Appendix N. Impaired Streamflow Classification

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1. Introduction

Environmental flows (flows that address human and riverine ecosystems needs) can mimic components of the natural flow regime, with the purpose of restoring flows that address the lifecycle needs of fish, amphibians, riparian vegetation, birds and wildlife. Human development has caused changes in flow regimes, disconnected habitats (upstream, floodplain), increased water temperature, brought in invasive species, increased consumptive use (salinity changes), changing magnitude, timing, frequency, and rate of change in flows. In California, river ecosystems are adapted to the Mediterranean climate: floods during wet winters, snowmelt flows during spring and low flows during summer. Nine classes were identified for the State of California (Figure 1) that can be combined into three main categories: snowmelt, rain and mixed (Appendix B).

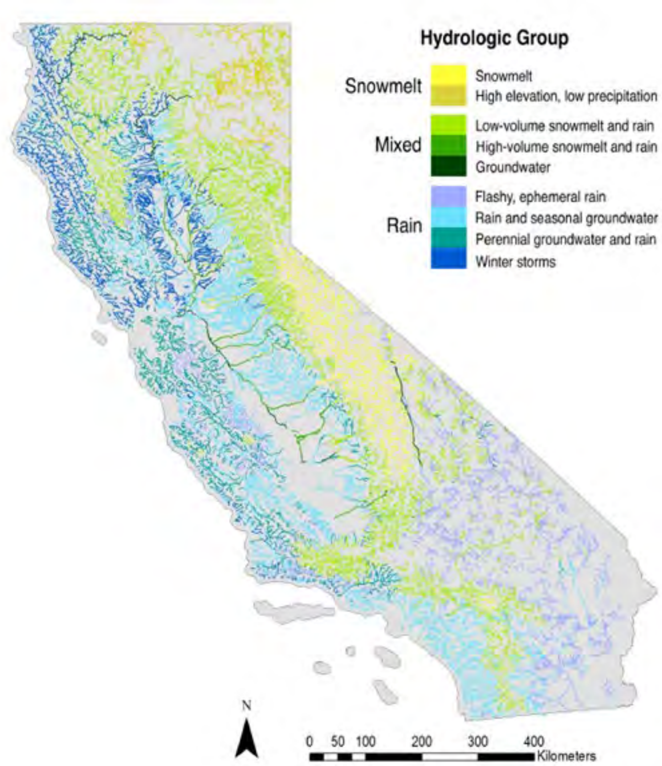

Figure 1 – Natural Streamflow Classification of California from Lane et al. (2018)

Humans have modified the natural flow patterns of the rivers in the Mediterranean climate by storing water during winter and using it during summer, as well as moving water where it is needed. As a result, alterations to the natural flow regimes have degraded riverine ecosystem. Having both intense climatic variability and highly altered rivers stresses the importance of understanding the diversity streamflow patterns. This appendix describes the methods for determining an Impaired Streamflow Classification and the associated flow regimes that are the result of human alteration. Alterations to flow regimes for water management objectives have degraded river ecosystems worldwide (Falcone et al., 2010). Alterations are mostly seen in Mediterranean climate regions like California where there is strong climatic variability and highly adapted riverine species to flooding and drought disturbances.

2. Methodology

The Impaired streamflow classification was developed considering specific objectives: (1) identify the non-reference streamflow gages, (2) classify gages by their impairment for the entire state of California, and (3) spatially predict the altered streamflow classes throughout the river network. Figure 2 shows the workflow for determining the impaired streamflow classification.

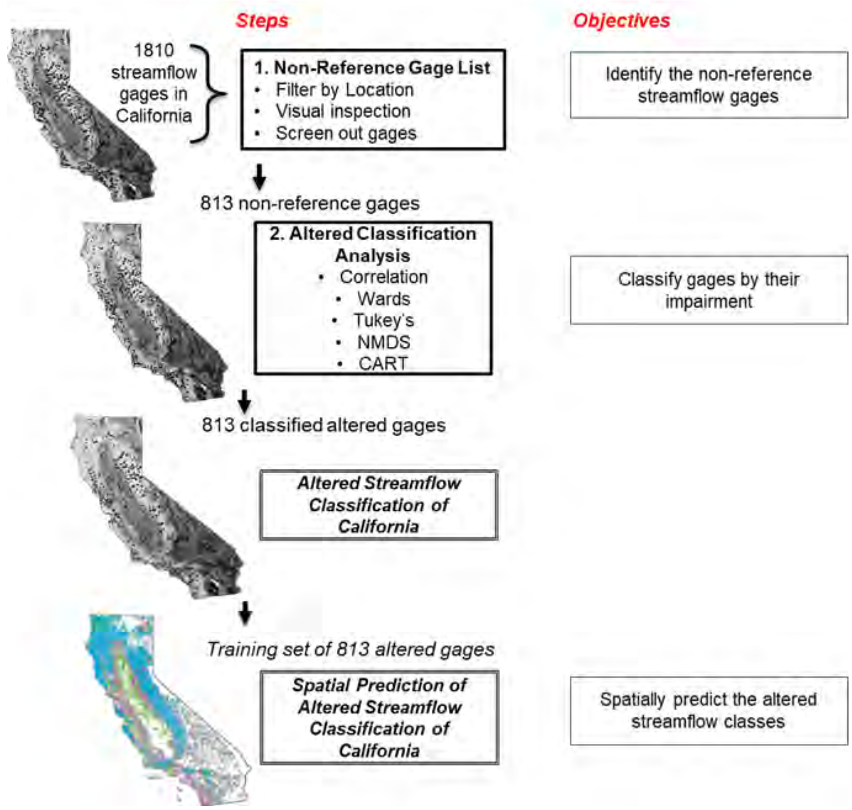

Figure 2. Workflow to develop an Impaired Streamflow Classification of California

2.1 Non-reference gauge list

This section describes the methods, steps and assumptions made for determining the list of Non-reference streamflow gauges for the state of California. Streamflow gauges that are deemed as Reference are those that do not exhibit human induced alteration in their streamflow time series data (Lane et al. 2018) and Non-reference gauges are those that exhibit anthropogenic alteration and are located along the river network (i.e. not including intakes, ditches, aqueducts, canals, etc.).

The U.S. Geological Survey (USGS) streamflow gage data, Gages II, were analyzed to determine the non-reference streamflow gages (Falcone et al., 2010). This dataset, referred to as GAGES II (Geospatial Attributes of Gages for Evaluating Streamflow, version II), provides geospatial data and classifications for stream gages maintained by the USGS. The sites comprise all USGS stream gages in the conterminous United States with at least 20 years of complete-year flow record from 1950–2019. From the USGS list of streamflow gages in California, there were a total of 1810 gage stations (Falcone et al., 2010). Three primary sources of information were used in identifying reference-quality streamgages: (1) filtering by location based on ArcGIS location, (2) visual inspection of every stream gage and drainage basin from recent high-resolution imagery, and (3) screen out of gages.

