1-, 2-, 5-, 10-, 25-, 50-, 100-, and 500-year Mean Annual Precipitation	Mean Mean + 1SD Mean + 2SD

This report includes a summary of the data sources used in the analyses (Section 2), technical methods applied to develop the database (Section 3), key results from analyzing future rainfall projections (Section 4), and a summary including further considerations and potential expansions of the database (Section 5).



SOURCE: ESA, 2024

Sonoma Water Future Rainfall

Figure 1

Map of Study Area

ESA

2. DATA AND APPROACH

The database leverages the latest advancements in downscaling applied to general circulation models (GCMs) run as part of the sixth assessment report from the Intergovernmental Panel on Climate Change (IPCC, 2021). The GCMs were developed, and output aggregated, under the IPCC's Coupled Model Intercomparison Project Phase 6 (CMIP6, Stockhause *et. al.* 2021). The IPCC also defines model input for future emissions and socioeconomic conditions in the GCMs. The future rainfall database developed for Sonoma Water uses downscaled CMIP6 GCM data for key future scenarios to derive MAP scalars and design rainfall scalars and depths. This section describes the downscaled data, the IPCC emissions scenarios, and present-day depth-duration-frequency data used to develop future estimates of extreme rainfall depths.

2.1 Downscaled Climate Data

Global climate models typically utilize computational grids >100km. Downscaling is the process by which output from global climate models are reproduced at a higher spatial resolution using either statistical or dynamical methods. Statistical methods rely on statistical relationships between observed and modeled data for the historic training period to downscale the future GCM output. Dynamical methods directly model physical climate processes at the downscaled resolution using the GCM data as input to the dynamical model.

A primary resource used in many California applications, including the statewide climate assessment reports, is based on the method of 'locally constructed analogs' (LOCA), a statistical downscaling method developed and applied by researchers at the Scripps Institute of Oceanography (Scripps) in 2015 (Pierce *et. al.* 2015). A second version of the LOCA dataset, which improved the methodology and increased the spatial resolution for a California-specific domain (California LOCA2), was released in May 2023 (Pierce *et. al.* 2023). The California LOCA2 dataset contains daily temperature and rainfall data spanning the period from 1950 to 2100. The data is divided into two periods, a historical period used for training (1950-2014), and a future scenarios period (2015-2100). Raw California LOCA2 datasets were downloaded by ESA from the Cal-Adapt Analytics Engine in large files (netcdf format) containing daily rainfall depth for each model and emissions scenario.

One of the distinguishing features of the California LOCA2 dataset is its hybrid downscaling method which applies both statistical and dynamical methodologies. In addition to the statistical method outlined above, California LOCA2 incorporates late-century weather patterns from a set of four Weather Research and Forecasting (WRF) dynamically downscaled simulations. The integration of these dynamic simulations into the statistical downscaling process allows the dataset to better predict changes in weather patterns that might occur in the coming decades. Furthermore, the California LOCA2 dataset draws from a subset of 15 models from the CMIP6 suite, screened for high performance over the California domain (Krantz *et. al.* 2021). Of this 15-model ensemble, only 13 models from the California LOCA2 dataset contained output for the two emission scenarios selected for this study. The models used to develop the future rainfall database are summarized in Table 2.

TABLE 2. DOWNSCALED GCMS USED FOR THE FUTURE RAINFALL DATABASE

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

NOTES: SQKM = KILOMETERS; MODELS ARE LISTED ALPHABETICALLY
SOURCE: Scripps Institution of Oceanography La Jolla, CA

2.2 Shared Socioeconomic Pathways and Representative Concentration Pathways

IPCC climate models rely on projected scenarios of future socioeconomic conditions and greenhouse gas mitigation strategies as model input to assess future climate conditions. To enable consistency in these assessments, the IPCC has developed a suite of socioeconomic scenarios (Shared Socioeconomic Pathways (SSPs)) (IPCC 2021) that are each associated with a projected greenhouse gas emissions pathway (Representative Concentration Pathways (RCPs)). The RCPs are numbered according to the increase in radiative energy (in W/m^2) on the earth's surface over the 21st century. Two SSP-RCP scenarios were selected for inclusion in the future rainfall database:

- **SSP2-4.5**, a medium-high pathway, assumes moderate socioeconomic challenges to mitigation and adaptation. RCP4.5 assumes that future earth-surface radiative energy increases from 2000 to 2100 by 4.5 W/m^2. It's a "middle-of-the-road" scenario, where trends do not shift markedly from historical patterns, making it a useful reference for assessing moderate climate responses.

- **SSP5-8.5**, represents a high greenhouse gas emissions trajectory, assuming high challenges to mitigation and, due to advances in technology, low challenges to adaptation. RCP8.5 assumes unmitigated emissions resulting in a future radiative energy increase of 8.5 W/m^2. This scenario represents a future condition with unmitigated emissions, serving as a 'worst-case' reference.

These scenarios were selected to align with prior and ongoing climate change analyses, including the California statewide climate assessments (fourth assessment report published in 2019, fifth report currently in development), the state Department of Water Resource's Climate Action Plan (DWR, 2018) and Sonoma Water's Climate Adaptation Plan (Sonoma Water, 2021). This ensures consistency and continuity in Sonoma Water's approach to climate adaptation and resilience.

2.3 Precipitation depth-duration-frequency

Sonoma Water adopted NOAA Atlas 14 rainfall for design applications in the 2020 update to its Flood Management Design Manual (Sonoma Water, 2020). The NOAA Atlas 14 dataset contains depth-duration-frequency relationships at a grid cell resolution of 800 meters covering the nation. Modeled scalars from the LOCA2 dataset were applied to NOAA Atlas 14 to estimate future Depth-Duration-Frequency (DDF) relationships for the future rainfall database.

3. METHODS

3.1 Raw data extraction from LOCA2 files

A series of MATLAB scripts were developed by ESA to process the downloaded raw climate data from the California LOCA2 CMIP6 3km resolution dataset. The LOCA2 files were extracted for each model and emissions scenario and a daily time series was developed at each downscaled model cell in the study domain. Those daily time series data were archived in excel files with one excel file per model. Each column in the excel files corresponds to daily rainfall for one 3km grid cell. The header label for each column-grid cell corresponds to California LOCA2's naming convention (climate ID). The database includes a shapefile (LOCA2_Grids_SonomaFutureRainfallScenarios.shp) containing the LOCA2 model cells with fields for climate ID, latitude, and longitude. Additional excel files were developed containing daily time series for the maximum of all models, the minimum of all models, the mean of all models, and the model mean+1SD and +2SD. Annual maxima were extracted for each grid cell for each model and emissions scenario in each water year as a pre-processing step for the precipitation frequency analysis used to derive the projected scalars.

