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Social and Environmental Justice Considerations for Forecast-Informed Reservoir Operations (FIRO) in California

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**Social and Environmental Justice Considerations for Forecast-Informed Reservoir
Operations (FIRO) in California**

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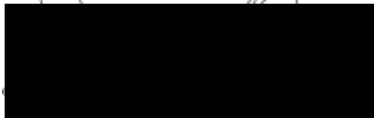
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Abstract

Climate change is causing both increasingly intense precipitation events and droughts, resulting in the need for more efficient water management strategies. Forecast Informed Reservoir Operations (FIRO) is a water management strategy that has the potential to enhance flexibility and efficiency in reservoir management. FIRO uses weather and water forecasts to better inform water management decisions. Previous studies have focused on the technical feasibility of FIRO, but less attention has been paid to the implications of FIRO for social and environmental justice concerns. This study aims to better understand what social and environmental factors may impact flood risk in communities. Four social and environmental justice tools are used, including the Climate and Economic Justice Screening Tool (CEJST), the Social Vulnerability Index (SVI), the EPA's EJScreen, and the California Communities Environmental Health Screening Tool (CalEnviroScreen), and are compared to assess how their results vary in the context of flood vulnerability. The statewide analysis examines the environmental and social vulnerability of 26 reservoirs across California identified as potential FIRO candidates. Downstream structures at each location were intersected with the social and environmental justice screening tools with a focus on indicators related to educational attainment, elderly populations, and proximity to environmental contamination. Lastly, this study investigates the impact of community involvement in water management with a case study in the Yuba-Feather watershed to explore how stakeholder engagement and environmental justice considerations can inform FIRO implementation. Results demonstrate that mapping tools can be used to prioritize FIRO implementation by identifying areas with social and environmental factors that may impact flood vulnerability or resilience. Additionally, there is substantial variation among environmental justice screening tools, with variations most noticeable between the tools used by federal agencies and the state of California. These findings suggest that reliance on a single screening tool may overlook important dimensions of social and environmental vulnerability. The Yuba-Feather case study highlights the importance of community engagement and inclusive decision-making in water management planning. The results indicate that the combination of mapping tools and community involvement can improve understanding of downstream flood risk and support more equitable implementation of FIRO and other climate-resilient water management strategies.

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1. Introduction

Equitable access to safe and affordable drinking water is a fundamental human right. Globally, the demand for water is rising, and water scarcity is predicted to increase with rising temperatures as a result of climate change (*Goal 6*, n.d.). Water has other important uses, including but not limited to sanitation, ecosystem services, hydropower, agriculture, and industry. Climate-resilient water management in the western United States is increasingly critical as we see rising temperatures and more intense extreme weather events. California, the focus of this paper, is a Mediterranean climate characterized by wet winters and warm, dry summers with year-to-year variability in precipitation (Dettinger et al., 2011). In California, in particular, climate change is driving more severe and variable conditions, including prolonged droughts and extreme flooding, highlighting the need for strategic water management. Dettinger et al. (2023) note that while climate models do not agree on whether California's future will be drier or wetter, storms are likely to be clustered and more intense, suggesting that water resource managers should focus on strategies that keep water in the headwaters longer. Water is a vital natural resource, and effective, adaptive management is essential to ensure reliability and resilience in a changing climate.

Forecast-Informed Reservoir Operations (FIRO) is one approach employed to improve the efficiency of water management. FIRO is defined as a “reservoir-operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operation policies and rules with enhanced monitoring and improved weather and water forecasts.” (Delaney et al., 2020, and Jasperse et al., 2020). Typically, reservoirs are managed with a rule curve that establishes a maximum allowable water supply storage capacity based on average seasonal runoff patterns and requires a certain amount of storage availability during flood-prone seasons. Historically, these rule curves are often based on hydrological data from the first half of the twentieth century, do not consider climate change, and do not allow the use of weather and hydrologic forecasts (Delaney et al., 2020). FIRO provides an opportunity for flexibility in reservoir management by using medium-range hydrologic forecasts, which use regional weather and watershed conditions for the prediction of reservoir inflow. This can be used to inform water release and storage decisions in order to maximize water storage without compromising flood risk (Delaney et al., 2020).

The Center for Western Weather and Water Extremes (CW3E) at Scripps Institution of Oceanography, UC San Diego, has begun the process of implementing FIRO in reservoirs across California, including Lake Mendocino in the Russian River Watershed, Prado Dam in the Santa Ana River Watershed, and reservoirs in the Yuba and Feather River watersheds. These pilot locations have shown the viability of FIRO. Lake Mendocino was the first location to update its Water Control Manual to formally integrate FIRO into its water management strategy (USACE, 2026). The third stage of FIRO research and development includes efforts to expand FIRO to dams across the United States with the National FIRO Expansion Pathfinder Effort led by the U.S. Army Corps of Engineers (USACE) and the CW3E (Cordeira et al., 2025). This effort examines the quantitative precipitation forecast (QPF) and streamflow forecast skill from numerical weather prediction and/or operational forecast guidance to evaluate the feasibility of FIRO at reservoirs across the country. Twenty-six reservoirs in California were found to be potential candidates for FIRO. These 26 reservoirs are the focus of this statewide analysis. Additionally, this paper will focus on New Bullards Bar Reservoir on the North Yuba River and Lake Oroville on the Feather River as a combined case study for understanding environmental justice issues related to the FIRO program.

1.1 Purpose and Scope

The implementation of FIRO is promising in its potential to improve flexibility for water managers to maximize water storage, but it is important to consider other effects that this may have on the surrounding areas. Within water resource management projects, emphasis on efficient use often excludes or overlooks equity concerns, which can lead to the exclusion and marginalization of vulnerable communities (Seigerman et al., 2023). Additionally, studies that focus on environmental justice tend to only look at a single metric of equity, overlooking the trade-offs of different measurements of equity (Pollack et al., 2024). The purpose of this paper is to examine the socioeconomic and environmental characteristics that may be relevant for the equitable adoption of water resource management strategies such as FIRO. We evaluate three socioeconomic and environmental factors in relation to flood risk for communities downstream of reservoirs across four differing environmental and social justice tools. This paper asks the questions:

1. What socioeconomic and environmental factors are important to consider when evaluating vulnerability to flooding? What do these factors tell us about social and economic vulnerability downstream of FIRO candidates?
2. How much do differing social justice metrics vary, and how does that affect our understanding of vulnerability for communities in the floodplain?
3. What does the case study of the Yuba-Feather watershed tell us about the potential for equitable implementation of climate-resilient water management strategies such as FIRO?

The remainder of this paper is organized as follows. First, the paper provides background on environmental justice, reservoir management, FIRO, and the Yuba-Feather region. Next, the Data and Methodology section describes the social vulnerability metrics, datasets, and spatial analysis techniques used to evaluate downstream communities and dam locations throughout California, as well as the methodology used for the Yuba-Feather case study. The Results section then presents patterns identified through the statewide analysis, as well as conclusions from environmental justice discussions in the Yuba-feather region. Finally, the discussion and conclusion examine the implications of these findings for the equitable implementation of FIRO, as well as limitations and opportunities for future research.

2. Background

2.1 History of Environmental Justice

The environmental justice movement rose to prominence in the early 1980s, stemming from civil rights activism. A critical event that brought attention to environmental justice was the protests in North Carolina by civil rights activists against the dumping of soil contaminated with polychlorinated biphenyls (PCBs). The state of North Carolina proposed the creation of a landfill for the dumping of this soil in Warren County, which had the highest proportion of African American residents in the state. While the protests did not stop the state from dumping truckloads of soil in Warren County, they prompted research that proved the correlation between toxic waste sites and race in the United States and were pivotal for bringing attention to social impacts that the environmental movement had overlooked (Mohai et al., 2009).

In 1990, the Environmental Protection Agency (EPA) created the Office of Environmental Equity, which was later renamed to the Office of Environmental Justice, and in 1994, President Bill Clinton signed Executive Order 12898, which directed federal agencies to "make achieving environmental justice part of its mission." (Jones, 2024). The EPA defined environmental justice as, "The fair treatment and meaningful involvement of all people regardless of race, color, culture, national origin, income, and educational levels with respect to the development, implementation, and enforcement of protective environmental laws, regulations, and policies." (Jones, 2024). Under the Trump administration, the EPA no longer has this definition on its website and has closed all ten regional environmental justice offices. The state of California has a very similar definition of environmental justice (*Federal Environmental Justice Tracker*, 2025). California law defines environmental justice as "the fair treatment of people of all races, cultures, and income with respect to the development, adoption, implementation, and enforcement of environmental laws, regulations, and policies" (*Environmental Justice Program*, n.d.).

Environmental justice is also connected to flood risk through disproportionate exposure to flood hazards and inequitable access to resources for flood resilience (Xu & Qiang, 2024). This is because previous discriminatory policies, including racial zoning, residential segregation, and redlining, led to disinvestment in low-income and minority communities. Socioeconomic disadvantage reduces resilience to the adverse impacts of flooding. Previous literature has identified relationships between coastal hurricane regimes and their socio-economic disparities (e.g., Elliott & Pais, 2006; Collins et al., 2018; Highfield et al., 2014; Griego et al., 2020), but it is also critical to evaluate socioeconomic factors that may influence other types of flooding, such as inland, infrastructure-driven river systems across the country. This is becoming more prevalent with literature focusing more on inland systems (Wing et al. 2022; Bates et al. 2021; and Islam & Meng, Q. 2024).

2.1.1 The Injustice of Dams

The creation of dams on our waterways has caused harm in a variety of ways, including to local ecosystems and Indigenous peoples. One study in the United States by Randell & Curley (2023) found that approximately 139 dams have flooded 619,000 acres of land on 56 federal

reservations. Dams also have negative impacts on fish populations. The dams on the Klamath River had significant negative effects on fish populations, with a 92% to 98% decline in Chinook salmon populations. The dams not only inhibited salmon spawning but also created warm pools of water that caused fish to die from harmful algae blooms and disease. (U.S. Department of the Interior, 2013). Not only is this important for the ecological impacts, but the salmon population is a critical resource for the Indigenous peoples in the Klamath Basin, including the Yurok, Karuk, Hoopa, and others. Indigenous-led efforts advocating for dam removal on the Klamath River ultimately succeeded in 2024 with the removal of the final of four dams, now allowing for more than 400 miles of unobstructed river. The dams that were removed from the river in California and Oregon included J.C. Boyle, Copco No. 1, Copco No. 2, and Iron Gate, with the main functions of the dams being to produce small amounts of hydroelectric power (*Dam Removal on the Klamath River*, n.d.). This is an example of a successful dam removal project that can serve as a guideline for future dam removal in other areas.

The Truckee River watershed is another region that has struggled with the effects of dams and water diversion. The Truckee River, which flows from Lake Tahoe to Pyramid Lake, historically fed Lake Winnemucca in periods of heavy precipitation, but water diversions now prevent the lake from forming. Water diversions have resulted in an 80-foot drop in water level in Pyramid Lake, changes in water quality, and the decimation of the Cui-ui fish and Lahontan cutthroat trout (LCT) populations (Ghiglieri, 2020). These fish were no longer able to spawn up the Truckee River because of Derby Dam, so the Pyramid Lake Paiute Tribe uses fish hatcheries to maintain the fish population in Pyramid Lake. Derby Dam's primary purpose is to divert water from the Truckee River to supplement Carson River flows and irrigate agriculture (*Truckee Canal History & Significance*, n.d.). In 2020, the construction of a fish screen was completed at Derby Dam to allow LCT to spawn from Pyramid Lake (U.S Department of Interior & Bureau of Reclamation, 2025). This is an example of a location where dam removal could potentially improve local fish populations and the river ecology, but it also highlights the complexity of dam removal, as communities and users receiving water diverted from Derby Dam would likely be adversely impacted.