Filtering by location based on ArcGIS location. The USGS GAGES II database contained 1810 gage stations located in the states of California, Nevada, Oregon, Arizona, and the border of Mexico. For the purpose of this research only the ones located in California were selected.

Visual inspection of every stream gage and drainage basin from recent high-resolution imagery. A mapping and analytics platform (ArcGIS) was used to visually inspect the sites. The information used was the site name, location (latitude and longitude), California's main rivers and streams, and a basemap. The basemap served as a reference to identify if the sites were located along any water infrastructure, e.g. intakes, aqueducts, ditches, drains, canals, diversions, hydropower plants, etc. This research main objective is to develop a classification for the rivers that have been altered, not of the streamflow in water infrastructure. Thus, gage sites that were located on water infrastructure were not considered.

Screen out of gages. Gage screen out required a careful analysis of site inspection of location and information presented from USGS. Each site had information regarding common identifiers, gage type (Reference, Non-reference, and NA), and period of record from 0 to 39 years. The common identifier (ComID) of the NHDFlowline feature of the gage location is used. The sites that did not have a ComID were not selected. Part of this research study is to spatially predict the altered streamflow classes and without a ComId the spatial prediction would not be possible. Each gage had additional breakout point notes like redundant gauge II reference site, insufficient record, failed preliminary OE screen, NA, probable hydro alteration, no evidence that was carefully investigated prior to deciding on whether it should be selected or not. Sites whose period of record was less than 5 years were not selected.

Streamflow gauges that are deemed as Reference, are those that do not exhibit human-induced alteration in their streamflow time series data (Lane et al. 2018). Non-reference gauges are those gauges that exhibit anthropogenic alteration in the streamflow time series data and are located along the river network (i.e. not including intakes, ditches, aqueducts, canals, etc.). Of the 1810 gage stations USGS located in California, these two conditions must be met for a gage to be deemed as Non-Reference. This condition is important because the objective of the project is to develop a classification for rivers that have been altered, not to classify the alteration in the water infrastructure, which can be monitored by streamflow data in intakes, aqueducts, ditches, drains, etc. Figure 2 shows the process and analysis for selecting Non-reference gages.

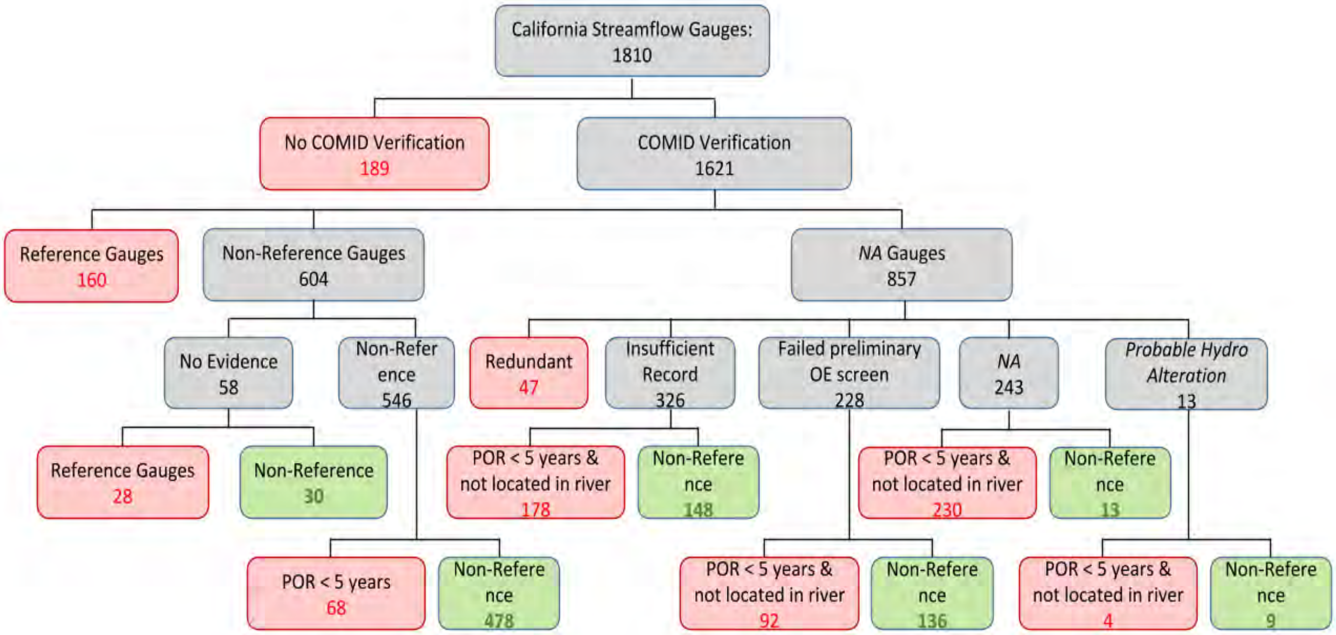

Figure 2. Streamflow gauge analysis to determine the definitive list of Non-Reference streamflow gauges

First, a verification on the ComID location was done for each gage, resulting in only 1621 of the 1810 gauges located in California. The remaining 189 gage stations were considered: not available, not found, or suspect and were not considered in this study. The filtering of the following analysis can be seen in Figure 7.

Second, we analyzed the list of 1621 streamflow gauges, of which 160 gage sites were classified as Reference, 604 as Non-Reference, and 857 as NA. For the 160 Reference streamflow gauges, we inspected their periods of record and verified that no records were available before or after the period for which they were deemed Referenced. The authors compared the 160 reference streamflow gauge of GAGES II with the 223 reference gauges identified by Lane et al. (2018). Out of the 160 reference gauges identified in this study, only 131 coincide with those identified by Lane et al. (2018). The remaining 29 Reference gauge stations were not included in Lane et al. (2018) because of the short period of record, incomplete data, or suspicious information.

Third, we further analyzed the 604 gage stations considered Non-Reference. Out of these 604 gages, 546 were already classified as Non-Reference by Falcone et al. (2010) and 58 classified as No-Evidence. The list of 546 streamflow gauges was visually inspected and only 493 are included in the definitive Non-Reference list. For the remaining 58 No-Evidence gages (referring to no evidence of hydro-alteration during the specified periods), we evaluated if there was streamflow data before or after the period of Reference record. 30 streamflow gauges found to have data after outside the period that was considered Reference were also included in the definitive Non-Reference list.

Fourth, we split the list of 857 gauge stations classified as “NA” into five groups: (1) 47 gauge stations classified as Redundant with gauge II reference site, (2) 326 gauge stations classified as Insufficient Record, (3) 228 gauge stations classified as Failed preliminary OE screen, (4) 243 gauge stations classified as NA, and (5) 13 gauge stations classified as Probable Hydro Alteration. The 47 gage stations were disregarded from the definitive Non-

Reference list because through a visual inspection there was no evidence of hydrologic alteration and they were noted as Redundant in the USGS gauge list.