3.2 Precipitation frequency analysis

Frequency analysis was conducted to estimate projected changes in design rainfall events by fitting a Generalized Extreme Value (GEV) curve, fitted using the method of L-moments, to annual maxima values for each downscaled grid cell for each model and emissions scenario. The L-moment GEV frequency distribution is widely used for rainfall frequency relationships and is the method applied to develop DDF relationships from spatially interpolated gage data in the NOAA Atlas 14.

For the future rainfall database, frequency relationships were computed for the historic period for each model using annual maxima for the 55-year period from 1950 through 2014. Projected frequency relationships were computed for each model for future periods using 30-year blocks of annual maxima for 2015-2045 (early century), 2046-2075 (mid-century), and 2070-2100 (late century). Gridded scalars were then computed for each model, scenario, recurrence interval, and time-period as the ratio of each future period frequency relationship to the historic frequency relationship. Scalars were computed first for each individual model. Then ensemble statistics, including model mean, mean+1SD and mean+2SD, were calculated from the distribution of scalar values across the models.

The LOCA2 scalars for each design event were used to scale NOAA Atlas 14 precipitation frequency rasters for the 24-hour duration storm, for 1-, 2-, 5-, 10-, 25-, 50-, 100-, and 500-year recurrence interval events. The result is scaled 24-hour design rainfall depth rasters (800m resolution) for each future time horizon, emissions scenario, and model ensemble statistic.

3.3 Mean Annual Precipitation

To calculate the mean annual precipitation (MAP), ESA summed the daily precipitation values for each model, for each water year then divided the sum by the number of years in each time period (55 for the historic period, 30 for future periods). The percent change between each future scenario and historic baseline conditions were computed for each LOCA2 grid cell under each model, scenario, and time period. Scalars for changes in MAP were computed first for each individual model. Then ensemble statistics, including model mean, mean+1SD and mean+2SD, were calculated from the distribution of scalar values across the models.

3.4 85th percentile rainfall

ESA computed 85th percentile rainfall at each model cell for each model and emissions scenario. Depending on the scenario, many of the climate models resulted in zero values for the 85th percentile values. This caused substantial differences across the study domain in 85th percentile when model mean, and standard deviation statistics were computed. Given the heterogeneity of the results for this metric, it was not included in the final database.

3.5 GIS processing

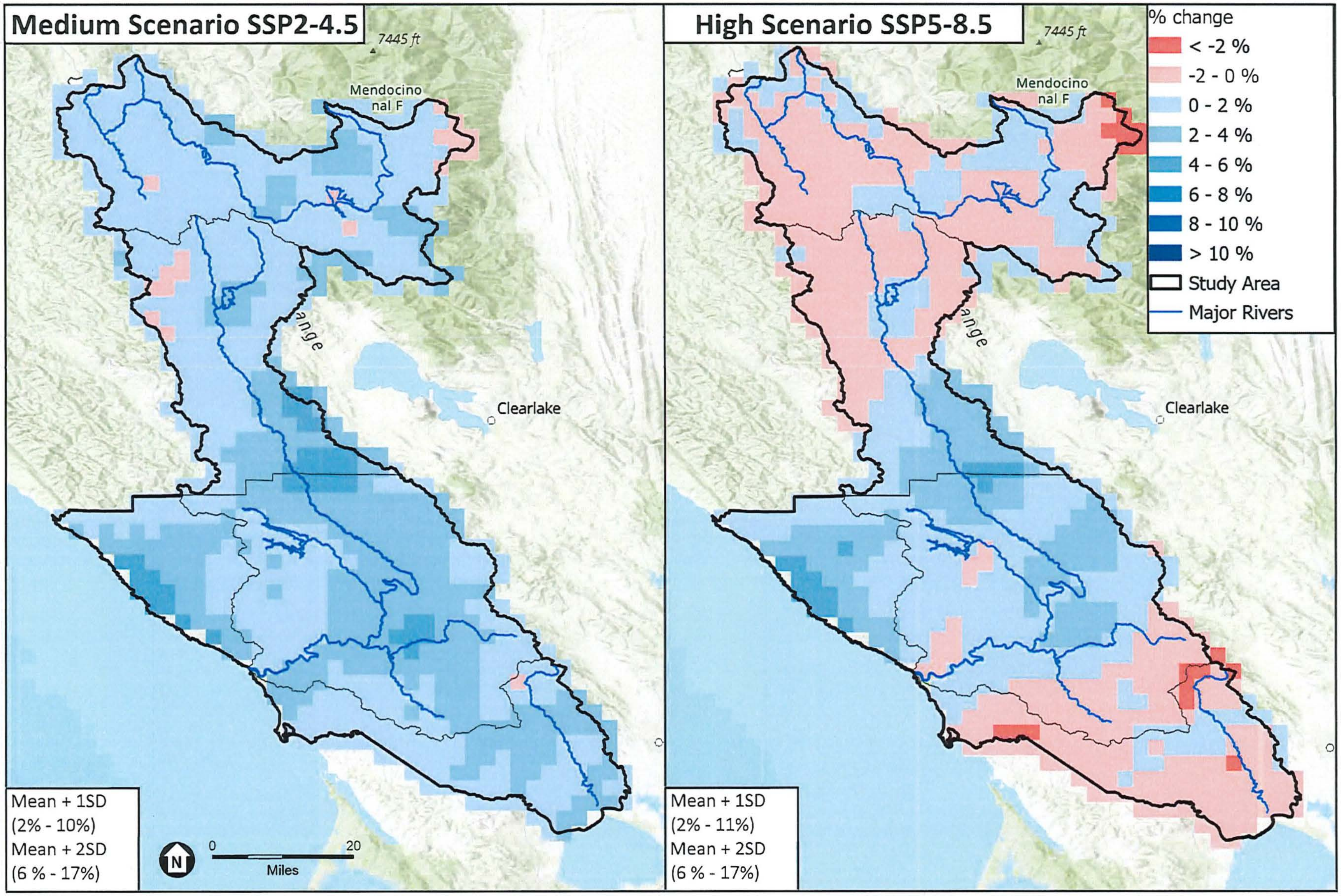
As described in 3.2 above, to produce scaled DDF rasters, the design rainfall scalars for different return interval storms (3km grids) were intersected with the corresponding 24-hr duration NOAA Atlas 14 grids (800m grids) so that an area-weighted scalar was applied to each NOAA grid cell based on its coincident area with one or more LOCA2 grid cells. Scaled design rainfall depth rasters (800m grids) were organized by early century (2015-2045), mid-century (2046-2075), and late century (2070-2100) time periods, between SSP2-4.5 and SSP5-8.5 scenarios, and by recurrence interval. Mean Annual Precipitation for each LOCA2 grid cell was processed in ArcGIS Pro into 3km scalar rasters.