2.2 Reservoir Management

Within the state of California, there is a complex system of water management ranging from the local to the federal level. At the federal level, the Bureau of Reclamation operates the Central Valley Project, a system of twenty dams and reservoirs that provides flood control and water supply throughout California. The majority of this water goes to irrigation districts in the Central Valley. The Bureau of Reclamation (BOR) owns and operates Lake Shasta, the largest reservoir in California (*Central Valley Project*, 2024). The Army Corps of Engineers is involved in the operation of dams and reservoirs in California that operate for flood control, and they are responsible for Water Control Manuals, which are management documents that specify the operating rules for a dam, when to release water, how much, and under what conditions. The California Department of Water Resources (DWR) is also responsible for water management in California. They operate the State Water Project, which also functions for flood control and to supply water across California, with most of its water supplying urban users such as in the Metropolitan Water District of Los Angeles and Southern California. Lake Oroville is the largest reservoir operated within the State Water Project and is one of the case studies in this paper (*State Water Project*, n.d.). There are also reservoirs that are privately owned and managed by local water agencies. An example of this is New Bullards Bar reservoir and dam, which is owned by Yuba Water Agency, operated under a USACE water control manual, and will be the case study that this paper focuses on.

Traditionally, reservoirs are operated under rule curves, which identify the maximum allowable water supply storage capacity based on average seasonal runoff patterns from available hydrologic information at the time of construction or the most recent update to the guidelines. In some cases, the rule curves can be decades old and do not take into account climatic variations or predicted impacts of climate change. In California, many reservoirs are also managed for the purpose of flood control. In this case, reservoirs will have a reserved flood control space above the water supply pool as defined by the guide curve to capture flood flow and reduce flooding downstream. To account for seasonal availability, the rule curve will require more available space during flood-prone seasons, often at the expense of water storage (Delaney et al., 2020).

2.3 FIRO as a Reservoir Management Strategy

FIRO is an important water management strategy that can enable more flexible management that does not fully depend on fixed rule curves and is able to take future forecasts into account. FIRO can be a more flexible strategy by using weather forecasts to save more water through periods that are expected to have less precipitation, while allowing for excess water release before large forecasted precipitation events, which can reduce flood risk while also allowing for increased water storage for drought periods. The USACE implemented temporary FIRO guidelines for a pilot study at Lake Mendocino for the 2019 and 2020 water years as part of the first phase of FIRO research and development efforts led by USACE and CW3E. The pilot study found that in the 2020 water year, Lake Mendocino retained approximately 19% additional storage using FIRO. The third stage of FIRO research and development includes efforts to expand FIRO to dams across the United States, with the National FIRO Expansion Pathfinder Effort led by the USACE and the CW3E (Cordeira et al., 2025). This effort considers the quantitative precipitation forecast (QPF) and streamflow forecast skill from numerical weather prediction and/or operational forecast guidance to evaluate the feasibility of FIRO at reservoirs across the country. While there are examples of successful water storage, the effectiveness depends on factors such as regional conditions, the accuracy of quantitative precipitation forecast (QPF), the accuracy of streamflow forecasts, forecast lead time, controlled water outlets, Water Control Manuals, and legal or technical barriers (Cordeira et al., 2025)

More flexible water management is one of the main benefits of FIRO but there is also the potential for additional benefits. Some of the social and economic benefits of FIRO identified for the Yuba-Feather watershed include flood risk management, municipal and industrial water supply, agricultural water supply, groundwater recharge, and recreation (Ralph et al., 2025). The potential to increase the reliability of water supply can also help to ensure the potential for clean energy generation through hydropower. Another potential benefit of FIRO is environmental services. The Yuba and Feather watersheds provide critical habitat for salmon, and water releases help maintain river flow and water temperatures. Additionally, the water released for New Bullards Bar and Oroville helps to maintain the health of wetlands in the Sacramento-San Joaquin Delta by helping with the control of salinity intrusion (Ralph et al., 2025). As climate

change intensifies both flood and drought risks, FIRO offers a promising approach to improving water management while maximizing the benefits of existing reservoir infrastructure.

2.4 The Yuba-Feather Watershed

The Yuba-Feather watershed includes the Yuba and Feather Rivers and their tributaries, fed by precipitation and snowpack from the Sierra Nevada Mountains. The Yuba River has three main tributaries, including the North Yuba, Middle Yuba, and South Yuba. The Feather River flows from the northern end of Sierra Valley, with the North Fork, Middle Fork, and South Fork being major tributaries (*Feather River*, n.d.). The Feather River meets the Yuba River near Yuba City and the City of Marysville, as seen in Figure 1. The Yuba River ultimately feeds into the Sacramento River, which flows through Sacramento to the San Francisco Bay Delta. Historically, the Yuba River was settled during the gold rush for gold panning productivity. As this natural resource ran out, the region shifted towards using the river water for agricultural purposes at the turn of the century. The Yuba River has a history of catastrophic flooding. There have been ten major floods since California became a state in 1850, with significant floods in 1950, 1955, 1986, and 1997. The flooding event in 1955 was the result of a series of storms hitting the Sierra Nevada mountains, causing water to rush over New Bullards Bar Dam and flood communities below, leading to the evacuation of 300,000 people and 40 deaths (*The Yuba River Watershed*, n.d.). This major flooding event led to the creation of the Yuba Water Agency. Flooding events in 1986 and 1997 occurred due to levees breaking downstream of the dam.

Figure 1. Map of Butte, Sutter, and Yuba Counties

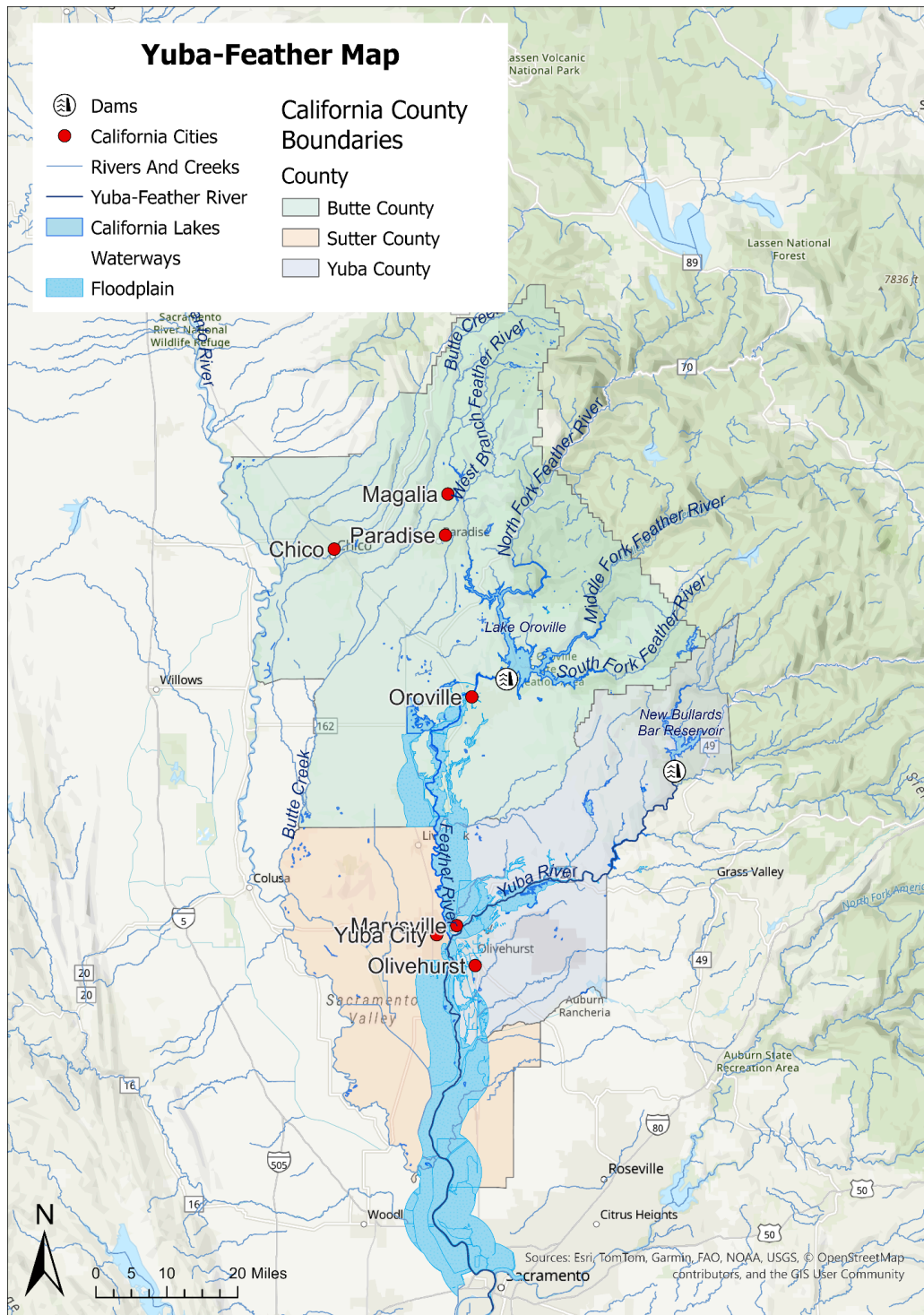


Figure 1: Regional map of Butte County, Sutter County, and Yuba, including cities within those counties. Primary water infrastructure landmarks include Lake Oroville and New Bullards Bar Reservoir alongside their respective dam sites.

More recently, Lake Oroville had a “spillway incident” in February of 2017 during an El Niño year, where the Feather River received an entire year’s average runoff, 4.4 million acre-feet, in 50 days. On February 7th, 2017, officials discovered damage to Oroville's main spillway, which was unable to handle the influx of water from an atmospheric river hitting in the following days. This storm caused Lake Oroville to spill over the emergency spillway, an uncontrolled concrete weir that allows water to pour over onto a bare hillside, for the first time in the dam’s history. This prompted the evacuation of the city of Oroville, including over 180,000 residents (*Cal OES Revisits the Oroville Dam Spillway Incident and Its Impacts Five Years Later* | *Cal OES News*, n.d.). These flooding events have impacted many surrounding communities, including the cities of Linda, Olivehurst, Marysville, Yuba City, and more (*Agency History*, n.d.). It also highlights the importance of levees in this region for protecting communities against flooding.

3. Data and Methods

3.1 Social and Environmental Justice Data

This paper will focus on the data from four social and environmental justice metrics to analyze the characteristics of communities downstream of reservoirs that may impact their flood vulnerability or resilience. The four metrics include three federal tools: the Biden administration White House’s Climate and Economic Justice Screening Tool (CEJST), the Social Vulnerability Index (SVI), and the EPA’s Environmental Justice Screening and Mapping Tool (EJScreen), in addition to a tool specific to the State of California: CalEnviroScreen. This work will analyze the variation between the different tools regarding the indicators they use, their purposes, and their functions.