For the remaining three groups (326, 228 and 243 streamflow gauge lists) the following analysis was conducted. First, we analyzed the name of each gauge station and disregarded any gauge that included one of the following infrastructure names: diversion, canal, ditch, aqueduct, drain, release, weir, conduit, combined, powerhouse, bypass, tunnel, powerplant. The goal here was to eliminate any gauge located along anthropogenic infrastructure rather than along the river corridor. Second, we spatially located each gauge and added a buffer of 5 meters of diameter. Then we selected those that were located within the river corridor and disregarded the 500 gages that were not (178 from the insufficient record, 92 from Failed preliminary OE screen and 230 from NA). From this analysis, 297 gage stations were included in the definitive Non-Reference list. Finally, the 13 gages classified as Probable Hydro Alteration were visually inspected and only 9 were included in the definitive Non-Reference list.

In the end, there were 829 gage stations selected as part of the definitive list of which only 813 had actual data (flow and dates). Thus, the final count for the streamflow gages used to identify impaired classification in California is 813.

2.2Non-reference gauges Classification Analysis

GAGES II identified eight anthropogenic influences (see Table 1) which were used as input parameters for the non-reference classification. The eight anthropogenic influences are shown in Table 1.

Table 1. Nine indicators of disturbance estimated by Falcone et al. (2010)

Indicator name	Description
PctUrbLo2006Cat	Percent of catchment area classified as developed, low-intensity land use (NLCD 2006 class 22)
PctUrbMd2006Cat	Percent of catchment area classified as developed, medium-intensity land use (NLCD 2006 class 23)
PctUrbHi2006Cat	Percent of catchment area classified as developed, high-intensity land use (NLCD 2006 class 24)
PopDen2010Cat	Mean population density (people/square km) within catchment
Stor_Nor_2009	Normalized upstream (from gage) reservoir storage from 1950-2006.
DamDensWs	Density of georeferenced dams within watershed (dams/ square km) based on the National Inventory of Dams
CropsNLCD06	Percent of watershed in cultivated crops (NLCD class 82)

Pct_Irrig_Ag	Percent of watershed in irrigated agriculture, from published USGS sources

Figure 4 shows an overview of the methods used to determine the non-reference classification including:

- Pearson Correlation
- Non-metric Multidimensional Scaling (NMDS)
- Hierarchical Clustering using Ward's Algorithm
- Tukey's box and whisker plots
- Classification and Regression Tree Analysis (CART)

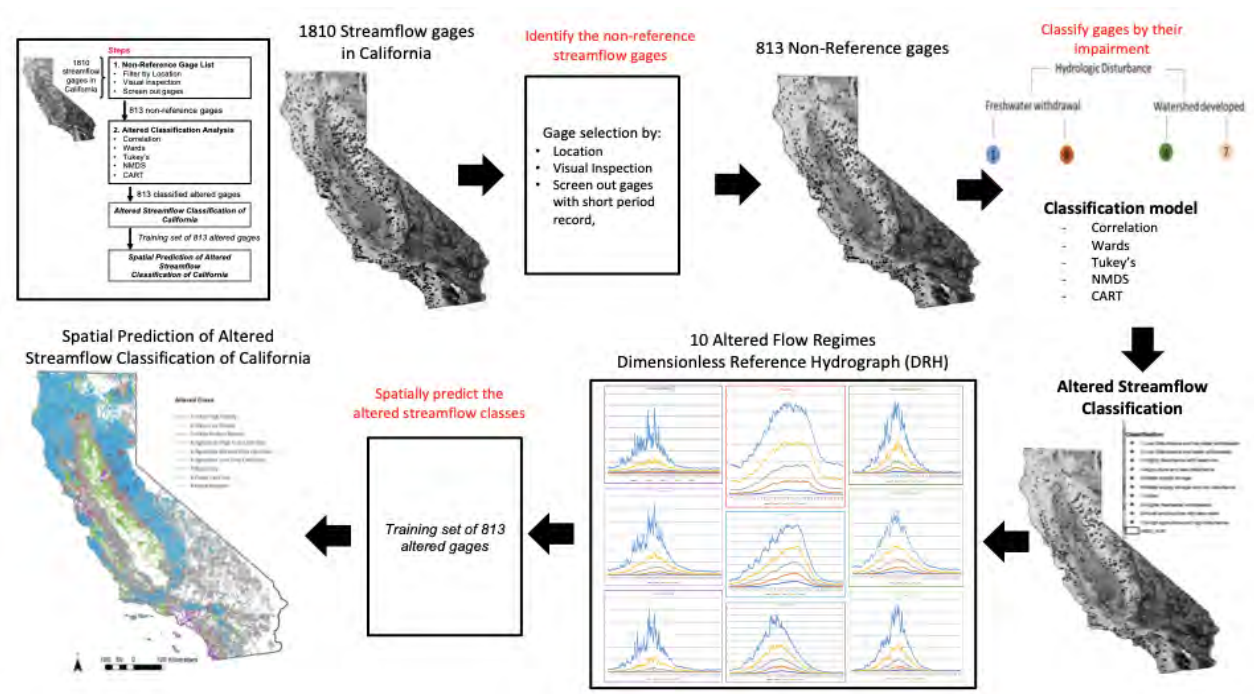

Figure 4. Overview of the methods used to determine the Impaired Streamflow Classification

Pearson Correlation

First, we determined if any of the nine anthropogenic influences to be used in the statistical analysis are highly, linearly correlated. If two attributes were highly correlated, one of the two would be removed.

Non-metric Multidimensional Scaling (NMDS)

NMDS is a statistical approach used to better understand how the sites cluster in multivariate space and which nine parameters are driving the clustering. The NDMS is not used as a final statistical classification.

Hierarchical Clustering using Ward's Algorithm

Hierarchical Clustering using Ward's Algorithm utilizes variance to determine which sites have the most similarities and which sites are most dissimilar. The amount of dissimilarity between sites is represented through the vertical axis of the associated dendrogram. The connections at higher levels represent combinations of more dissimilar sites.

Classification and Regression Tree analysis

The CART analysis is used to achieve a multivariate classification that makes physical sense with respect to the nine anthropogenic influences. CART is a classification tree that splits all sites into smaller groups based on values at each site. On the other hand, Ward's hierarchical clustering starts with individual sites and combines sites into larger groups. Our goal is to have a high classification tree prediction rate defined by hierarchical clustering. The prediction rate will be used when performing a cross-validation to better understand the classification.

Tukey's honestly significant differences and box and whisker plots

Box and whisker plots are used to observe differences in individual influences and to interpret the classification based on differences between the nine anthropogenic influences. Analysis of variance between all of the groups provides Tukey's honestly significant differences. This provided a heuristic approach for defining the class names.