4. RESULTS

This section displays selected results for ensemble model means for 100-year rainfall scalars and scaled precipitation depth, as well as MAP. The percent change for MAP under the medium-high (SSP2-4.5) and high (SSP5-8.5) emissions scenarios is shown for early-, mid-, and late century in Figure 2, Figure 3, and Figure 4 respectively. The percent change in 100-year rainfall depth is shown for these scenarios in Figure 5, Figure 6, and Figure 7. The scaled 100-year depth is shown in Figure 8, Figure 9, and Figure 10. Each figure shows mapped model mean for each variable and the model distribution for mean+1SD and mean+2SD is shown in the corner of each map panel.

Mean annual precipitation showed modest decreasing trends in the northern and southern part of the study area, while SSP2-4.5 scenario showed greater increases in mean annual precipitation in the lower Russian River Watershed compared to SSP5-8.5 (Figure 2 ~ 4). Mean projected changes to 100-year rainfall remain mostly identical between the two emission scenarios in early and mid-century. By late century, SSP5-8.5 scenario showed a greater increase than SSP2-4.5 near Lake Sonoma (Figure 5 ~ 7). Scaled NOAA Atlas 14 future rainfall depth for 100-year 24-hour duration storm showed more than 18 inches of rainfall in Upper Russian River Watershed in SSP5-8.5 scenario, while having low variability in early- and mid-century between emission scenarios (Figure 8 ~ 10).

Design rainfall results from the database for a single grid cell located over the Mirabel & Wohler water supply collection intakes are shown in Figure 11. This figure shows the distribution of changes over the design rainfall events at early, mid, and late-century conditions for the two emissions scenarios. The plots show changes for model mean (solid lines) and +/- one and two standard deviations (dotted lines). This plot captures the general trend in the data which shows larger changes mid-century relative to late century, and higher changes for the medium-high emissions scenario relative to the high emissions scenario for both early and mid-century.



SOURCE: ESA, 2024

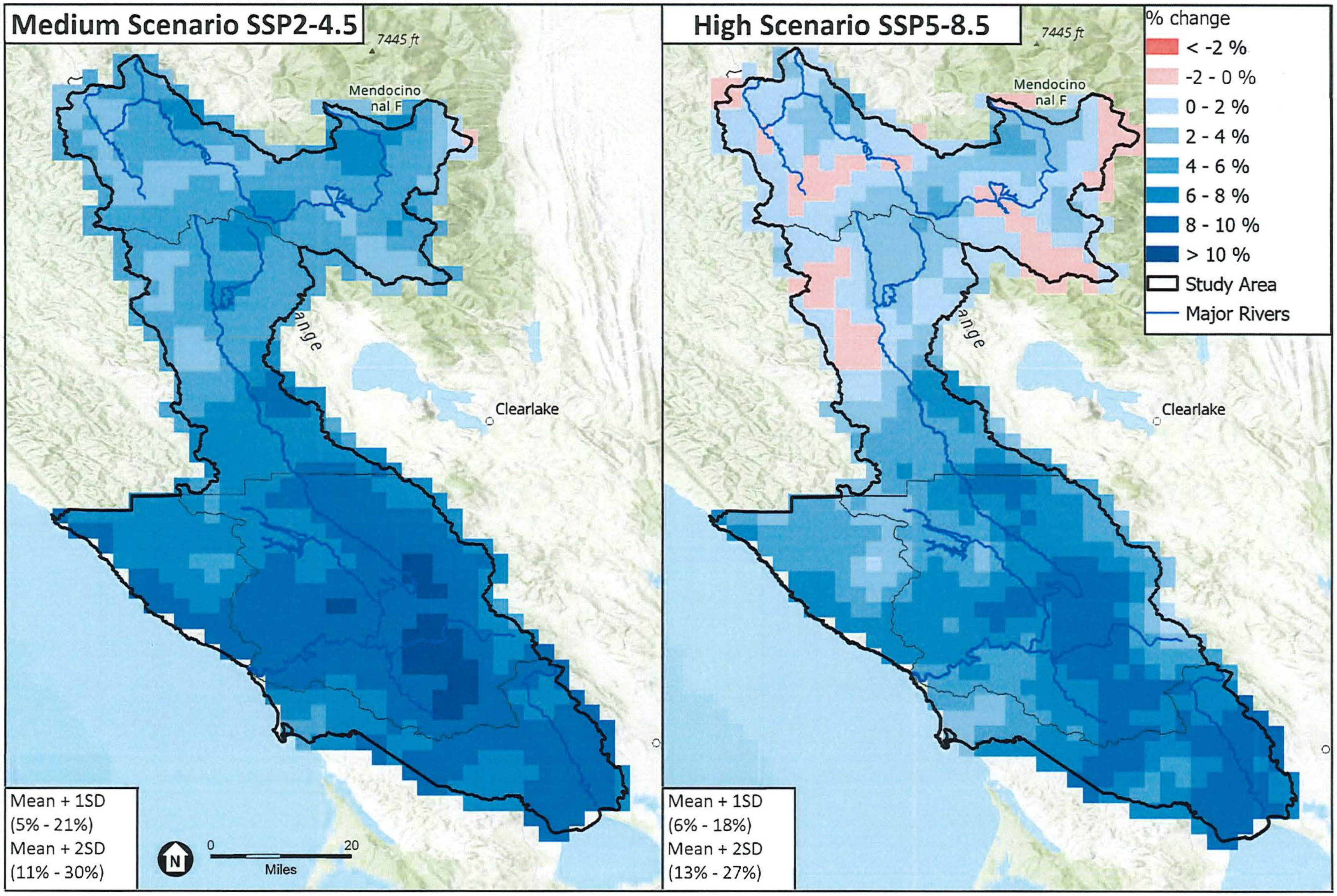
NOTE: Percent change is relative to the historic period (1950-2015)

Sonoma Water Future Rainfall

Figure 2

Model Mean % Change in Mean Annual Precipitation
Early Century (2030)