3.1.1 CalEnviroScreen

CalEnviroScreen is a mapping tool that helps identify communities in California that are affected by several forms of pollution, and where people are often especially vulnerable to pollution’s effects. CalEnviroScreen uses environmental, health, and socioeconomic information

to produce scores for every census tract in the state (a census tract typically contains about 4,000 residents and can vary in size depending on whether it is located in an urban or rural area). The environmental and social justice scores are mapped so that different communities can be compared. An area with a high score is one that experiences a higher pollution burden than areas with low scores. CalEnviroScreen ranks communities based on data that are available from state and federal government sources. Senate Bill 535 required CalEPA to identify "disadvantaged communities" for the investment of proceeds from the state's cap-and-trade program, incentivizing the creation of the mapping tool. The "disadvantaged communities" are areas in the 25% highest scoring census tracts in CalEnviroScreen 4.0, previously identified tracts in the top 25% in CalEnviroScreen 3.0, census tracts with high amounts of pollution and low populations, and federally recognized tribal areas as identified by the Census in the 2021 American Indian Areas Related National Geodatabase (*California Climate Investments to Benefit Disadvantaged Communities*, n.d.). The tool has 21 indicators, which are separated into four main categories: exposure indicators, environmental effects indicators, sensitive population indicators, and socioeconomic factor indicators (OEHHA, 2021).

3.1.2 Climate and Economic Justice Screening Tool

CEJST was created under Section 222 of Executive Order 14008, signed by President Biden in January 2021. It was designed to allow federal agencies to identify disadvantaged communities that are underserved and overburdened by pollution. It was used for the Justice40 initiative, which sought to deliver 40% of overall benefits from federal investments in climate and clean energy to disadvantaged communities. The tool was developed by the Council on Environmental Quality (CEQ) and uses data at the census tract level (Lea, 2023). The tool is binary, meaning it identifies if a census tract is disadvantaged or not disadvantaged based on the criteria.

The tool features eight categories, including climate change, energy, health, housing, legacy pollution, transportation, water and wastewater, and workforce development. Under these categories, there are 18 indicators. Communities are considered disadvantaged if they meet 90th percentile thresholds for any of the 18 indicators and are "in the 65th percentile or above for the number of households with income less than twice the federal poverty level." (Lea, 2023).

Furthermore, all communities that are within Federally Recognized Tribes are classified as disadvantaged, as are all communities that are “completely surrounded by other disadvantaged communities and are at or above the 50th percentile for low-income as disadvantaged communities.”(Lea, 2023). CEJST requires a tract to be above the 50th percentile of individuals below 200% of the Federal Poverty Line to qualify as “disadvantaged” rather than using the area median household income (AMI) as its measure of poverty (Lea, 2023).

3.1.3 Environmental Protection Agency EJScreen

The development of EJScreen began in late 2010, and EPA staff began using an early version in 2012. EJScreen provides standard reports that bring together environmental and demographic data in the form of indices, which are summarized as percentiles to put the information in perspective and facilitate comparisons between locations (US EPA, 2014). This tool combines environmental and demographic indicators in maps and reports. This information can be used to help highlight geographic areas and the extent to which they may be candidates for further review, including additional consideration, analysis, or outreach (*EJScreen Technical Documentation for Version 2.3*, 2024).

According to the EPA in 2015 under the Obama administration, EJScreen is a pre-decisional screening tool, and was not designed to be the basis for agency decisionmaking or determinations regarding the existence or absence of environmental justice concerns. Instead, EJScreen is designed as a starting point to highlight the extent to which certain locations may be candidates for further review or outreach. EJScreen’s initial results should be supplemented with additional information and local knowledge whenever appropriate, for a more complete picture of a location. Additional considerations and data, such as national, regional, or local information and concerns, along with appropriate analysis, should form the basis for any decisions. (EJScreen Environmental Justice Mapping and Screening Tool Technical Documentation, 2015)

EJScreen contains 12 environmental indicators, which range from estimates of human health risk to proxies for potential exposure such as proximity to hazardous waste sites. The tool also contains six demographic indicators, which are combined into two separate demographic indices. A demographic index is combined with an environmental indicator to create an associated EJ Index. A percentile in EJScreen shows roughly what percent of the US population

lives in a block group that has a lower value (or in some cases, a tied value). This means that 100 minus the percentile tells us roughly what percent of the US population has a higher value (*EJScreen Technical Documentation for Version 2.3*, 2024).

3.1.4 Social Vulnerability Index

The Social Vulnerability Index (SVI or SoVI) is a mapping tool developed by the Centers for Disease Control (CDC) for the management of natural disasters. The purpose of the tool is to “help public health officials and local planners better prepare for and respond to emergency events to decrease human suffering, economic loss, and health inequities”(CDC, 2024). A group of social scientists, geographers, and a statistician within the Geospatial Research, Analysis, and Services Program (GRASP) began developing the Social Vulnerability Index in 2007, with the first database being released in 2011(Flanagan et al., 2011). The current version of the CDC Social Vulnerability Index uses 16 U.S. Census Variables from the 5-year American Community Survey to identify communities that may need support before, during, and after natural disasters. The variables are sorted into four themes of social vulnerability and combined into an overall score of social vulnerability (CDC, 2024).

3.2 Key Indicators

This paper focuses on three indicators that are included across each environmental justice screening tool analyzed in the study. Although each tool combines multiple variables to calculate an overall vulnerability or environmental justice score, this analysis examines individual indicators in order to compare patterns across datasets. Each tool includes a combination of indicators to calculate an overall score specific to the tool. This paper uses the data from the indicators within each tool to compare them. The indicators selected for analysis are educational attainment, the percentage of adults aged 65 and older, and proximity to environmental contamination (see Table 1). These are based on prior research findings that communities that are typically highly vulnerable to flood hazard include low-income communities, minorities, the elderly, children, people with disabilities, and lower education levels (Islam & Meng, 2024; Rhoades et al., 2018; and Muttarak & Lutz, 2014). Additionally, extensive analyses have shown

that environmental disparities and environmental hazards are based on race, income, or both (Mohai et al., 2009). Together, this literature helped inform the selection of indicators used in this analysis.

3.2.1 Adults aged 65 and older

The number of adults aged 65 and older was chosen as a key metric because adults over 65 are potentially more vulnerable to the impacts of flooding and less resilient after a flooding event. Elderly people often require assistance with flood evacuation, making them more vulnerable. They may also be more susceptible to injury in flooding events and take longer to recover from injuries. The elderly may also be reliant on electricity for medical devices that could be compromised in the event of a flood, causing power loss (Rhoades et al., 2018).

3.2.2 Education Level

Education level was chosen as a key metric because previous studies have found that education level is correlated with flood vulnerability. Islam and Meng (2024) identified lower educational attainment as one factor that significantly impacts flood vulnerability in Birmingham, Alabama, and Jackson, Mississippi. Because lower educational attainment may negatively impact one's income and socioeconomic status, it may signify that people have fewer financial resources for proactive or retroactive measures that would increase flood resilience (Torpey, 2018). Highly educated people are reported to have both better preparedness and response to disasters, along with the ability to recover faster (Muttarak & Lutz, 2014).

3.2.3 Proximity to Environmental Contamination

Proximity to environmental contamination is a key metric because it may be important to consider the impacts of flooding events on water quality in areas within proximity to environmental contamination. The spread of environmental contaminants from a flood could lead to adverse health impacts that have long-term effects on communities in these areas. A study by Erickson et al. (2019) notes that water from hydroclimatic events such as flash floods can be

mixed with chemical spills, heavy metals, biotoxins, invasive species, sewage, and debris that contaminate fresh water supplies. If these contaminants get into drinking water, they can cause adverse human health impacts. Identifying communities in floodplains with environmental contaminants is important for understanding how toxic waste sites may play a role in flood vulnerability and human health.

3.3 Statewide Analysis Methodology

The statewide analysis portion of this paper considers 26 reservoirs across California that have been identified to meet the criteria for successful FIRO implementation with “standard barriers” in the National FIRO Expansion Pathfinder Effort. In order to analyze the potential vulnerability of the populations downstream of these reservoirs, the following two methods were used by the Center for Western Weather and Water Extremes (CW3E) to calculate the number of structures in the downstream floodplain that are used in this analysis. The first method uses National Hydrography Dataset flowline features from the NHDPlus geodatabase to create a starting and ending river reach for each dam’s location. ReachCode is used to construct the downstream trace. This downstream trace is clipped to an extent of 100km downstream and buffered to 5 km to delineate the area of potential flood exposure. The ArcPy MultipartToSinglepart tool is applied to ensure the buffered trace is a single polygon, which is then intersected with the 100-year and 500-year flood hazard layers from the FEMA National Flood Hazard Layer (NFHL). This trace is then intersected with the USACE National Structure Inventory (NSI) to calculate the number of structures within the 100-year and 500-year floodplains. The second method uses ArcPy functionality, the TraceDownstream, to identify the flowpath. This flowpath is clipped to 100km downstream and buffered to 5km. Similar to the previous procedure, this is intersected with the NFHL 100-year and 500-year flood hazard layers and subsequently intersected with the NSI dataset. The resulting layers of structures in the downstream floodplain are then intersected to create a union of structures downstream. This analysis focuses on the 100-year flood hazard layer, but future research could expand to include both the 100 and 500-year flood hazard layers to incorporate a broader range of flooding scenarios. This union layer for the 100-year flood hazard is intersected with the four social and environmental justice tools.

The data from the social and environmental justice tools that are used are in the form of a percentile. The percentile data from the social and environmental justice tools are intersected with the downstream structure layer. The number of structures and the percent of structures above a set percentile threshold are calculated and mapped in ArcGIS for the visual identification of the prevalence of socioeconomic factors that may impact the flood risk of downstream communities. The percentile chosen for this analysis was the 75th percentile because this is the threshold that is used by the California EPA to identify disadvantaged communities for investment funding under Senate Bill 535. This data is visually represented with the color of each dam location representing the percentage of structures above the 75th percentile, and the size of the circle representing how many structures are in the floodplain downstream of the reservoir. The percent of structures above the threshold is split into twenty percent increments, with each increment assigned a color ranging from green (0 to 20% of structures above the 75th percentile) to red (80 to 100% of structures above the 75th percentile).

3.4 Case Study Methodology

This paper also provides a more in-depth, focused analysis specific to the Yuba-Feather Watershed. This includes New Bullards Bar Dam and Reservoir and Lake Oroville and the Oroville Dam on the Yuba and Feather rivers, respectively. Part of the statewide analysis was the creation of maps that depict the Feather River, the Yuba River, Lake Oroville, Oroville Dam, New Bullards Bar Reservoir and Dam, the downstream floodplain from the dams, cities in the region, including Oroville, Marysville, Yuba City, and the relevant counties, which include Butte County, Sutter County, and Yuba County (figure 1).

A second step in the mapping portion of the case study of this region was the creation of smaller-scale maps from the same data used in the statewide analysis. These maps were created with metrics that assess the combined social and environmental vulnerability identified across the themes within each tool. CEJST, EJScreen, and SVI all used a form of the total number of flags identified within the block group or census tract. That data is intersected with the structures that are in the downstream floodplain of Lake Oroville and New Bullards Bar. CalEnviroScreen data is presented as overall census tract percentiles based on the tool's evaluation criteria. The percentiles are further grouped into deciles, which categorize the data into ten-percent ranges.