3. Results

Figure 5 shows the results for the correlation analysis for the eight indicators of disturbance. Pearson Correlations are blue if positive and red if negative. In the upper-right portion of the plot, correlations are represented visually. Narrow and darker colors represented more highly correlated. In the bottom-left portion of the plot, correlation values presented. Figure 6 shows the Non-metric Multidimensional Scaling results. Figure 7 shows the dendrogram of hierarchical clustering with Ward's algorithm. Connections at higher levels represent combinations of more dissimilar sites. Figure 8 shows a plots of the nine indicators of disturbance attribute values in order of hierarchical dendrogram. Figure 9 shows the classification tree using individual channel attributes to achieve the same classification as the hierarchical clustering. Figure 10 shows the box and whisker plots representative of statistical differences between anthropogenic types for each anthropogenic influence.

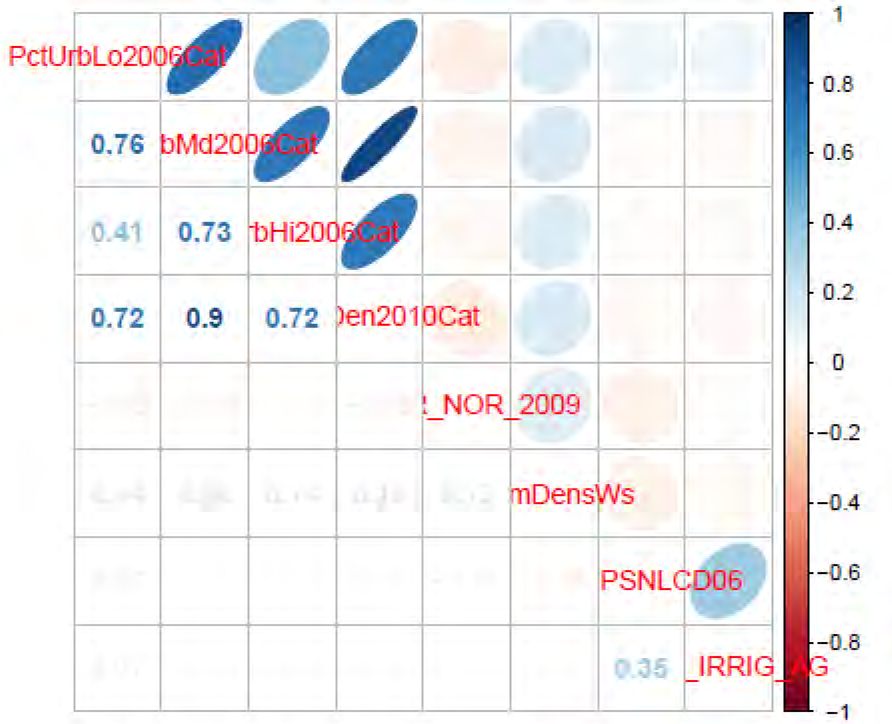

Figure 5. Results of the Correlation Analysis for the nine indicators of disturbance

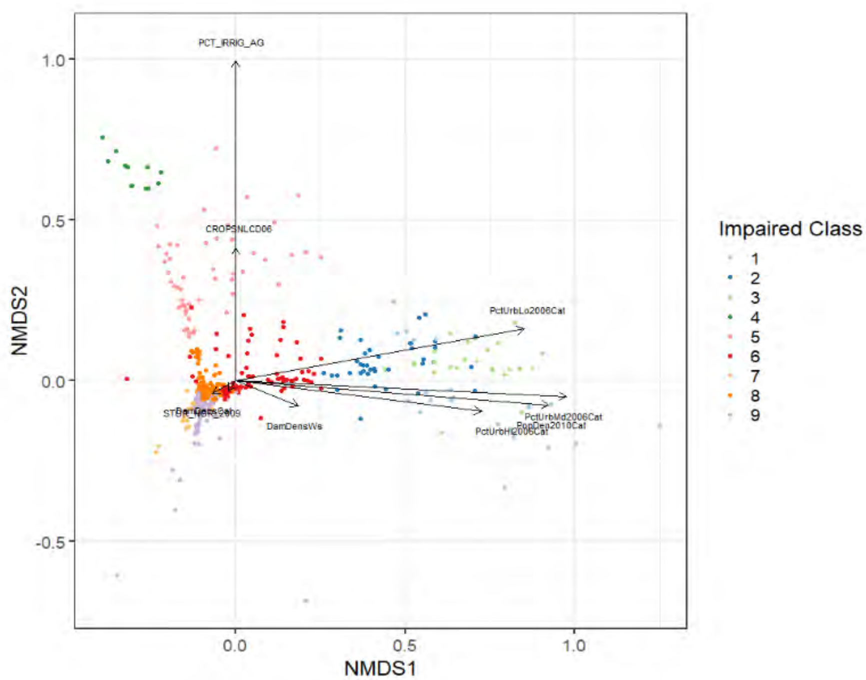

Figure 6: NMDS Plot (Note: Colors defined by final anthropogenic influences)