ESA



SOURCE: ESA, 2024

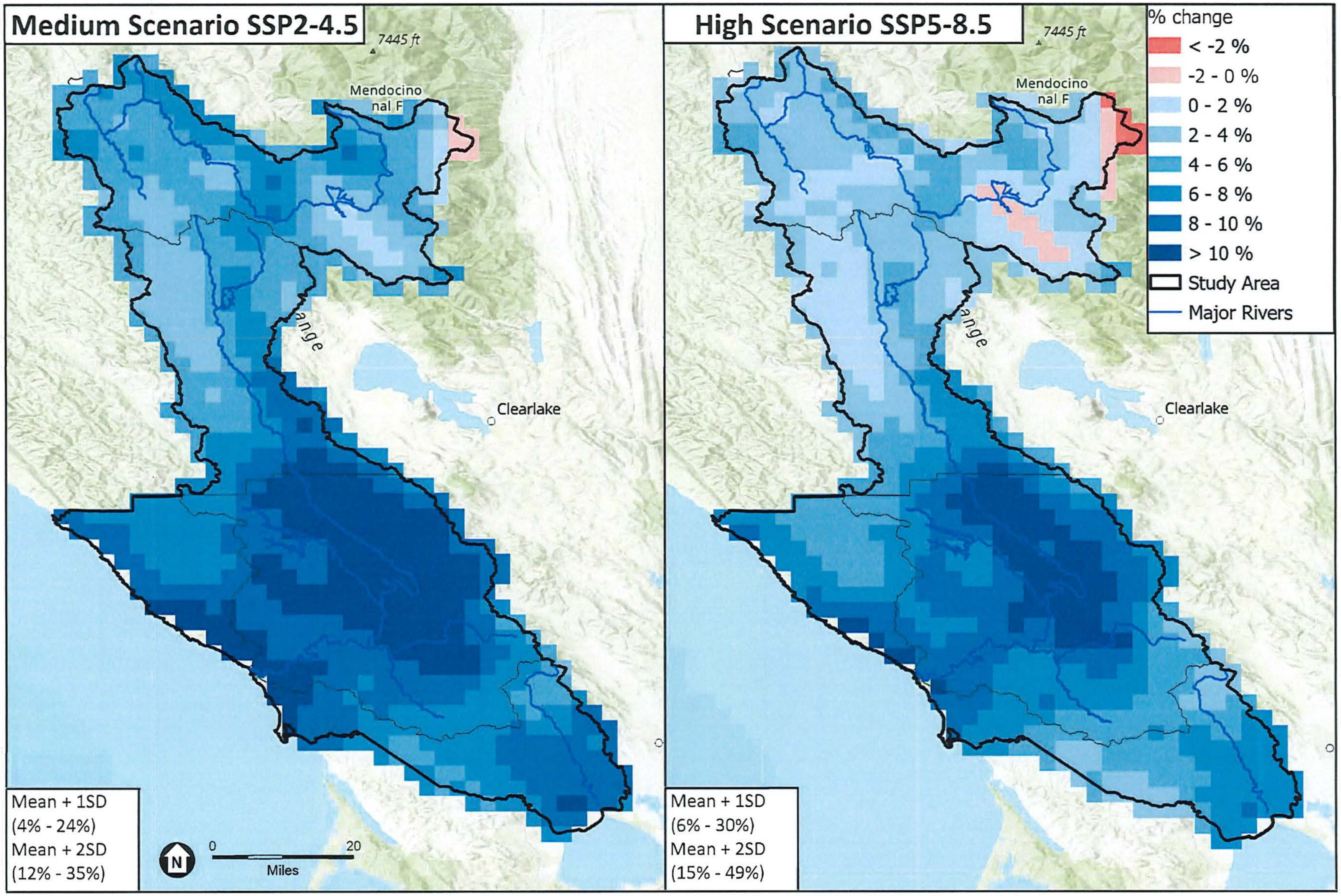
NOTE: Percent change is relative to the historic period (1950-2015)

Sonoma Water Future Rainfall

Figure 3

Model Mean % Change in Mean Annual Precipitation
Mid Century (2060)

ESA



SOURCE: ESA, 2024

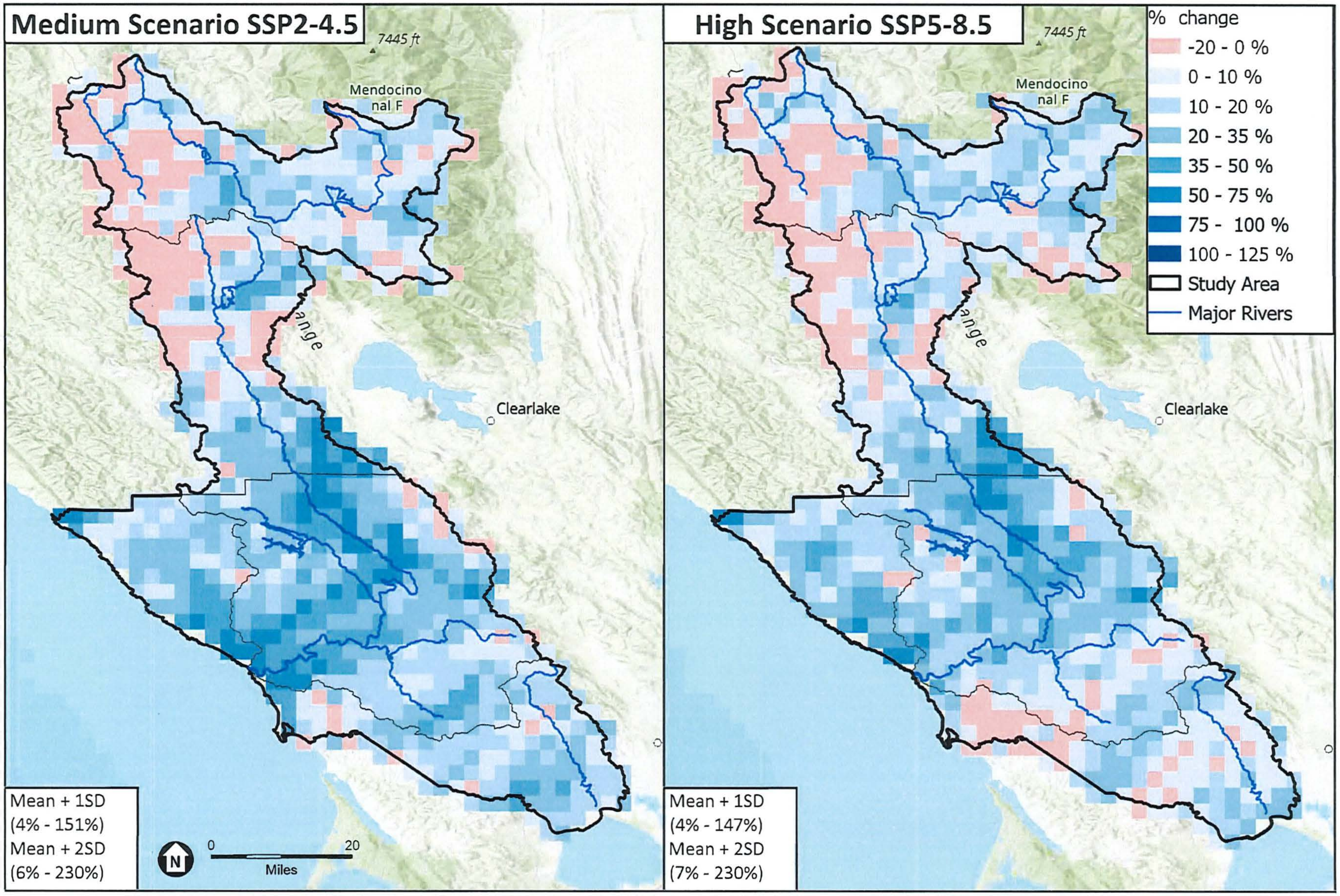
NOTE: Percent change is relative to the historic period (1950-2015)