This includes creating a map depicting disadvantaged communities and severely disadvantaged communities in Yuba County, Sutter County, and Butte County, and an identification of how water from the Yuba-Feather watershed gets from the headwaters to consumers. This entailed identifying who manages and receives water from New Bullards Bar reservoir on the Yuba River. This process was repeated with Lake Oroville on the Feather River. This was drafted in Canva to connect relevant entities with pipes and arrows to indicate the flow of water. The snowpack is included because it is a critical water source for the Yuba-Feather watershed.

A second aspect of the analysis considers community participation in an Environmental Justice and FIRO workshop in the region. This focuses on the key takeaways from the workshop held in Marysville, California, led by Dr. Tom Corringham and Sarah Ogle at CW3E and the Socioenvironmental and Education Network (SEEN), a water justice nonprofit operating in the Central Valley. The workshop was held in January of 2025 and had six community members present, along with representation from Yuba Water Agency, SEEN, and CW3E. This focuses on the main takeaway from this workshop, that “Community members have expressed the need for clearer information on how water management decisions are made”.

4. Results

4.1 Statewide Analysis

Several consistent observations emerged from comparing maps across social justice tools for similar data categories. The federal social justice tools were more similar to each other than to CalEnviroScreen, the state of California tool. Also, despite the federal tools being more similar to each other, the current versions of each tool often yielded different results for at least a few dams, despite using the same data source. This was due to differences in time frames or scales used by different tools. The differences between the state of California tools and the federal tools were more pronounced because CalEnviroScreen frequently uses different baseline data for the tool, including data collected by California state agencies rather than federal agencies. This was compounded by differences in the timeframe of the data used, as well as by the methods used for calculating the data, such as how it was weighted. These differences among social justice tools are important to take into account when using these tools to understand the

socioeconomic characteristics of communities in the downstream floodplain of reservoirs and how that may impact flood resilience.

4.1.1 People Aged 65+

Both SVI and EJScreen include percentile categories for people aged 65 and older. The maps from these data were similar, with a majority of the dams having under 20% of the structures downstream located in census tracts that are above the 75th percentile threshold (Figure 2). Three dams stood out in the maps with higher percentages of downstream structures above the threshold. These included Shasta Dam, Coyote Valley Dam, and Warm Springs Dam, with the first having 40-60% above the threshold in both maps, and Warm Springs Dam having the highest percentage above the threshold. The maps show different percentages for Warm Spring Dam, with the SVI map showing it in the 60 to 80% range, while EJScreen shows it in the 80-100% range. All three of these locations with higher percentages also have relatively few structures in the downstream trace. In Figure 1, the dam locations with higher percentages of structures above the 75th percentile are also shown as small circles. This suggests that if these areas were to flood, there would be fewer structures impacted, but the populations living in this area may have a more difficult time evacuating and recovering from a flood event.

Figure 2. Age 65 and Over Statewide Analysis Map

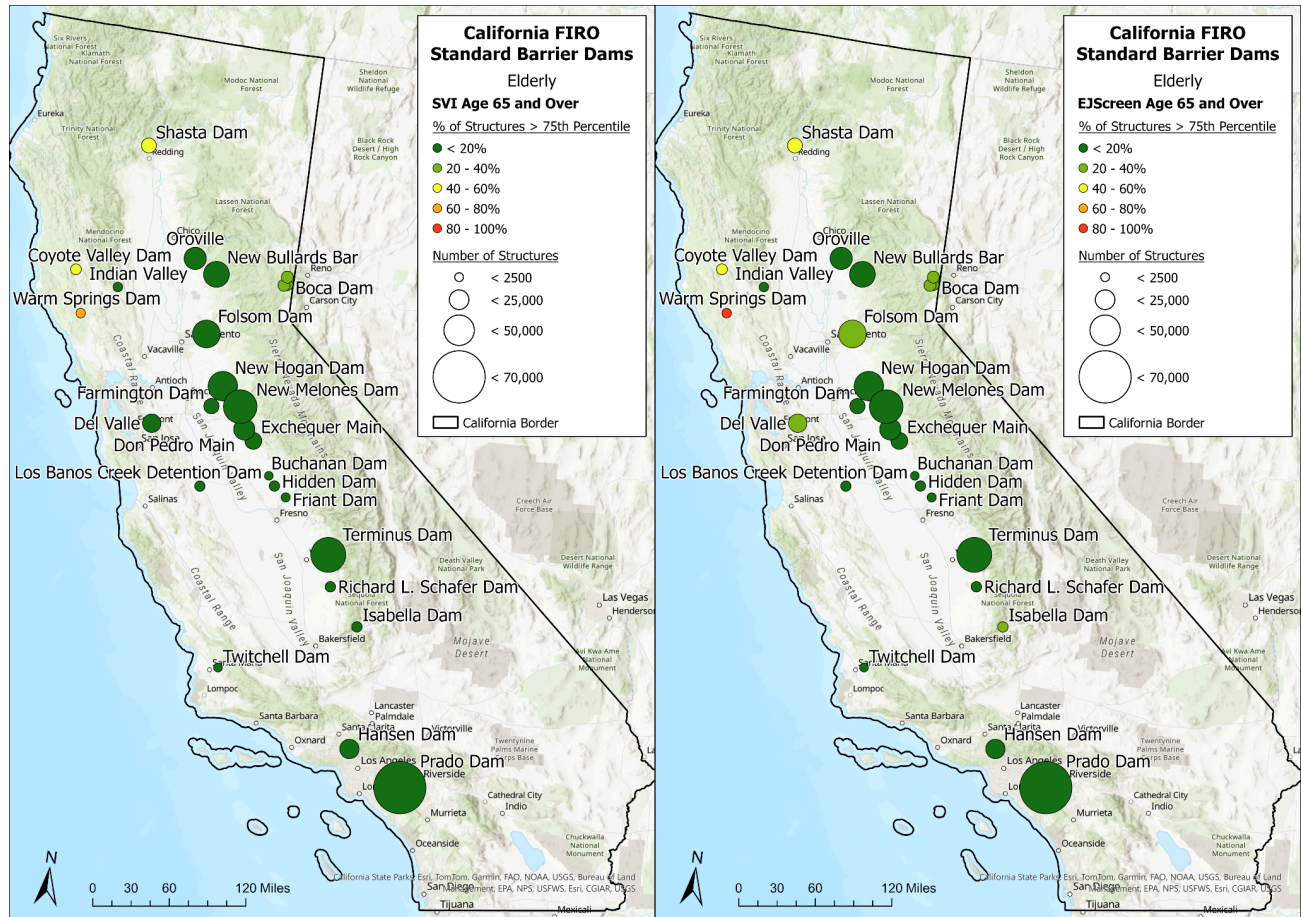


Figure 2: Depicts the percent of structures above the 75th percentile threshold for people aged 65 and older for the tools SVI and EJScreen.

Both the SVI and EJScreen are federal tools, but they have some differences in the maps generated from their data when comparing the “elderly” attribute (Figure 2). The SVI has more locations that are in the under 20% category and has no dams in the 80-100% above the threshold range. Folsom Dam, Del Valle, and Isabella Dam are in the under 20% category in SVI but are in the 20-40% category in the EJ Screen map, highlighting some differences between the tools. Both of the education metrics in these tools calculate the percentile of people 65 and older from the U.S. Census Bureau American Community Survey (ACS) data, so it is unclear why there are differences in the map results.

4.1.2 Less Than High School Education

The social justice metrics compared for Education level are SVI, EJScreen, and CalEnviroScreen (Figure 3). All three of these metrics have a percentile score for the population of adults aged 25 and older without a high school diploma, which specifically focuses on the population that is not graduating from high school. Across all three maps, dams in the Central Valley, specifically Richard L. Schafer Dam, Friant Dam, Hidden Dam, and Buchanan Dam, have higher percentages of the population above the 75th percentile threshold. All of these dams have over 60% of the downstream structures above the percentile threshold across all three social justice metrics, with Twitchell Dam, Richard L Schafer, Friant, and Buchanan having 80% or more of the population above the threshold in two out of the three metrics. Hidden Dam is the only location to have 80% or more above the threshold in all three social justice metrics. The dams in the southern Central Valley also have smaller numbers of downstream structures. Prado and Hansen Dam also have notable results. Prado Dam has the highest number of downstream structures out of all the locations, with over 68,000 structures in the downstream floodplain, and has over 60% of downstream structures above the 75th percentile in two out of the three metrics. Hansen Dam also has over 60% of downstream structures above the 75th percentile in two out of the three metrics and over 80% in SVI. The number of structures is not as large as the Prado Dam, but there are still approximately 25,000 structures downstream, making it stand out in terms of size and education.

Figure 3. Less Than High School Education Statewide Analysis Map

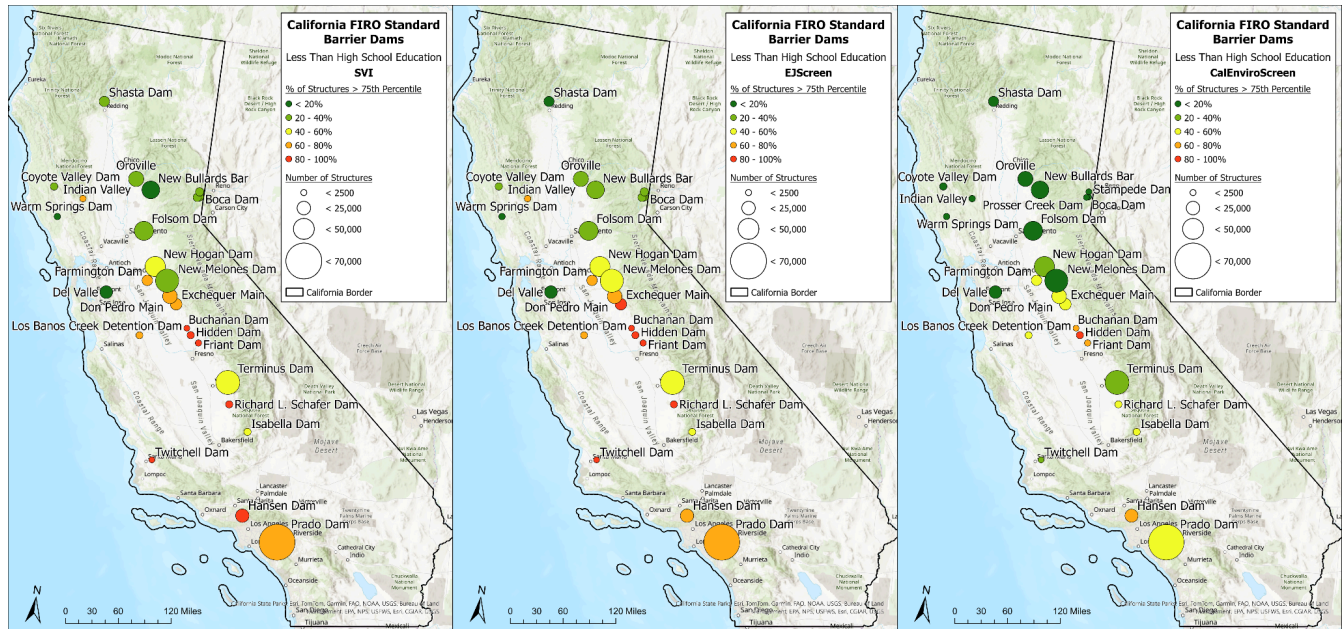


Figure 3: Depicts the percent of structures above the 75th percentile threshold for people aged 65 and older. This map includes SVI, EJScreen, and CalEnviroScreen.