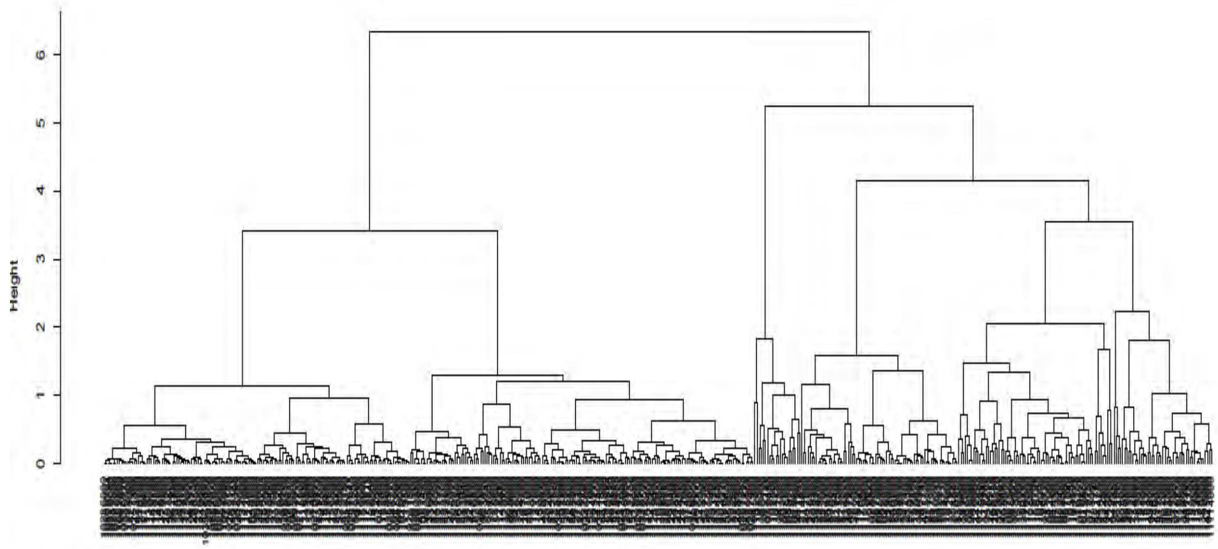

Figure 7: Dendrogram of hierarchical clustering with Ward's algorithm

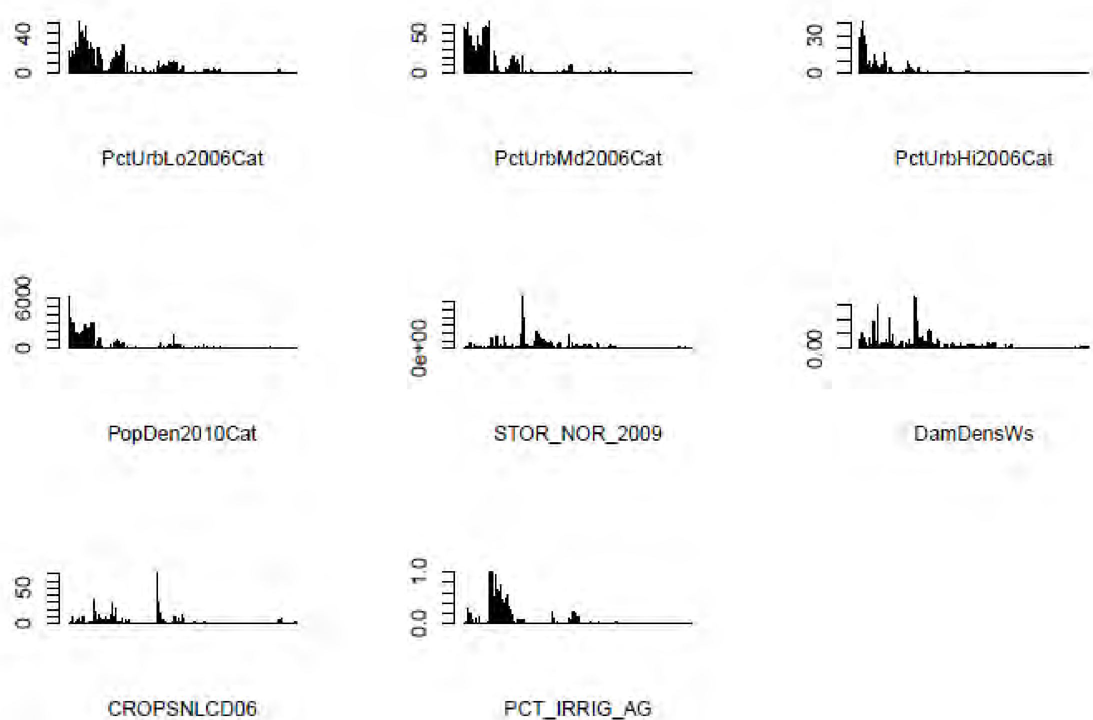

Figure 8: Channel attribute values in order of hierarchical dendrogram.

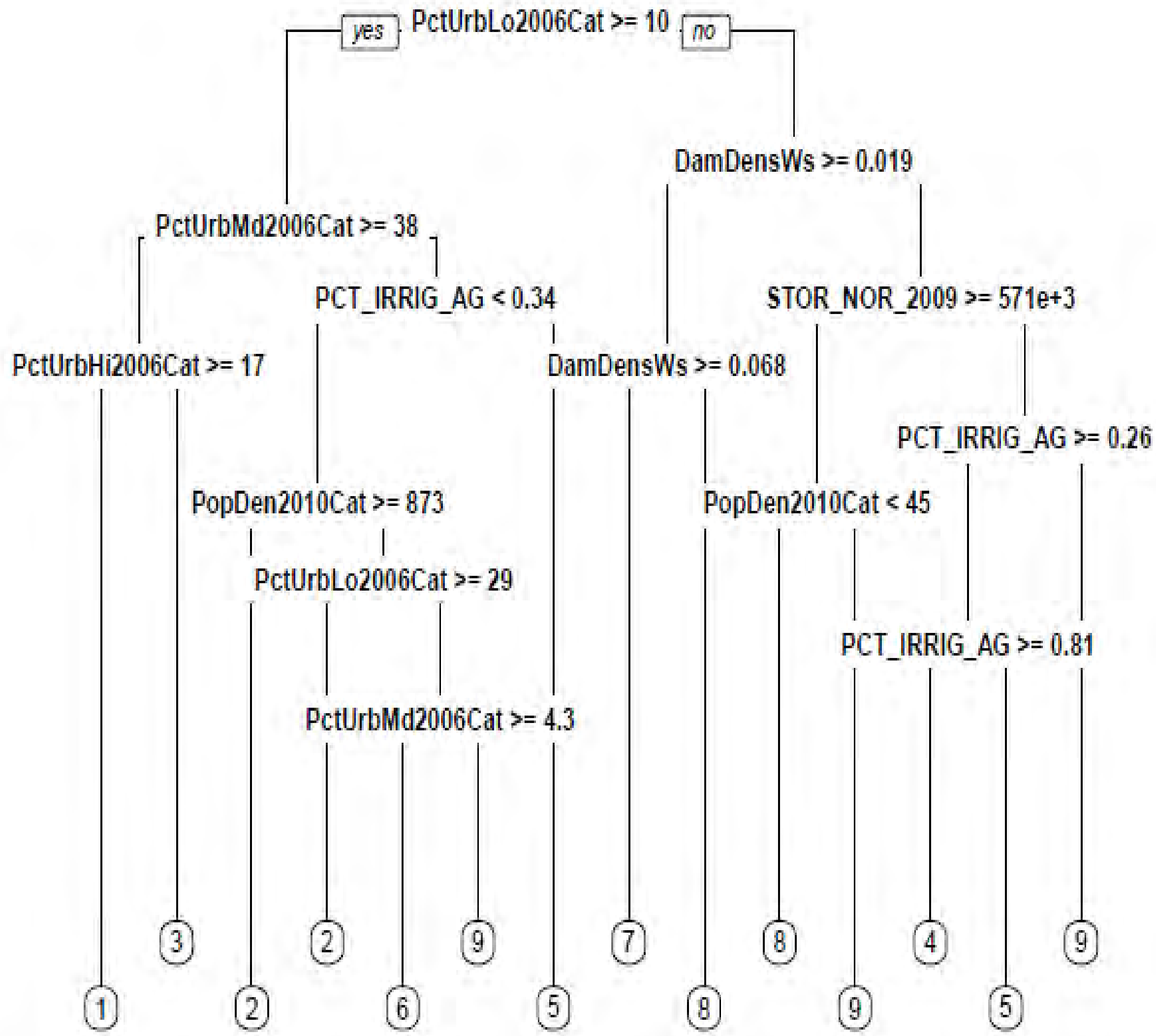

Figure 9: Classification tree for the impaired classes.