Sonoma Water Future Rainfall

Figure 4

Model Mean % Change in Mean Annual Precipitation Late Century (2085)

ESA



SOURCE: ESA, 2024

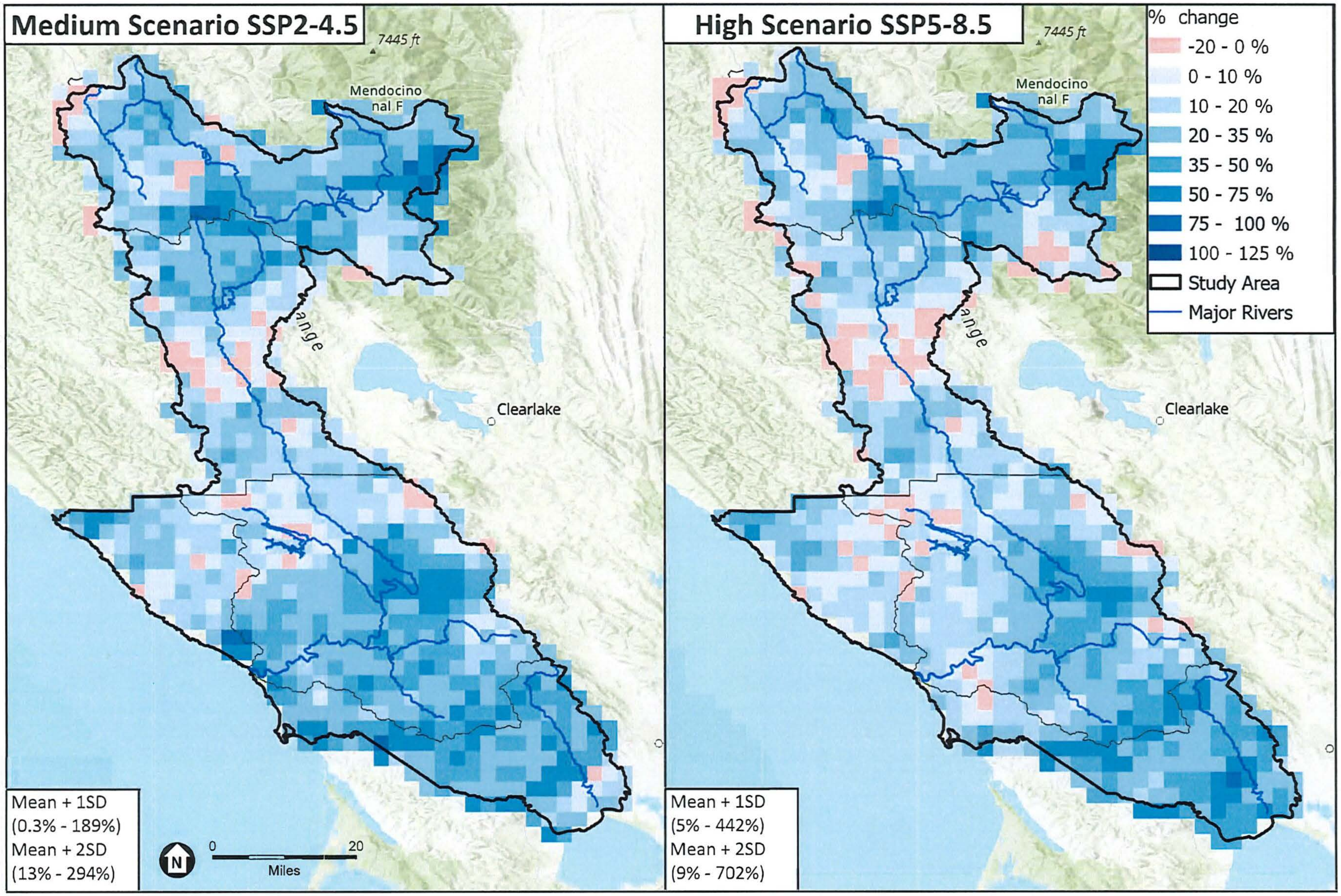
NOTE: Percent change is relative to the historic period (1950-2015)

Sonoma Water Future Rainfall

Figure 5

Model Mean % Change in 100-year rainfall
Early Century (2030)