Across the three social justice tools, the tools created by the federal government are more similar to each other than CalEnviroScreen, but are not exactly the same. The differences between EJScreen and SVI are within one category. For example, Hansen Dam is above 80% in SVI and in the 60-80% category in EJScreen. The CalEnviroScreen metric had greater differences compared to the other two metrics. For example, Twitchell Dam is above 80% in both SVI and EJScreen, but is in the 20-40% category in CalEnviroScreen. CalEnviroScreen has generally lower percentages across all of the dams, with only one over 80%, and 3 more with over 60%, with the rest below that. Additionally, some dams fall into different categories in all three maps, including Don Pedro Main Dam and New Melones Dam. New Melones Dam has a comparatively higher number of downstream structures than other dams, and so such differences between tools highlight uncertainty between tools that may be critical to work out in order to better understand the reality of education level downstream and its impact on flood resilience in downstream communities. Despite the differences in results, there are a few locations that are consistent across all three maps, including Warm Springs Dam, Del Valle Dam, and Isabella Dam.

4.1.3 Proximity to Contaminants

The social justice metrics that had data on environmental contaminants include CalEnviroScreen, CEJST, and EJScreen. Of these metrics, all had multiple categories related to different types of contamination. The maps of contaminants are split into three categories: hazardous waste, Cleanup Sites, and Water Contamination. Figure 3 shows the statewide analysis maps for Hazardous waste site proximity. There was no clear trend for hazardous waste site proximity across all three maps, but there was a clearer consensus between the two federal metrics, CEJST and EJScreen. The only dam to have 60% or more of the downstream structures above the 75th percentile across all three metrics is Hansen Dam. In terms of proximity to hazardous waste sites, Prado Dam, Hansen Dam, and Del Valle Dam stand out for EJScreen, and CEJST, and Prosser Creek Dam and Boca Dam stand out in CalEnviroScreen. In terms of both percent and number of structures, Prado Dam stands out the most among other large dams. Folsom Dam, New Hogan Dam, and New Bullards Bar Dam also stand out despite having lower percentages and fewer structures than Prado Dam.

Figure 4. Hazardous Waste Proximity Statewide Analysis Map

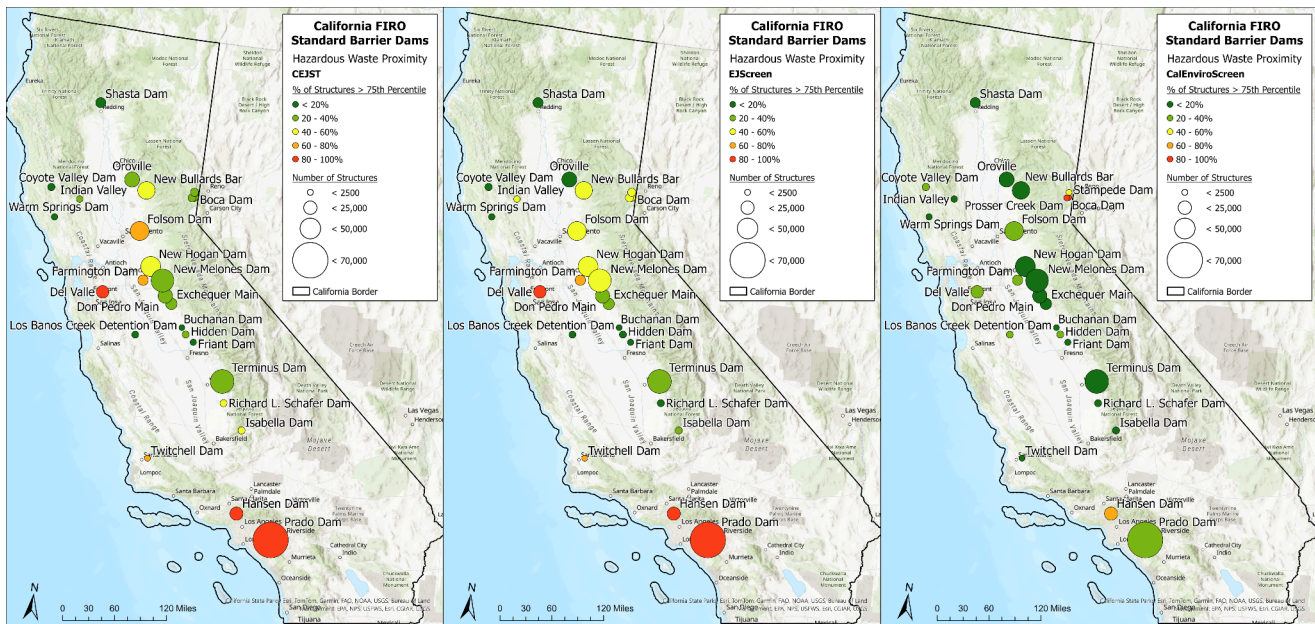


Figure 4: Depicts the number of downstream structures and the percent of structures above the 75th percentile for hazardous waste site proximity.

Across all three social justice tools, there are differences between them, similar to the previous maps. The differences between CalEnviroScreen and federal tools are significant for Prado Dam because of the high number of downstream structures, as well as the large variation in the results for the percent of downstream structures above the 75th percentile.

CalEnviroScreen overall has lower percentages above the threshold than other maps, except for dams on the Truckee River, which include Stampede, Boca, and Prosser Creek dams. While the two federal tools were more similar, they again did have some key differences, such as Richard L. Schafer dam, with over 40% of structures above the threshold in CEJST and less than 20% of structures above the threshold in EJScreen.

4.1.4 Cleanup Sites

The social justice metrics with categories for cleanup sites are EJScreen, CEJST, and CalEnviroScreen. Both CEJST and EJScreen use National Priority List (Superfund Sites) data from the Superfund Enterprise Management System (SEMS) database managed by the US EPA. CalEnviroScreen uses the California Department of Toxic Substances Control (DTSC) EnviroStor database. CalEnviroScreen cleanup site data is also weighted by site status, while the other two are not weighted and use a binary variable, which may impact differences in dam locations between the state and federal tools. The dams that stand out in Figure 5 are Farmington Dam, with over 80% of structures above the 75th percentile threshold in CEJST and EJScreen, and Hansen Dam, being in the 60-80% range in the same maps. In the CalEnviroScreen map, most of the dam locations have less than 20% of the structures downstream above the threshold. Terminus Dam had the highest percentage above the threshold in the 40-60% range, and every other dam had less than 40% of structures above the threshold.

Figure 5. Cleanup Sites Statewide Analysis Map

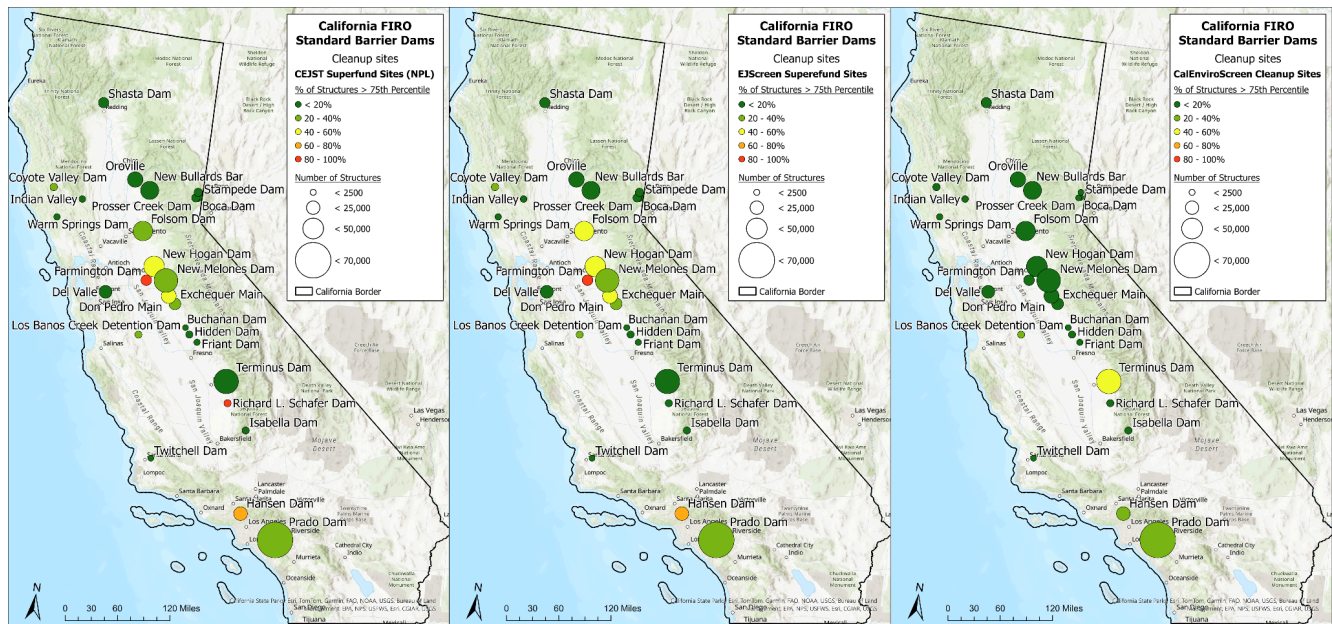


Figure 5: Depicts the percent of structures above the 75th percentile threshold for cleanup site proximity.

In Figure 5, the CEJST and EJScreen maps have the most similarities out of the three. The CEJST and EJScreen maps are almost completely identical except for two dam locations: Folsom Dam and Richard L. Schafer Dam. Folsom Dam is in the 40-60% category in EJScreen, while in the 20-40% category in CEJST. On the other hand, Richard L. Schafer goes from being below 20% above the threshold in EJScreen to being above 80%, which is a pretty stark difference since they are using the same dataset.

4.1.5 Water Contamination

Figures 6 and 7 show four different categories of water contamination mapped. EJScreen and CEJST both had a category on wastewater discharge, which is included, but CalEnviroScreen did not have that exact category. The key metrics used from CalEnviroScreen are water contaminants and impaired water bodies. These results are compared with each other and compared with the key metric of wastewater discharge used in federal tools. The water contamination metrics had clear variations in the maps across all of the social justice tools, with differences especially noticeable between the federal tools and the CalEnviro Screen. The dams

that stood out from the EJScreen and CEJST Wastewater Discharge maps were Hansen Dam, Terminus Dam, and Prado Dam. Despite there being more similarities between these two metrics, there were significant differences at some dam locations that may require further research to identify the cause of the differences. For example, Richard L Chasfer dam is in the 60-80% above the percentile threshold category in EJ Screen but is in the below 20% category in CEJST, which is a noticeable difference.