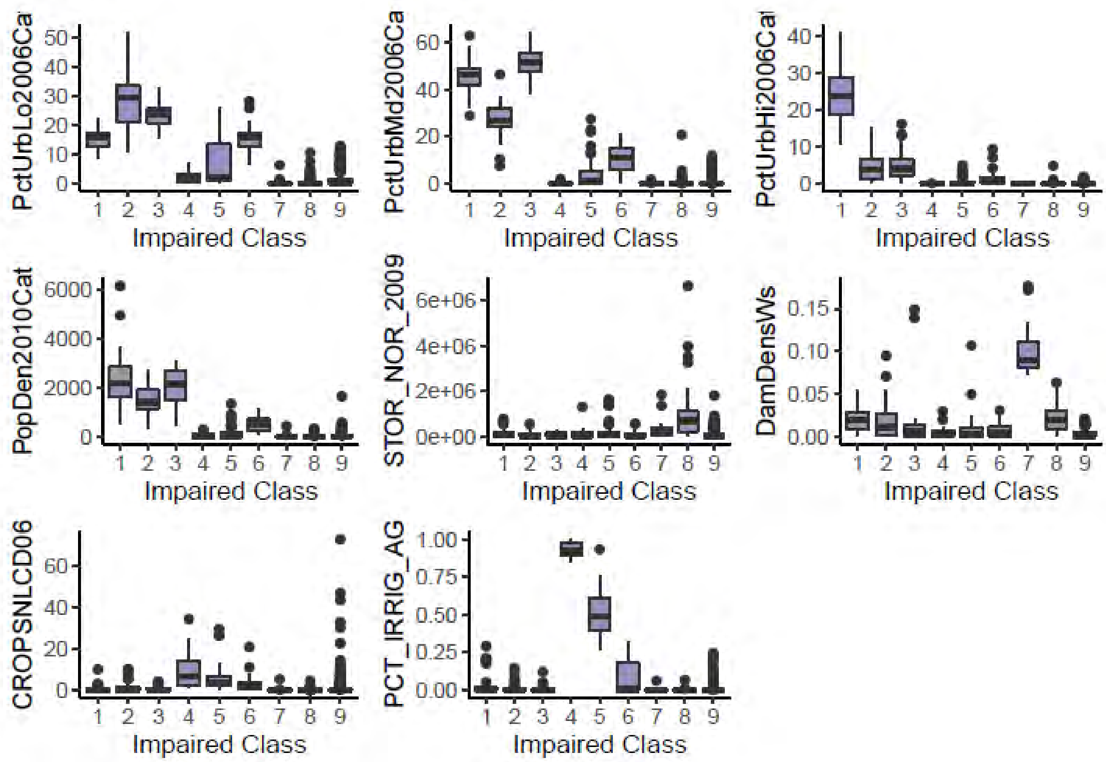

Figure 10: Box and whisker plots representative of statistical differences between anthropogenic types for each anthropogenic influence.

4. Impaired Streamflow Classification

Figure 11 shows the 813 non-reference gages classified into nine impaired flow classes distinguished across California. Table 2 provides a description for each altered class. The class names were determined according to variables identified from the classification tree:

1. Urban High Density (UH). Number of gauge: 25. Relative Frequency: 3%
2. Urban Low Density (UL). Number of gauge: 40. Relative Frequency: 5%
3. Urban Medium Density (UM). Number of gauge: 27. Relative Frequency: 3%
4. Agriculture (High Crop land Use) (AgH). Number of gauge: 12. Relative Frequency: 1%
5. Agriculture (Medium Crop land Use) (AgM). Number of gauge: 53. Relative Frequency: 7%
6. Agriculture (Low Crop land Use) (AgL). Number of gauge: 39. Relative Frequency: 5%
7. Reservoirs (Dam). Number of gauge: 185. Relative Frequency: 23%
8. Forest and Land Use Change. Number of gauge: 185. Relative Frequency: 23%
9. Mixed Low Alteration (Mix). Number of gauge: 247. Relative Frequency: 30%