ESA



SOURCE: ESA, 2024

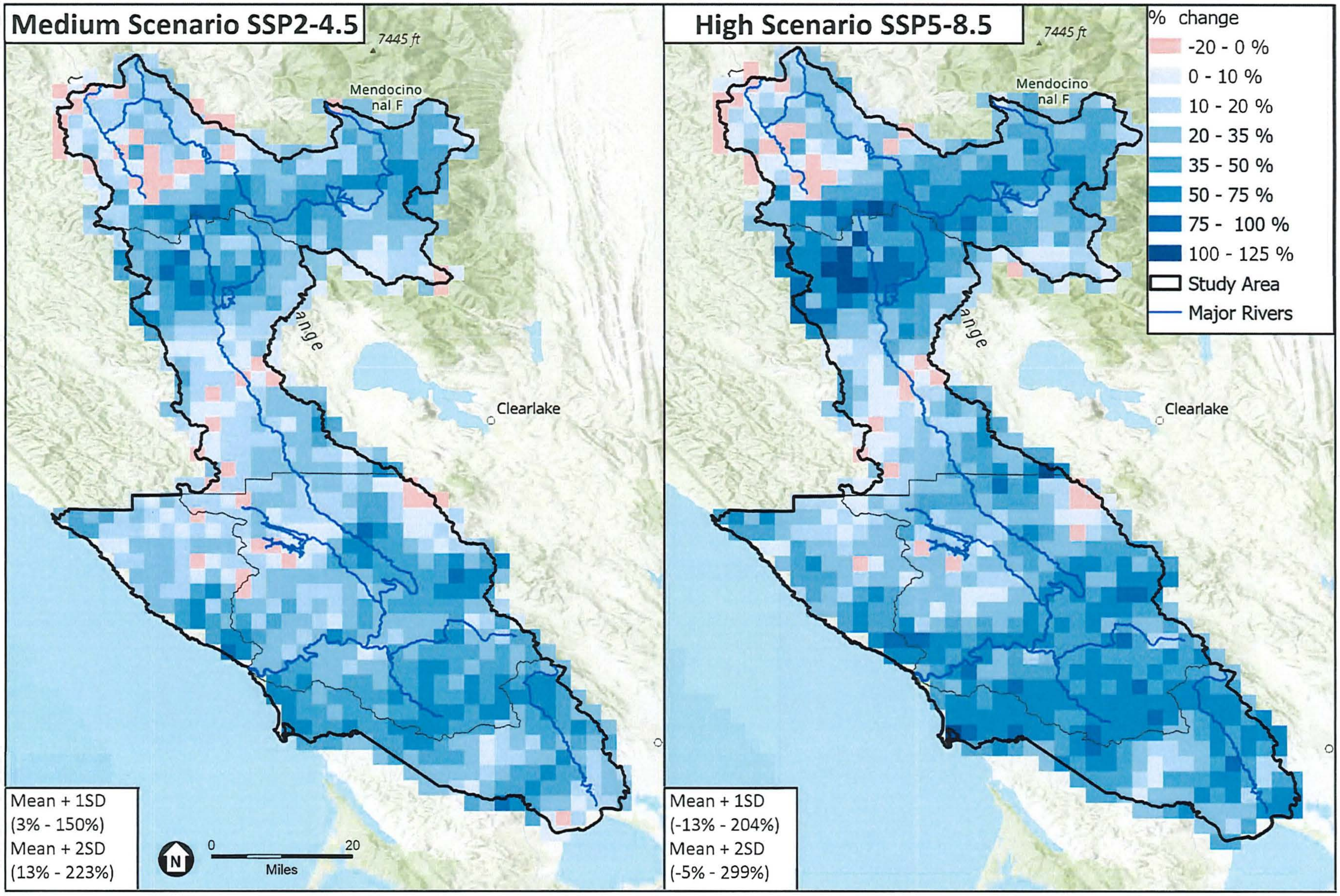
NOTE: Percent change is relative to the historic period (1950-2015)

Sonoma Water Future Rainfall

Figure 6

Model Mean % Change in 100-year rainfall
Mid Century (2060)

ESA



SOURCE: ESA, 2024

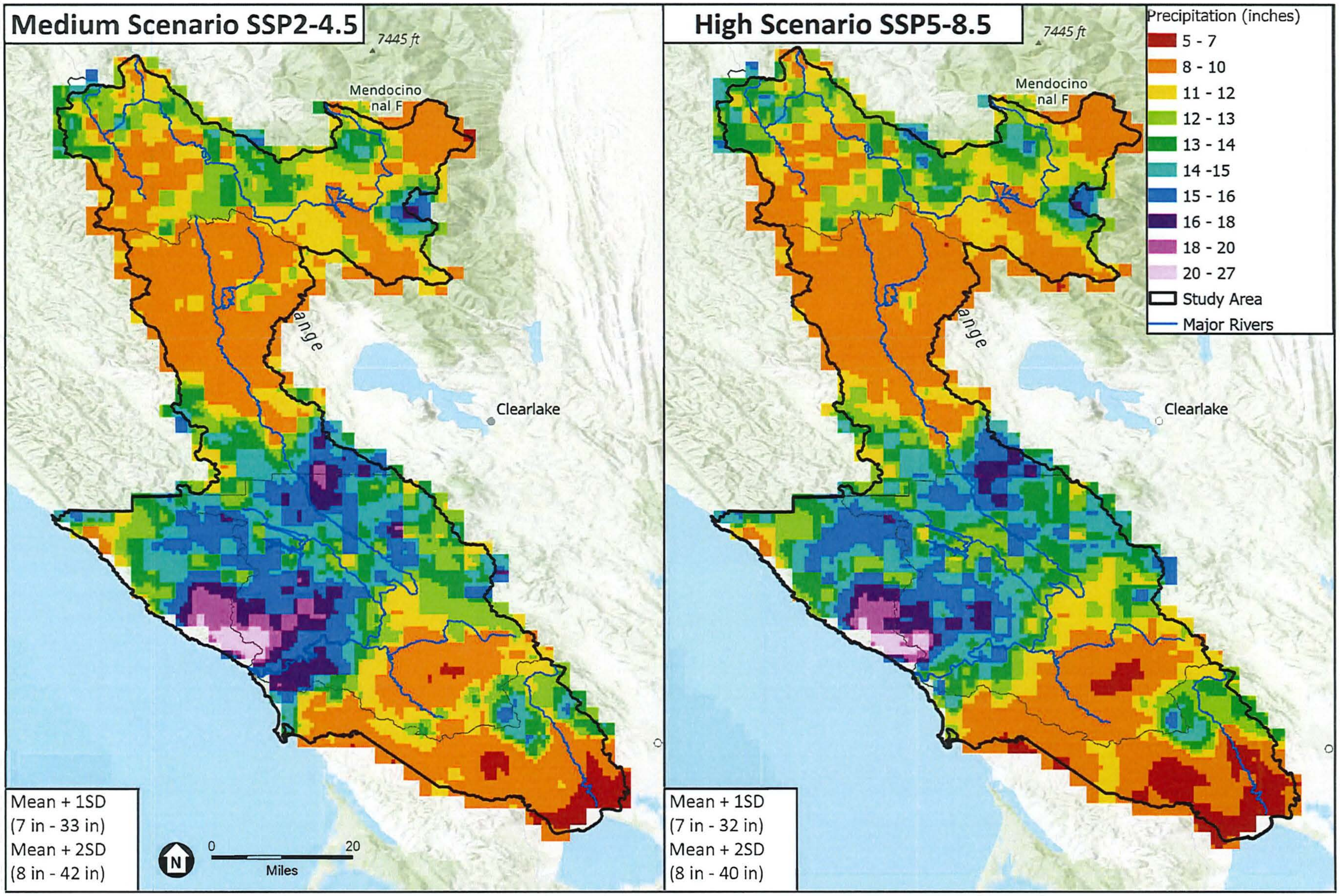
NOTE: Percent change is relative to the historic period (1950-2015)