Figure 6. CalEnviroScreen Water Contamination Maps

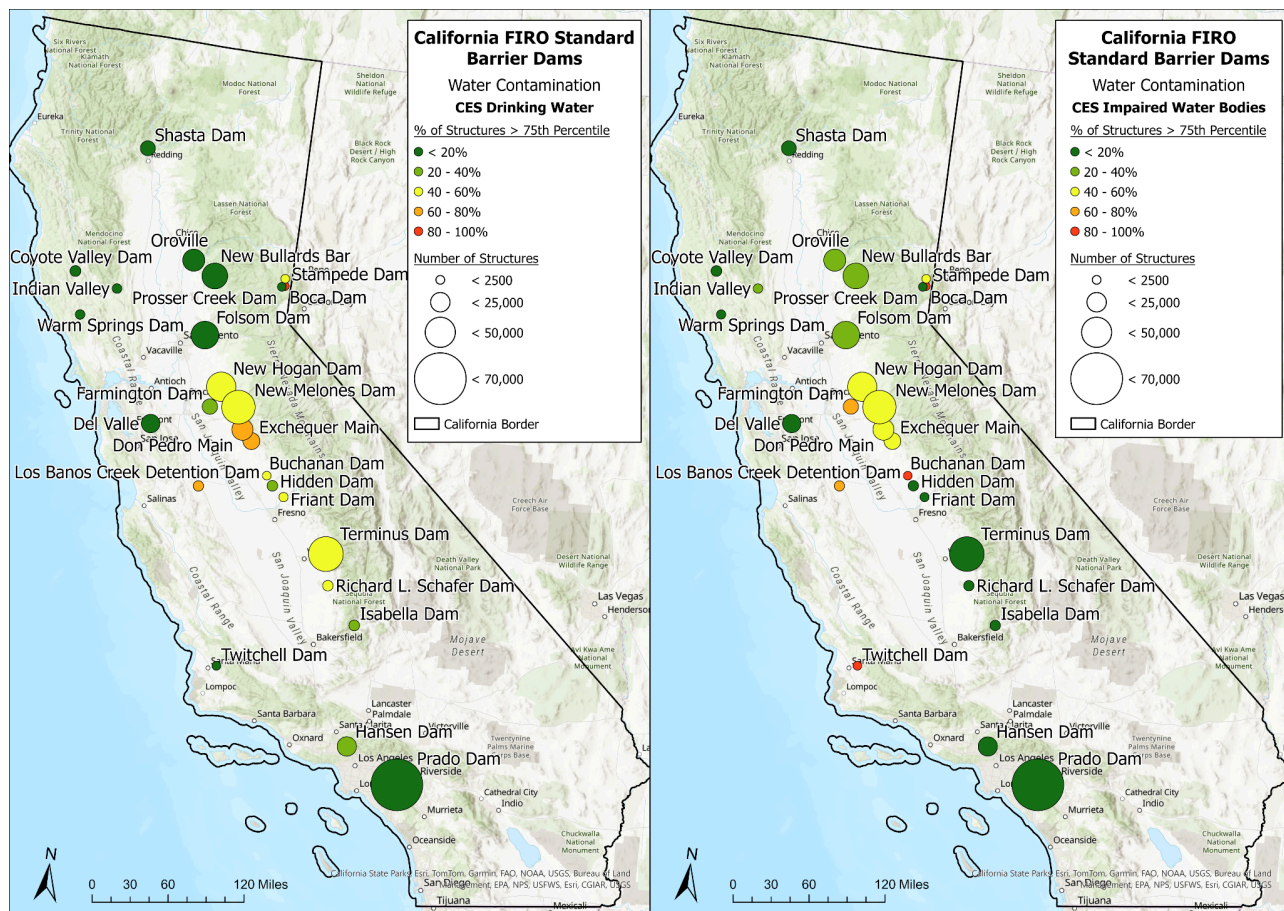


Figure 6: Depicts the percent of structures above the 75th percentile threshold for CalEnviroScreen drinking water contaminants and impaired water bodies. The circle size represents the number of structures in the downstream floodplain.

Figure 7. Wastewater Discharge Maps

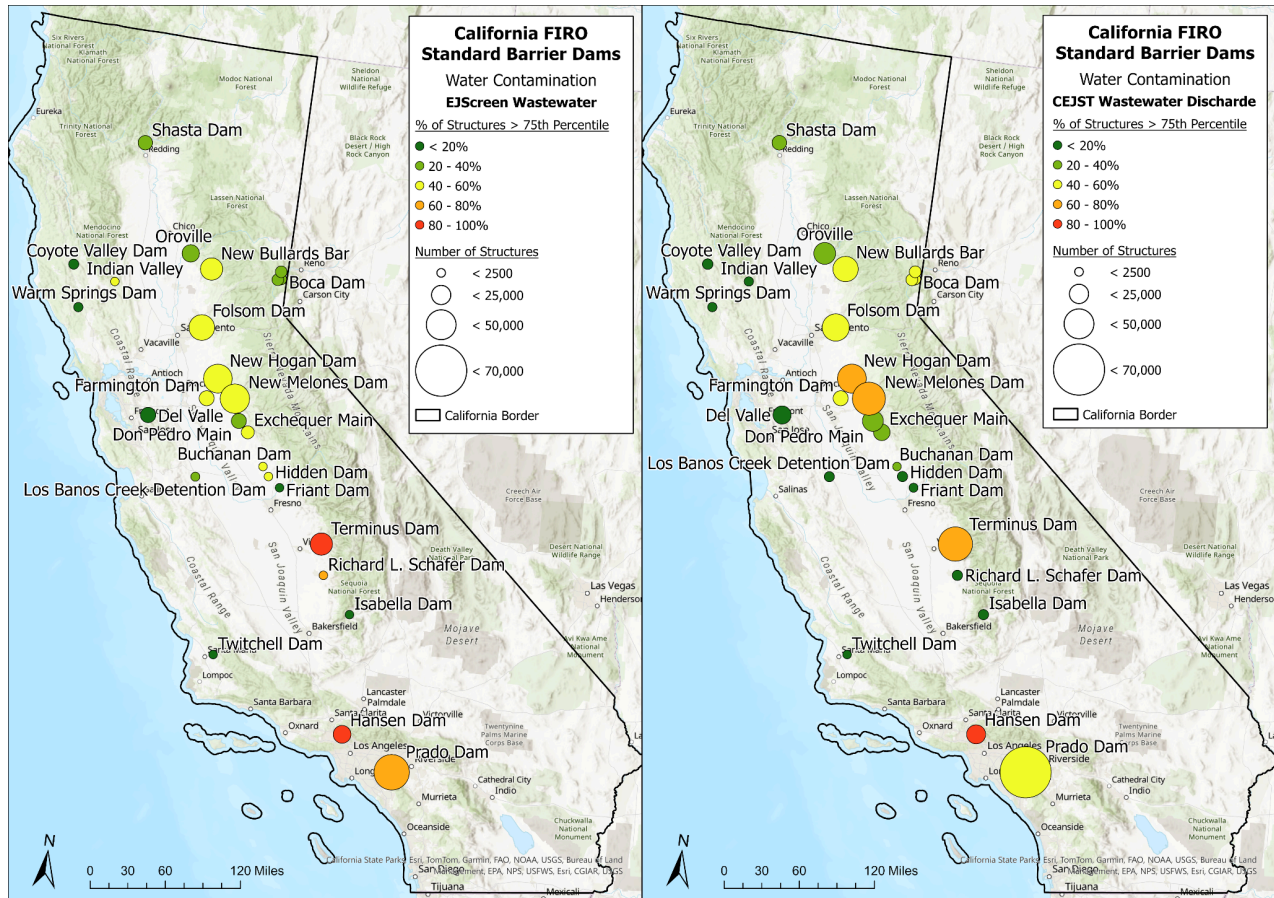


Figure 7: Depicts the percent of structures above the 75th percentile threshold for EJSreen and CEJST wastewater discharge, with circle size representing the number of downstream structures in the floodplain.

The two wastewater discharge maps also had differences that may require additional information to understand the cause. In these two maps, multiple dams, including Richard L. Schafer, Hidden Dam, and Indian Valley Dam, vary by over 20 percentage points. One important factor to point out is that the EJSreen Map pulled a lower number of structures when intersected with the social justice data than what is consistent across the other maps at multiple dam locations, including at Prado Dam, Terminus Dam, New Melones Dam, and others, which tended to be dams with over 25,000 downstream structures. Another important factor to take into account for the two CalEnviroScreen maps is that while they are both related to water quality, they are different categories of data. Overall, the variation in results across different tools and

different categories related to water contamination is varied to an extent that it makes it difficult to identify areas that could be prioritized for water contamination.

4.2 Yuba-Feather Case Study

4.2.1 Downstream Structures Analysis

For the Yuba-Feather case study, this paper examines maps that show all of the downstream structures in the region intersected with the four social justice metrics. Each environmental and social justice screening tool includes multiple indicators that measure different dimensions of social or environmental vulnerability. A location receives a "flag" when it exceeds the threshold for a given indicator. The overall score is then calculated by combining the number of flags across all indicators, providing a cumulative representation of vulnerability within that area. Figure 8 depicts the maps for SVI and CEJST based on the total number of flags. Areas that stand out in these maps include Sacramento, Yuba City, Marysville, and Olivehurst. Additionally, structures surrounding and slightly south of Lake Oroville are in the middle range for the number of flags.

Figure 8. Yuba-Feather SVI and CEJST Maps

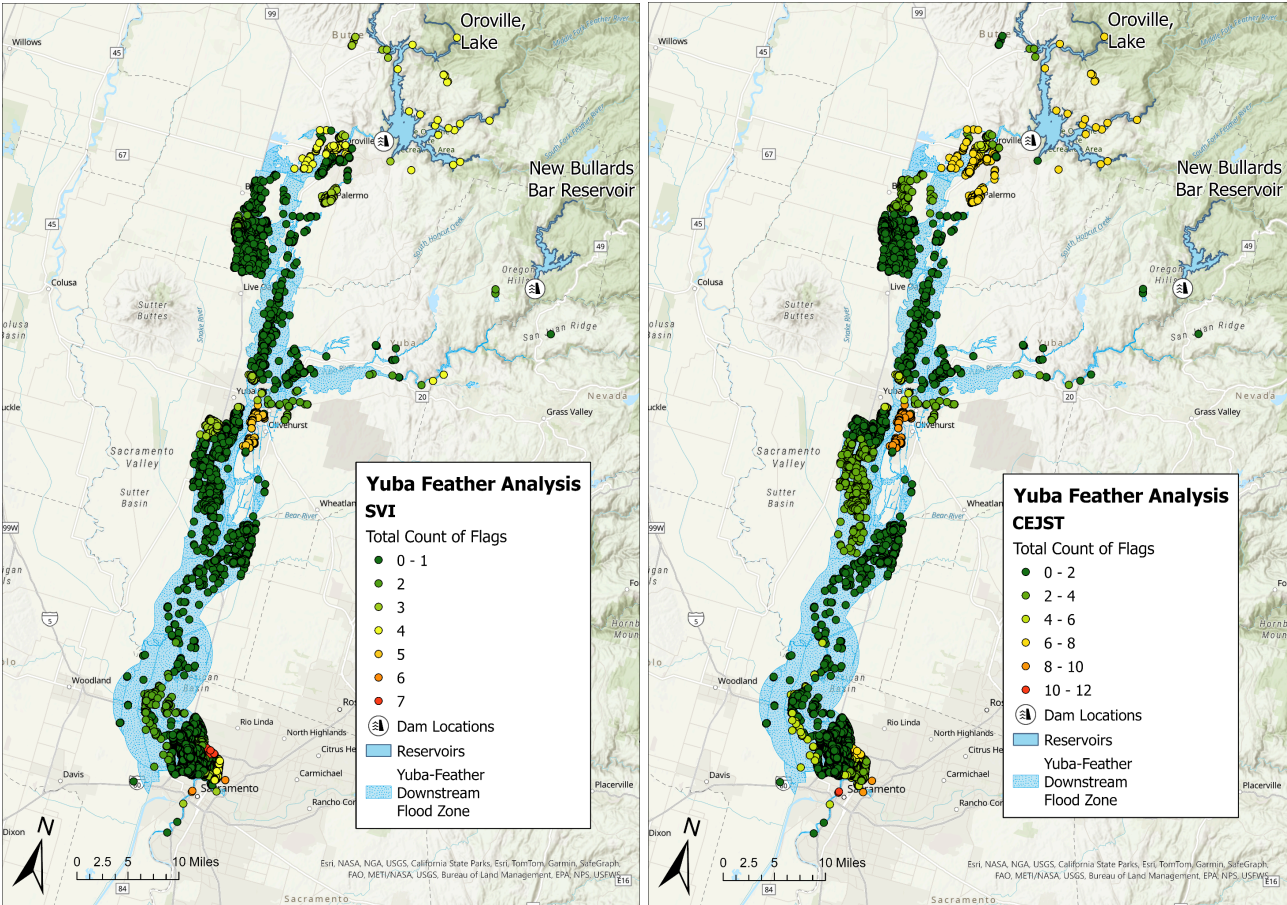


Figure 8: Depicts structures downstream of Oroville Dam and New Bullards Bar Dam overlaid with the total counts of flags for SVI and CEJST.