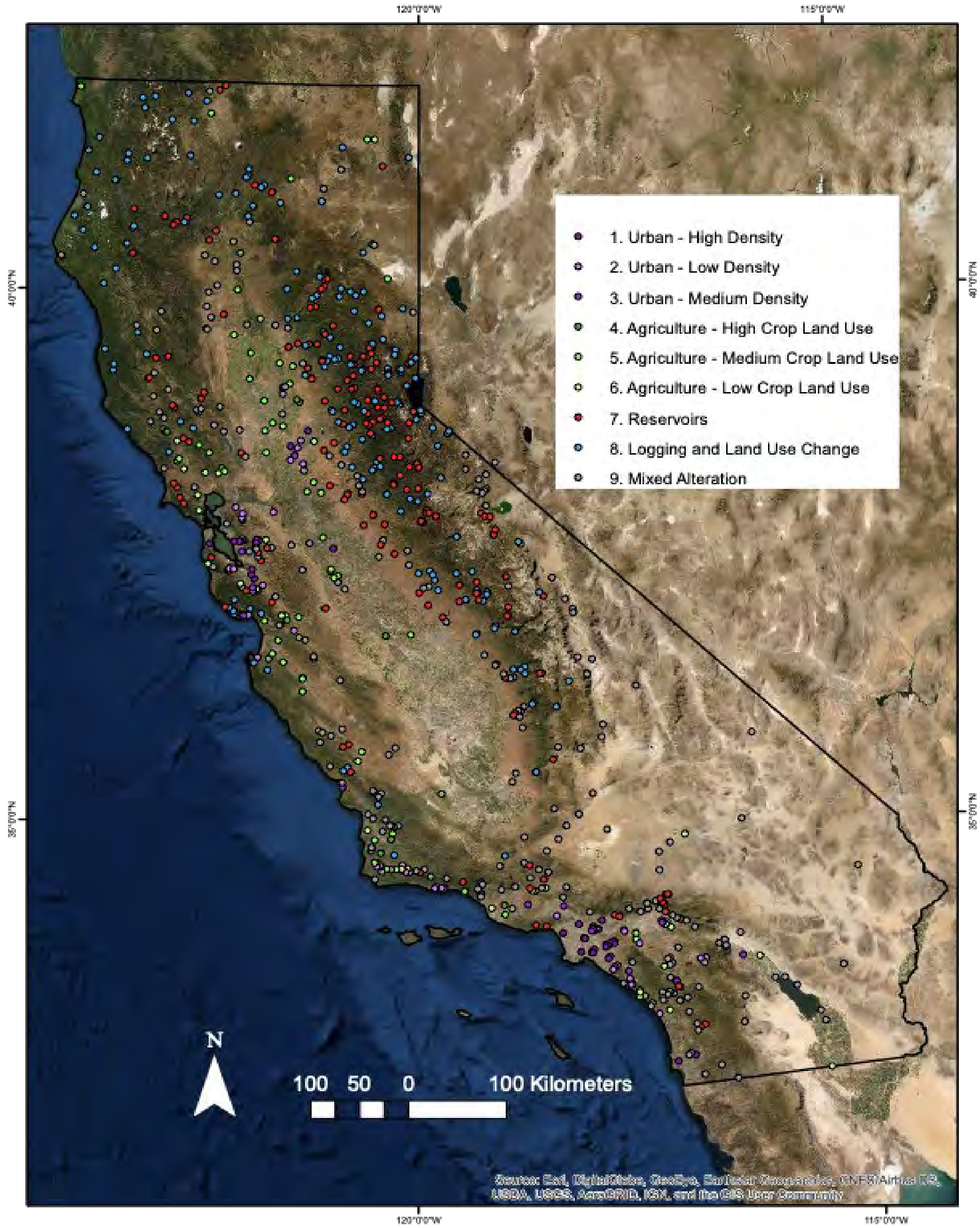

Figure 11: Impaired Streamflow Classification for the State of California

Table 2. Description of the nine altered classes

Classification	Description
1. Urban High Density (UrH)	Gages and river reaches in this class exhibit a high percent of catchment area classified as high-intensity urban land use with high population density. These sites are located in the areas of San Francisco, South Bay, Modesto, Sacramento, Los Angeles, Santa Monica, and San Diego.
2. Urban Low Density (UrL)	Gages and river reaches in this class exhibit a high percent of catchment area classified as low-intensity urban land use with low population density. These sites are located in the areas of Sacramento, Elk Grove, Walnut Creek, Palo Alto, Hollister, Santa Cruz, Monterey, Pomona, Anaheim, Oceanside, and Santa Barbara. This is the most common class related to urban land use.
3. Urban Medium Density (UrM)	Gages and river reaches in this class exhibit a high percent of catchment area classified as medium-intensity urban land use with medium population density. These sites are located in the areas of San Leandro, Santa Cruz, Los Gatos, Hayward, San Bernardino, Palm Desert, Santa Ana, and Morro Bay.
4.Agriculture - High Crop Land Use (AgH)	Gages and river reaches in this class exhibit the highest percent of watershed in cultivated crops and a high percent of watershed in irrigated agriculture. These sites are located in the areas of Santa Maria, Santa Ynez, Santa Clara, Gilroy, San Joaquin Valley, Napa Valley, Santa Rosa, Dry Creek, and Sacramento Valley.
5. Agriculture - Medium Crop Land Use (AgM)	Gages and river reaches in this class exhibit a medium percent of watershed in cultivated crops and medium percent of watershed in irrigated agriculture. These sites are located in the areas of Central Valley, Napa Valley, Dry Creek, Pajaro Valley, Salinas, Santa Maria, Santa Ynes, Smith River Valley, and Santa Clara the Modoc Plateau. This is the most common class related to agriculture.
6. Agriculture - Low Crop Land Use (AgL)	Gages and river reaches in this class exhibit a low percent of watershed in cultivated crops and low percent of watershed in irrigated agriculture. These sites are located in the areas of Russian River, Santa Rosa, Sonoma Valley, Novato, Half Moon Bay, San Clemente, Indio, Oxnard, Santa Clarita, and Salinas.
7. Reservoirs (Dam)	Gages and river reaches in this class exhibit upstream reservoir storage and high density of georeferenced dams within watershed (dams/ square km) based on the National Inventory of Dams. These sites are located in areas of the Sierra

	Nevada foothills called rim dams (Shasta, Oroville, Folsom, New Bullard's Bar, New Melones, Friant dam, Lake McClure, Pine Flat), high elevation hydropower reservoirs in the Sierra Nevada, water supply reservoirs in the Trinity, Klamath, Russian, Eel, Salinas, and Santa Ynez, and small storage reservoirs in Southern California and along the coast of California.
8. Forestland and Land Use Change (FLU)	Gages and river reaches in this class are located in the forestland area of California dominated by trees generally greater than 5 meters tall, and typically with the forest cover greater than 20% of total vegetation. They exhibit land use change and the associated streamflow alteration by : • deforestation, logging and clear cutting due to timber extraction that produces reduction in time of concentration, increase in peak flows, erosion of soil, sediment transport and degradation of water quality, • cattle grazing and stocking that produce beneficial services by reducing understory biomass that prevent devastating fires, however if this activity is not well managed in the riparian corridor and meadows it can produce change in the hydrology, straighten and deepen of channels with the subsequent desiccation of meadows, erosion of channel banks, and degradation of water quality; and • land use change from forest to agriculture for cannabis production that produces similar streamflow alteration to clear cutting with the potential of runoff of pesticides and fertilizers used in high slope agriculture production areas. These sites are located in all national forests in California (Klamath, six rivers, Trinity, Shasta – Trinity, Lassen, Plumas, Tahoe, El Dorado, Stanislaus, Sierra Sequoia, Mendocino, Los Padres, Angeles, San Bernardino, and Cleveland) and the areas close to national forest with high forest density, such as land holdings of timber industry.
9. Mixed Low Alteration (Mix)	Gages and river reaches in this class are located in the Central Valley, California's deserts and dry land areas (Paso Robles and East San Joaquin). In the Central Valley, they are located in the foothills along the perimeter of the Central Valley, in the areas of transition between altered classes, for example from dam alteration in the Sierra Nevada to agriculture in Central Valley, where the main impairment is land-use modification, such as native vegetation to orchards or urban development, or they are located in the catchments of small tributaries, e.g. Antelope, Creek, Battle Creek, Mariposa Creek where similar

	land-use change occurs. This impaired class occurs in the dry land areas of California, namely Paso Robles and the east side San Joaquin basin, where the main impairment is land-use modification from native lands use to agriculture. In addition, this impaired class occurs in California's deserts (Mojave Desert, Death Valley, Owens) where there might be few impairments, but high rates of natural erosion and expansion of urban areas are the main impairment. This is the largest altered class in California.

Figure 12 shows the dimensionless reference hydrographs (DRHs) of the nine impaired streamflow classes. A DRH is a scalable representation of reference hydrology based on streamflow data from unimpaired streamflow gauges in a hydrologic stream class. The y-axis is expressed in dimensionless units by dividing daily streamflows by average daily streamflow for that water year.