Sonoma Water Future Rainfall

Figure 7

Model Mean % Change in 100-year rainfall
Late Century (2085)

ESA



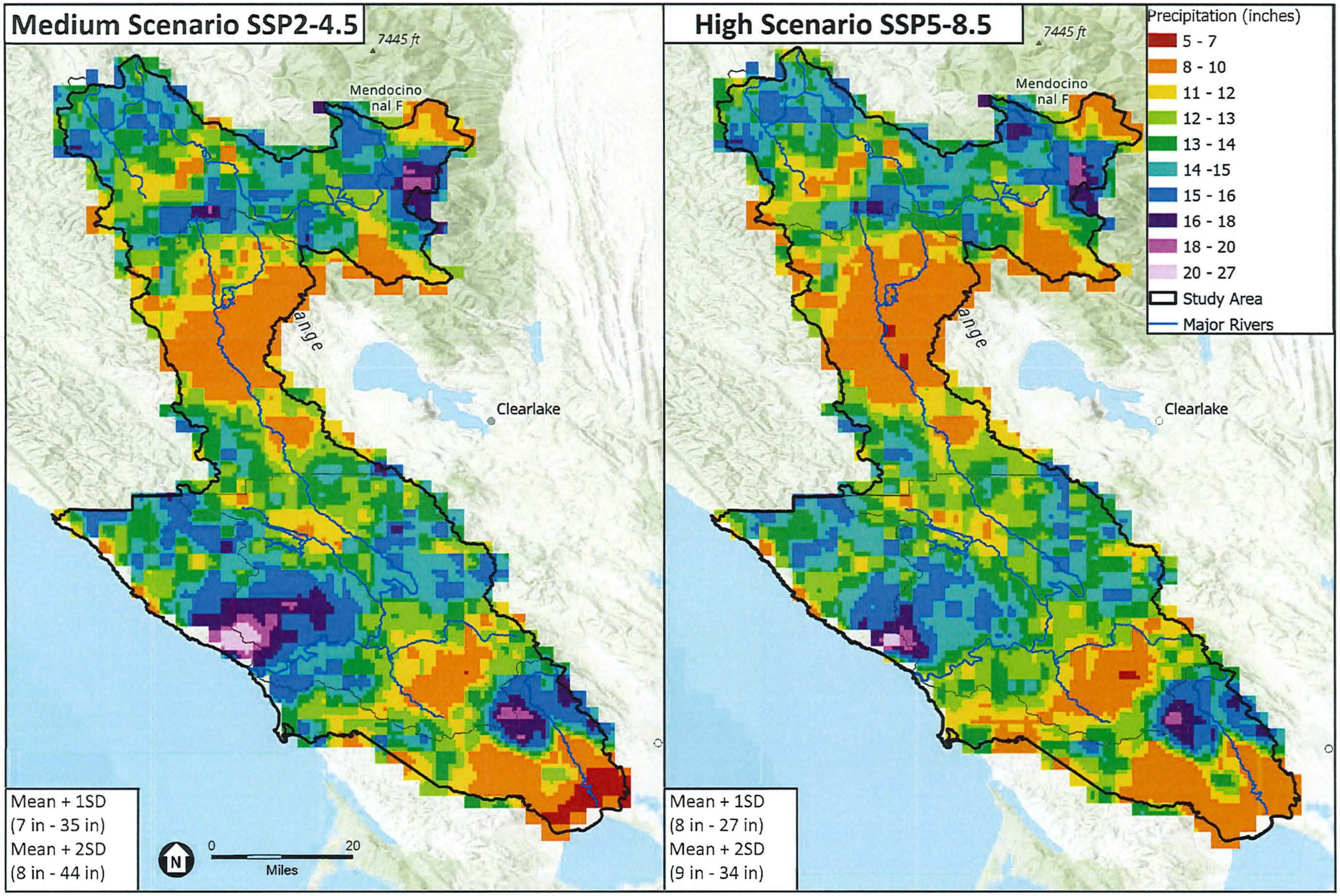
SOURCE: ESA, 2024

Sonoma Water Future Rainfall

Figure 8

Model Mean of Scaled 100-yr 24-hr Rainfall Depth
Early Century (2030)