Figure 9. Yuba Feather CalEnviroScreen and EJScreen Maps

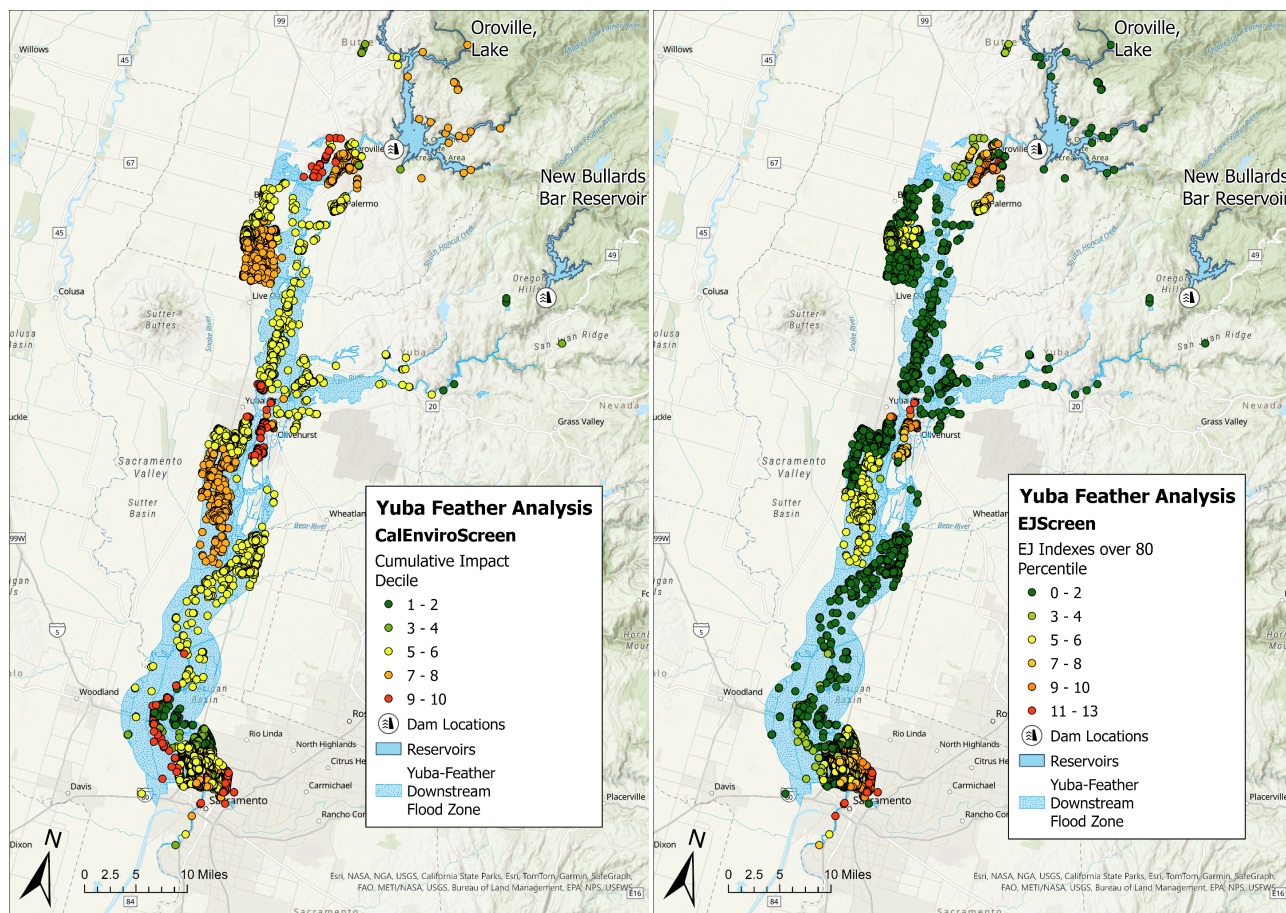


Figure 9: Depicts structures downstream of Oroville Dam and New Bullards Bar Dam overlaid with the cumulative impact decile for CalEnviroScreen and the total counts of flags for EJScreen.

Figure 9 includes maps of downstream structures intersected with SVI and CEJST. These maps show similar results with communities that have more social and environmental vulnerability near Sacramento, Yuba City, and Olivehurst. These maps also depict structures south of Oroville to be in the higher range. The CalEnviroScreen map overall has more structures identified to be in mid to high percentiles. These differences could be due to the variation in Data Sources used by CalEnviroScreen, as well as it being a tool specific to the state of California, while the other three tools are used across the United States. Additionally, the other three tools are depicted using the number of flags, while CalEnviroScreen uses percentiles.

4.2.2 Environmental Justice and FIRO Workshop

The “Yuba Forecast Informed Reservoir Operations Environmental Justice Workshop” held by SEEN and CW3E is an example of beginning the process of community involvement and engagement in water management. This is especially important given the history of flooding events in the region. Discussions with long-term community members found that many of these individuals still remember and hold trauma from the levee failures in 1986 and 1997. On the other hand, residents who are new to the area and have not lived through those events may not be aware that they live in a floodplain. This trauma affects their daily decisions during periods with high water levels. Residents identified specific areas where more education is needed, as well as communities that were missing from these water management discussions. Education on how water management decisions are made, such as water rate structures, funding mechanisms, as well as levee maintenance, importance, and damage prevention, was requested by residents.

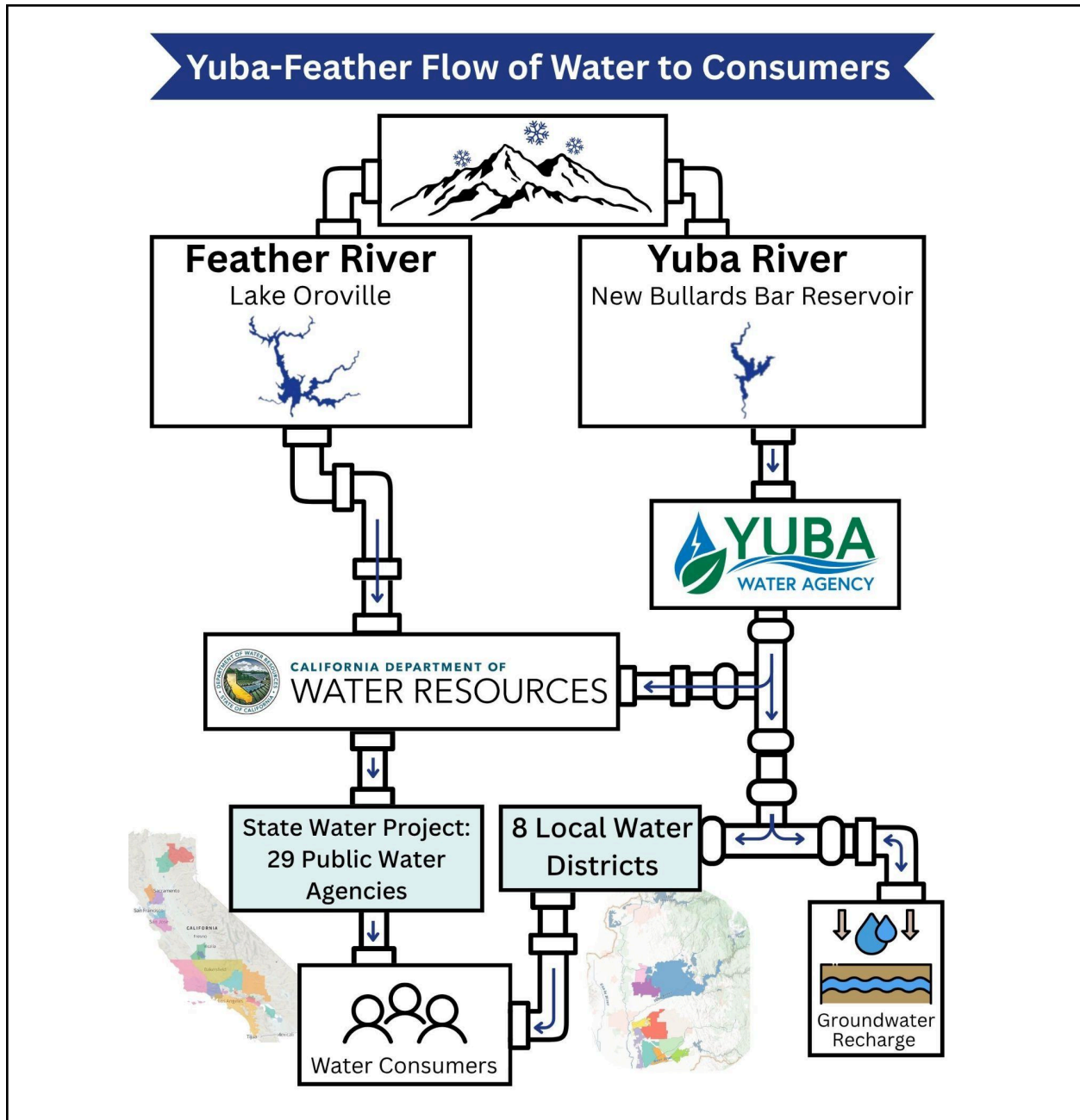
A second area of focus for education is on emergency preparedness, such as evacuation routes and procedures, shelter locations, and support for those without vehicles or with disabilities. Discussions also helped bring to light communities that were missing from water management and education conversations. One gap in representation was the lack of representation of the Punjabi-American community. They have ties to the Punjab region of northern India and Pakistan (*Yuba City Area*, n.d.). The need for multilingual education materials, such as in Spanish, Hmong, and Punjabi languages, is also crucial for the inclusion and education of underserved communities. Another finding from the discussion is that residents are prideful about water management in the region, but recent federal threats regarding California water management have made residents fearful of federal intervention.

Overall, the key finding from the workshop was that “Community members have expressed the need for clearer information on how water management decisions are made”. This workshop is an example of efforts to incorporate environmental justice into water management at a community level and offers insight into the unique local needs of communities. Larger analyses based on social justice on environmental justice tools are helpful to help understand downstream communities, but it often misses important details or nuance. Each dam location has unique communities and unique needs, making community involvement and discussions crucial for

equitable water management, especially as we adapt our water management strategies to meet the needs of climate change.