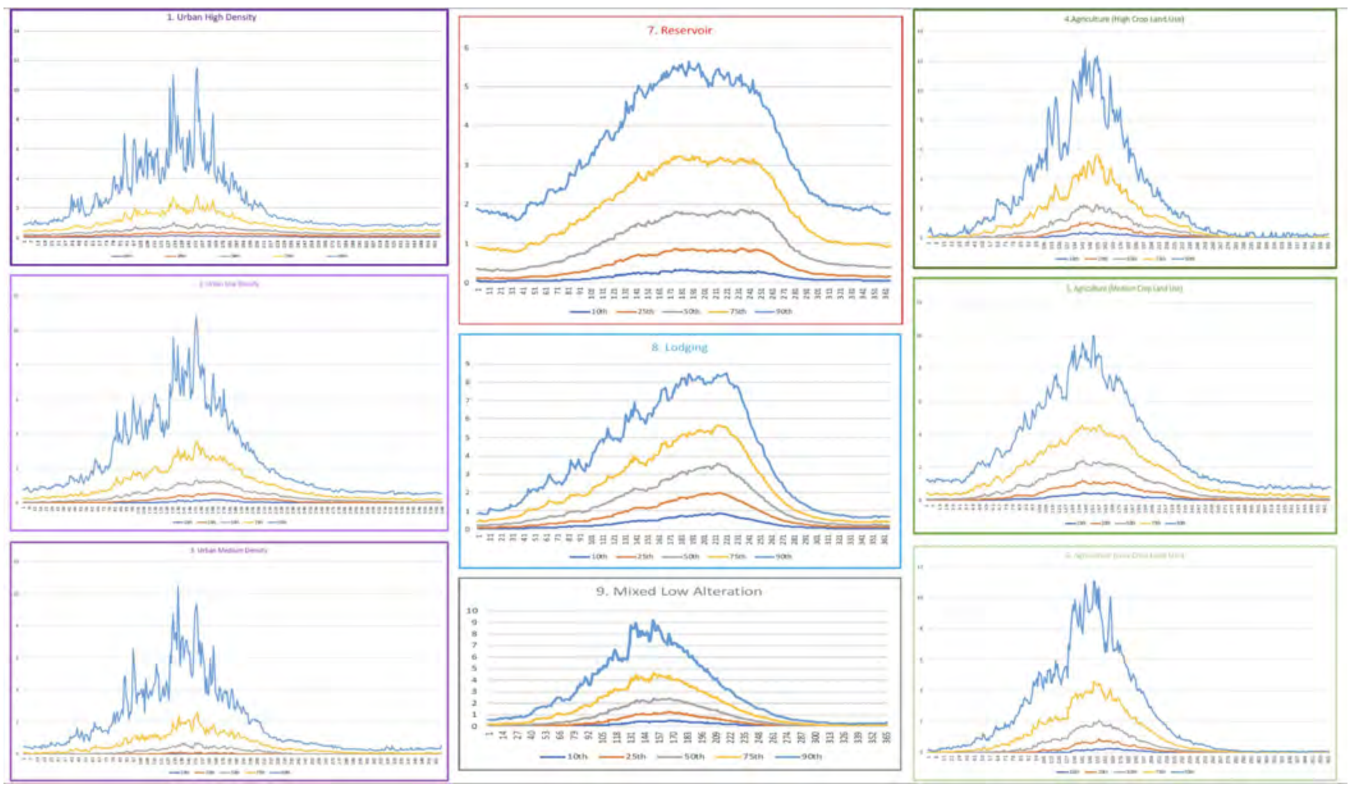

Figure 12: Dimensionless reference hydrographs for the ten Impaired classes

Predictor variables are the parameters used to classify river alteration. The statistical methods used in the previous sections resulted in nine impaired flow classes across California. The eight predictor variables were estimated at every 200-m river reach throughout the entire river network. The nine impaired streamflow classes were predicted in the river network using three machine-learning algorithms: random forest, support vector machine, artificial neural networks (Figure 13). Each model was trained using a ten-fold training data set, meaning the model was trained with 90% of the data end evaluated with the remaining 10% of the data left out. A cross validation technique was used to determine the algorithm that had the best performance, in essence, what was the percentage of the sites left out that were classified correctly.

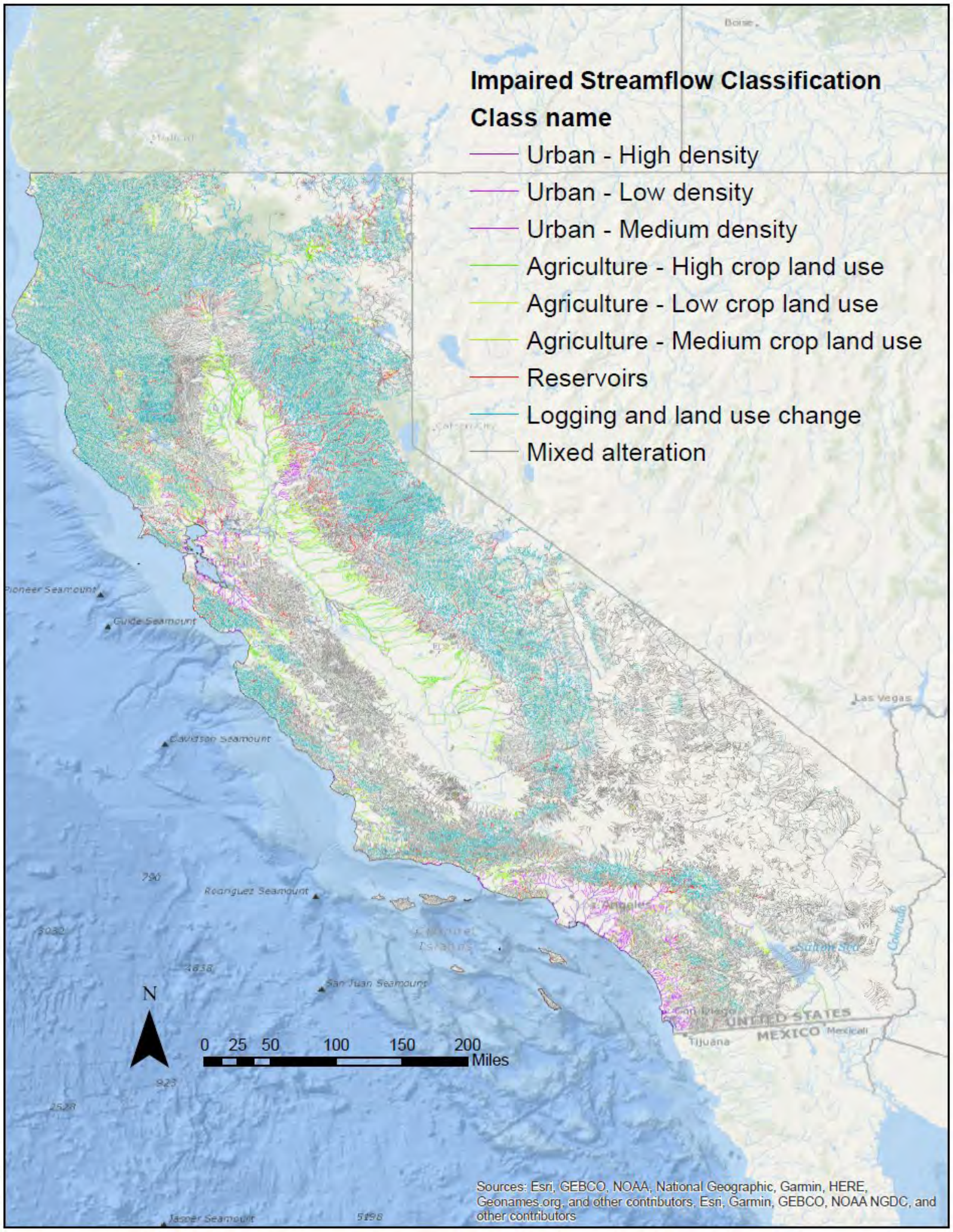

Figure 13. Impaired streamflow classification for the state of California

5. References

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