ESA



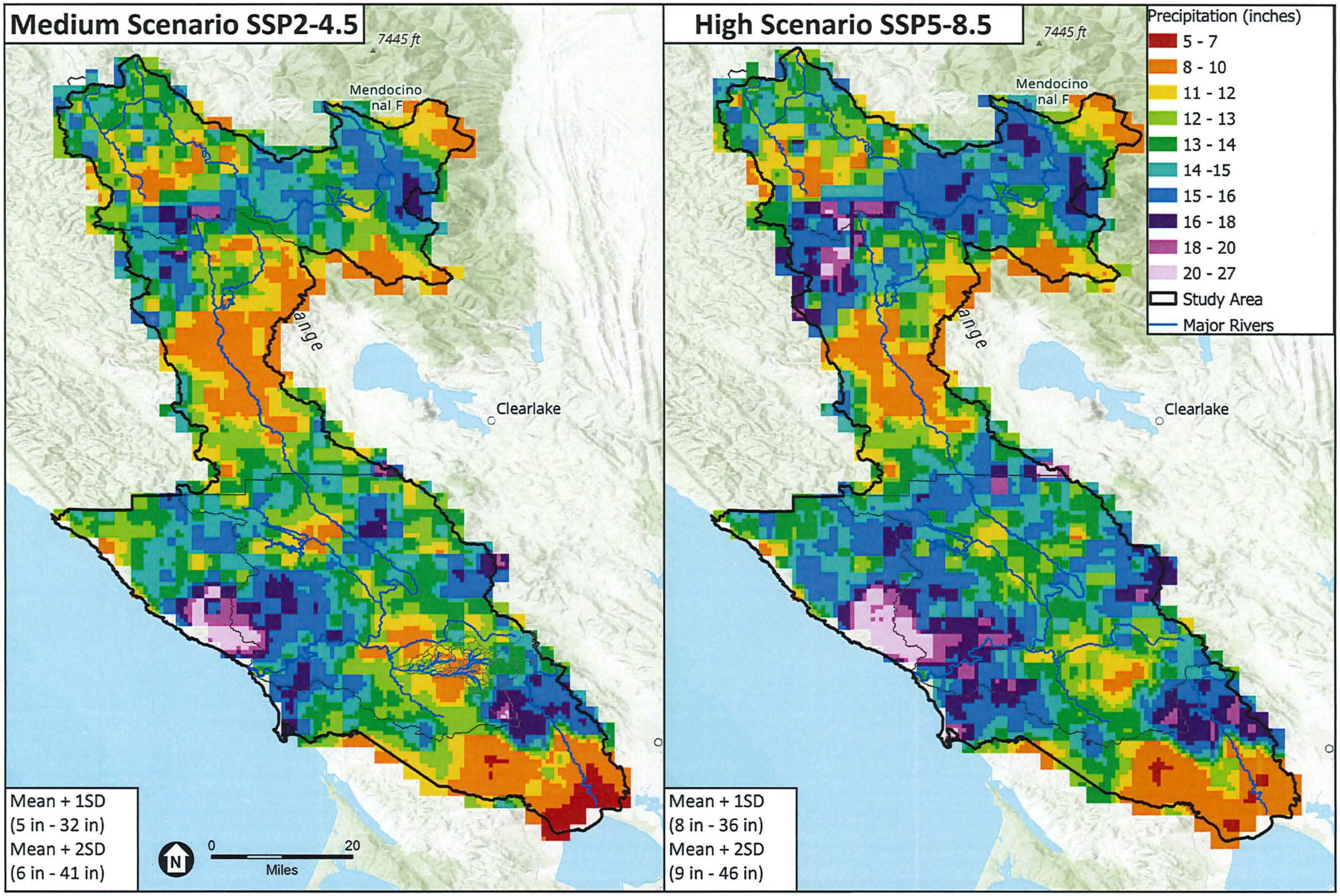
SOURCE: ESA, 2024

Sonoma Water Future Rainfall

Figure 9

Model Mean of Scaled 100-yr 24-hr Rainfall Depth
Mid Century (2060)

ESA



SOURCE: ESA, 2024

Sonoma Water Future Rainfall

Figure 10

Model mean of Precipitation Frequency Estimates for 100-year 24-hour Rainfall
Late Century (2085)

ESA

5. SUMMARY

This report serves as a technical reference for the methods and approaches used to develop the future rainfall database and a sample of results. The database includes time series files in excel format and future extreme rainfall raster data for early century, mid-century, and late century time periods, under medium-high and high emissions scenarios, for various model ensemble statistics including mean, mean+1SD, and mean+2SD. Access to the database will be provided by Sonoma Water.

While the database was developed using the latest climate model datasets, additional needs identified by Sonoma Water and Sonoma County communities as well as future advancements in climate science will present opportunities for refining, improving, and expanding on the database described in this report. Potential enhancements include:

- **Evaluation of shorter durations** – One potential enhancement would be to leverage climate datasets with high temporal resolution to quantify and evaluate projected changes in storm durations less than 24-hours. For example, the WRF dataset utilized to develop the California LOCA2 dataset includes hourly rainfall from 1950-2100. These data could be utilized to estimate changes in storm durations less than 24-hours, as well as improving the metric for peak annual 24-hour rainfall by capturing events that do not occur all on the same day. Existing studies using the WRF dataset have found that the intensity of short-duration storms are likely to increase at a greater rate than the intensity of 24-hour storms, potentially undermining the application of 24-hour rainfall scalars to sub-24 hour storms (City of San Francisco, 2023).

- **Longer duration events** – Just as there are many applications for datasets with shorter durations, there are many water resource management applications where longer-duration events are relevant to assessing and planning for the impacts of future climate change.

- **Temperature and other rainfall variables** – The LOCA2 datasets include temperature which could be processed into similar time series and geospatial datasets for use by Sonoma Water. Additionally, other rainfall metrics and products could be developed based on input from Sonoma Water and other stakeholders in the county.

- **NOAA Atlas 15** – Recognizing the need to account for future climate change, the next iteration of the NOAA Atlas will include future climate change scenarios. The timeline and approach for this product is still in development but as more information is released, Sonoma Water should evaluate benefits and tradeoffs of the future rainfall database in comparison to planned and released NOAA products.

- **Online climate dashboard** – Discussion with Sonoma Water has underscored the need for providing user-friendly access to the climate data produced for this study and follow up efforts. A popular approach taken by other entities such as Cal-Adapt, an online interface developed under collaboration between state agencies, universities, national labs

> and private sector researchers, has been to provide the data through an online tool that includes access to the data as well as simple geoprocessing tools to allow users to extract information tailored to their specific applications.

The Sonoma Water Future Rainfall Database developed by ESA and described in this report uses the latest downscaled daily data for California. The database will support Sonoma Water and communities in Sonoma County with estimating, planning for, and addressing future changes in rainfall characteristics and associated hydrologic impacts through the 21st century.

6. REFERENCES

City of San Francisco, 2023. San Francisco Bay Area Precipitation in a Warmer World. Volume 2. Future Precipitation Intensity, Duration, and Frequency.

DWR, 2018. Climate Action Plan. Phase 2: Climate Change Analysis Guidance.

Hosking & Wallis, 1997. Regional Frequency Analysis. An Approach Based on L-moments. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, https://doi.org/10.1017/9781009157896.

Krantz, W., D. Pierce, N. Goldenson, and D. Cayan, 2021: Memorandum on Evaluating Global Climate Models for Studying Regional Climate Change in California. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2022-09/20220907_CDAWG_MemoEvaluating_GCMs_EPC-20-006_Nov2021-ADA.pdf

Pierce, D. W., D. R. Cayan, E. P. Maurer, J. T. Abatzoglou, and K. C. Hegewisch, 2015: Improved bias correction techniques for hydrological simulations of climate change. Journal of Hydrometeorology, volume 16, page 2421-2442.

Pierce, D. W., D. R. Cayan, D. R. Feldman, and M. D. Risser, 2023: Future Increases in North American Extreme Precipitation in CMIP6 downscaled with LOCA. J. Hydrometeor., https://doi.org/10.1175/JHM-D-22-0194.1, in press.

Sonoma Water, 2020. Flood Management Design Manual.

Sonoma Water, 2021. Climate Adaptation Plan. October, 2021.

Stockhause, M., Matthews, R., Pirani, A., Treguier, A. M., and Yelekci, O.: CMIP6 data documentation and citation in IPCC's Sixth Assessment Report (AR6), EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-2886, https://doi.org/10.5194/egusphere-egu21-2886, 2021

7. LIST OF PREPARERS

Sonoma Water

Molly Oshun
Climate Resiliency Engineer

Carlos Diaz, P.E.
Deputy Director of Engineering

Environmental Science Associates

James Gregory, P.E.
Northern California Rivers and Watersheds Technical Analysis Lead

Christie Beeman, P.E.
Northern California Environmental Hydrology Business Group Director

Junjie Chen
Hydrologist