4.2.3 Yuba-Feather Figure for Water Consumers

Figure 10 was created as a visualization to help understand the organization of entities involved in water management and how water from the Yuba-Feather reached consumers. It depicts the flow of water beginning in the Yuba-Feather watershed and how that water is then distributed to water consumers. The Feather River water from Lake Oroville is used to supply water to the California Department of Water Resources, which goes into the State Water Project (Oroville, n.d.). The State Water Project supplies water to 29 public water agencies across the state of California, which ultimately provide water to the consumers within their regions (State Water Project, n.d.). On the Yuba River, the water from New Bullards Bar reservoir is managed by the Yuba Water Agency. They partner with eight local water districts, which then supply water mostly to farmers and ranchers in Yuba County (Partnering Districts, n.d.). Yuba Water also transfers water from the Yuba River to the California Department of Water Resources annually (Agency Overview factsheet, n.d.). The graphic also has a section on groundwater replenishment because Yuba Water delivers surface water from New Bullards Bar for the replenishment of the South Yuba Subbasin groundwater. This, combined with the local water districts supplying surface water to South Yuba County, has allowed for groundwater levels that plummeted by approximately 130 feet from 1949 to 1981 to be restored (Groundwater Management, n.d.). This graphic was created with the goal of being a tool to help with the understanding of the complex web of water management entities in California.



Note: This figure is preliminary. It is currently under review by Yuba Water Agency and is subject to revision.

5. Discussion and Conclusion

5.1 Limitations

There are multiple limitations to the analysis in this paper that are important to address. The social justice tools used for the statewide analysis have limitations in terms of their accuracy

in identifying disadvantaged communities. One limitation of this mapping technique is that the data that is intersected with structures is not accurate down to the structure level because the data is at the census tract or block group level. Individual structures that are within areas flagged in census tracts or block groups may not reflect the flag of the social justice tool. Additionally, people who are disadvantaged but may reside near less disadvantaged communities in the same zip code or census tract may be missed or underrepresented.

The results from the social and environmental justice tools have clear variations, which is potentially because of a few different factors. One explanation is the variation in years used from the American Community Survey (ACS). The most recent version of SVI used ACS data from 2020 to 2024, while the EPA EJScreen data uses 2018 to 2022. CalEnviroScreen also has key differences from the other two metrics, despite also using data from the ACS. The CalEnviroScreen 4.0 Version uses data from the 2015-2019 ACS, which is older than the other two metrics. For the maps on cleanup sites, there are differences in results between EJScreen and CEJST because of the years used. CEJST uses data from 2020, while EJScreen data was updated annually, and uses 2023/2024 data. Another key difference that may lead to different results is the use of different spatial groups. The EPA EJScreen is calculated at the block group level while SVI uses census tracts, which are typically less spatially resolved than block groups. CalEnviroScreen also uses census tracts and calculates percentiles using data only from California census tracts, while the other two metrics use data from census tracts or block groups from the entire country.

Some of the key metrics also vary in their sources of data. For example, the key metric of water contamination has clear differences. The CEJST and EJScreen data are derived from active discharge streams logged in the Permit Compliance System (PCS) and the Integrated Compliance Information System (ICIS). The main difference between these tools is the timeframe used, as CEJST uses data from 2020, while EJScreen uses data from 2023-2024. The CalEnviroScreen water contamination category relies on data from California State Water Resources Control Board (SWRCB) chemical tests for the compliance monitoring cycle spanning 2011–2019. The CalEnviroScreen impaired water bodies data is from the SWRCB Section 303(d) list of contaminated waters from the 2014–2016 California Integrated Report. The CalEnviroScreen Maps look at water contaminants and impaired water bodies, which are separate categories of data. For the indicator proximity to cleanup sites, there are variations

between CalEnviroScreen and the two federal tools because of differences in data used. CalEnviroScreen uses additional California-specific cleanup sites on top of incorporating federal superfund sites used by the other tools into the cleanup site proximity data. The differences in data categories for water contamination contribute to differences in mapping results, but looking at different forms of water quality measurements is helpful for understanding the whole picture of exposure for the communities downstream of the reservoirs. The variations in the results highlight the diversity in ways to measure environmental quality and are a reminder that just because one location comes up as having a low percentage of the population in proximity to water contaminants does not mean they may not have a high risk due to another form of contamination, such as Wastewater discharge that is missed by water contaminants data.

Another important limitation is that the Environmental and Social Justice tools in this analysis are not perfect. Certain characteristics or nuanced details may not be included in the tools' analysis, leading to the under- or over-representation of social or environmental vulnerability. For example, there have been criticisms of CEJST because of certain census tracts or communities within census tracts that narrowly miss out on being labeled as “disadvantaged” despite facing pollution or other factors that should likely qualify a community. CEJST also does not take race into account for legal reasons, despite this potentially being an important factor. An example of a community being missed by CEJST is McKinley Park, Chicago. These limitations impact the statewide analysis because they highlight that these federal datasets and tools are imperfect, and so using them to do an analysis may help to understand the downstream communities, but may miss important local details important for flood resilience

One limitation specific to the statewide analysis conducted in this paper is that grouping dams into five percentage ranges allows for the identification of dams with higher social vulnerability according to each social justice metric, but may overlook more nuanced differences in the percentage of downstream structures that exceed the threshold values. For example, dams assigned to adjacent categories may differ substantially in their underlying values. Two dams could fall into neighboring categories while differing by as much as 38 percentage points (41% and 79%), whereas another pair of dams could differ by only two percentage points (59% and 61%) despite also being placed in separate categories. As a result, relying solely on categorical groupings may obscure meaningful variation between dam locations that could be important for

site-specific analysis and prioritization. Further research with different strategies of visualizing the data could be done to understand how grouping structures this way affects the results.

Another limitation encountered in this analysis relates to both data availability and the interpretation of downstream risk. Differences were observed in the number of downstream structures identified when intersecting structure data with the social justice data for the EJScreen wastewater discharge category. This category produced a smaller number of structures at several dam locations, including Prado Dam, which may have influenced the results despite confirming that the same structure dataset was used across all EJScreen analyses. One possible explanation is that certain census tracts or geographic areas do not contain wastewater discharge data within EJScreen, causing some downstream structures to be excluded during the intersection process. Further research is needed to identify the cause of these differences.

Additionally, the use of downstream structure counts combined with social justice metrics to assess vulnerability introduces another limitation. Areas with fewer downstream structures may experience lower total monetary damages during flood events; however, these regions may also have more limited infrastructure and fewer available resources for disaster response. Rural communities often face constraints related to financial capacity, staffing, and emergency response resources, whereas urban areas may have greater access to transportation networks, healthcare facilities, and specialized expertise. As a result, structure counts alone may not fully capture differences in community resilience or recovery capacity following flood events. These generalizations also are not true across all urban and rural areas impacted by floods, furthering the importance of community engagement in understanding flood resilience.

5.2 Implications of the Results

The results from the analysis successfully identified dam locations with downstream vulnerability for the indicators of focus. While not always consistent, there was agreement across different social justice tools on areas that could be prioritized for FIRO implementation. The two dam locations that stood out the most across maps are Prado and Hansen Dam. Additionally, dam locations such as Farmington Dam and Twitchell Dam come up a few times across the maps in the red and orange categories, making them two potential locations for prioritization. Additionally, other indicators not included in this study may make dam locations not mentioned here stand out more than these ones, highlighting the need for further research. For additional

research, I would prioritize dams in the Central Valley that have larger numbers of downstream structures in the flood plain, such as Terminus Dam, New Hogan Dam, and New Melones Dam, among others. This is because they are near inland communities that rely on agriculture, have higher numbers of structures downstream, and often fall in the mid-range of vulnerability for the indicators looked at. Because of this, they did not initially stand out as prominently, but further research may identify specific communities that could greatly benefit from FIRO. While there are limitations to using social and environmental justice tools, they can still be useful in identifying regions to conduct additional research, as well as prioritizing the implementation of FIRO. The indicators of less than high school education, elderly population, and proximity to environmental contaminants can be useful to understand the flood vulnerability of communities downstream. These indicators are just a few of the relevant indicators, and future research should focus on creating a more comprehensive list of other social justice and environmental justice indicators that are relevant for flood risk and resilience. This research should also inform the creation of a new tool with the purpose of identifying social and environmental justice factors as they relate to flood risk. While a social or environmental justice tool can serve as a jumping-off point for understanding the socioeconomic and environmental factors impacting flood risk and resilience, it cannot serve as the only metric.

For this reason, the use of socioeconomic and environmental justice tools should not replace the need for community engagement and input. Understanding and engaging impacted communities is critical for identifying community needs and ensuring that climate-resilient water management strategies are tailored to address local priorities and conditions. The Yuba-Feather workshop served as an example that identified key community needs and communities missing from discussions. Community engagement also allows for site-specific needs to be brought up and addressed that may not be relevant across larger geographic resolutions. Community engagement allows for more diversity in viewpoints that can contribute to solutions, such as experiences from minority groups or traditional ecological knowledge. The implementation of FIRO can address historical injustices from the construction of dams by making dams used for flood control more efficient, allowing for dams that are older and no longer functioning for their intended purposes to be removed. Future research should continue to partner with and involve local communities in climate-resilient water management strategies.

5.3 Policy Recommendations

The theory of experimental governance outlines this idea that successful policy solutions cannot only rely on top-down or bottom-up solutions but must be a combination of the two (Sabel & Victor, 2022). In expanding the implementation of FIRO across the country, a tool specifically used for identifying socioeconomic and environmental factors that impact flood risk and resilience should be used to identify where FIRO could have benefits to adversely impacted communities to prioritize implementation, given that these locations also meet the technical criteria for FIRO implementation. Workshops should be held in communities downstream that have socioeconomic vulnerabilities as well as vulnerabilities to flood risk. The results from these workshops should inform implementation efforts of FIRO and identify goals to be included in Final Viability Assessments, as well as in Water Control Manual updates if relevant. Congress should provide dedicated funding to federal agencies to facilitate the equitable implementation of water management strategies across the country, given their potential to improve water-use efficiency and enhance water security for municipal, industrial, and agricultural sectors. There is also the potential for other benefits from FIRO implementation, including recreation, hydropower energy generation, groundwater recharge, and environmental services (Ralph et al., 2025). These benefits suggest that this investment is in the best interest of the United States, especially in the West, where water is a critical, limited resource.

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Appendix

Table 1. Social and Environmental Vulnerability Tools and key Metrics

Metrics of Interest			
Tool:	Key Metric/Theme:	Variable Name:	Data Field:
CalEnviroScreen	Education Level	Education Pctl	Education_Pctl
	Environmental Contamination	Drinking Water Pctl	drinkP
		Cleanup Sites Pctl	cleanupsP
		Haz. Waste Pctl	hazP
		Imp. Water Bodies Pctl	iwbP
SVI	Education Level	Education Percentage Percentile	EPL_NOHSDP
	Elderly Population	Elderly	EPL_AGE65
EJScreen	Education Level	Education Percentage	P_LESHSPCT
	Elderly Population	Elderly Percentage	P_OVR64PCT
	Environmental Contamination	Superfund Proximity	P_PNPL
		Hazardous Waste Proximity	P_PTSDf
		Wastewater Discharge	P_PWDIS
CEJST	Environmental Contamination	NPL (Superfund Sites) Proximity	NPL_PFS
		Hazardous Waste Proximity	TSDF_PFS
		Wastewater discharge	WF_PFS