CALIFORNIA STREAM GAGING PRIORITIZATION PLAN 2022

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Executive Summary

It is the State's responsibility to manage and protect California's water while also protecting, restoring, and enhancing the natural and human environment. A robust and reliable stream gage network can help State, federal, and local agencies manage water resources more effectively for multiple benefits and help avoid conflicts.

Over the past two decades, California's climate has experienced drastic changes in precipitation, resulting in longer droughts and record-breaking rainfall. The statewide water systems are highly engineered, moving millions of gallons of water for almost forty million people. The state's economy is highly dependent on these water systems. The state's $47 billion agriculture industry, local governments, private industry, and hydropower facilities all depend on reliable water supplies. Our vital ecosystems are heavily dependent on the magnitude, timing, and duration of water availability, and the ability to recreate in and around water is a way of life for many Californians. In addition to water availability needs, a significant portion of the state is at risk of flooding. With changes in precipitation patterns, volume, and intensity associated with climate change, the need to collect and use streamflow data for emergency preparedness and flood management is critical.

Senate Bill (SB) 19 (Statutes of 2019, Chapter 361, Dodd) directed the California Department of Water Resources (DWR) and the California State Water Resources Control Board (State Water Board) to develop a plan (SB 19 Plan) to deploy a network of stream gages to help address significant gaps in information needed for water management and the conservation of freshwater species. The legislation also states that the SB 19 Plan should include opportunities for (a) modernizing stream gages, (b) reactivating existing stream gages, (c) deploying new gages, including reference gages, and (d) a determination of funding needs. The legislation directs that priority be given to gages where lack of data contributes to conflicts in water management or where water can be more effectively managed for multiple benefits, including water supply, flood, water quality, and ecosystems. Integrating stream gage data and providing public access to water-related data are issues that have been identified for further action as part of the Open and Transparent Water Data Act (Assembly Bill 1755; Statutes of 2016, Chapter 506, Dodd).

SB 19 also directed that the SB 19 Plan be developed in consultation with California Department of Fish and Wildlife (CDFW), Department of Conservation (DOC), and Central Valley Flood Protection Board. Additionally, a Technical Advisory Committee, interested parties, and local agencies contributed input to the State agencies developing the plan.

An assessment of the existing gage network and its distribution throughout the state was an integral part of evaluating California's current stream gage network. This assessment is referred to as the *Gage Gap Analysis*. The University of California, Berkeley's Stream Network Analysis for Gages (SNAG) tool was used to complete the Gage Gap Analysis, which includes:

- An evaluation of the existing gage inventory (of gages that share their data publicly).
- The network of stream and surface waters of the State (stream network).
- An assessment of existing gage coverage in the stream network.
- Identification of stream reaches throughout the stream network that are well-gaged, almost well-gaged, or ungaged.
- A summary of the analysis at the local sub-watershed level (i.e., Hydrologic Unit Code 12), which typically range in size from 40 to 150 square kilometers.
- Identification of current and historic stream gage sites that should be prioritized for upgrades or reactivation.

Approximately 1,000 gages are operating and reporting data publicly in California. Of these, about 60 percent are operated by the United States Geological Survey (USGS), with the remaining gages operated by State or other agencies. A substantial number of gages are operated by third-party entities that are not publicly reporting data on statewide databases or lack sufficient data quality to be reported. The Gage Gap Analysis was not able to capture these third-party gages for assessment and inventory, but there are opportunities to incorporate existing third-party stream gages into the publicly available stream gage database and future analyses if parties are willing to provide such information publicly. Of the approximate 4,500 local sub-watersheds (Hydrological Unit Code 12 [HUC12]) in California, more than 3,200 (over 70 percent) of watersheds do not have any history of stream gaging. Less than half of the historically gaged watersheds currently have active, publicly accessible gages today.

The plan to improve the state's stream gage network is presented as four core recommendations. The recommendations will allow for near-term solutions and long-term planning. The recommendations are independent and do not rely on one recommendation being completed before another recommendation can be implemented. The core recommendations are:

- **Integrate Third-party Gages.** Integration of third-party gages into the public gaging system is a low-cost opportunity to significantly expand publicly available gage data. An effort is needed to identify local agency and private gages, minimum data standards for publicly available gage data, and mechanisms to integrate the local agency and private gage data into the public gaging system, which could involve mandates, funding incentives, or other approaches. The effort should include outreach to other agencies and private entities that operate stream gages to solicit input on how to incorporate their stream gage data into the public systems and understand any impediments. An approximate timeline is on the order of three years to develop a plan to integrate third-party gages.

- **Improve and Expand the State's Gaging System.**
  - **Reactivate Historical Gaging Sites.** Table A-2 in Appendix A identifies the top locations to install stream gages near historical gaging sites. The table identifies multi-benefit gages that support more than one water management need (e.g., water supply, water quality) or are located in high-priority watersheds. Gages on this list should be prioritized for reactivation if a qualified gage operator (most likely DWR, USGS, or local water managers) and funding source can be identified to support their installation and long-term operation, with consideration for why the gage was initially de-activated (e.g., funding, site access, etc.). Of the 1196 inactive gages, 156 are recommended for reactivation at an approximate cost of $5,148,000 and an approximate timeline of five years. The approximate annual operation and maintenance cost to sustain this recommendation is $4,680,000.
  - **Upgrade Existing Gages.** Table A-3 in Appendix A identifies the top existing gage sites for infrastructure upgrades to collect additional streamflow data with the installation of additional sensors (e.g., temperature, dissolved oxygen), equipped for telemetry (recording and transmitting of data without in-person effort), or at which a flow rating curve to convert stage to flow could be added. The table identifies multi-benefit gages that support more than one water management need or are in high-priority watersheds. Coordination with the existing gage operators and funding sources should be identified to implement upgrades at these sites, with consideration for why the upgrades are not currently active at the location (e.g., funding, site access, etc.). An approximate timeline is 2–5 years, depending on the number of sites and related site conditions, available resources, and gage operator. Of the 359 active-limited use gages, 39 are recommended for upgrade at an approximate cost of $1,287,000. The approximate annual operation and maintenance cost to sustain this recommendation is $1,170,000. These costs are estimated in early 2022 and do not account for escalation.

    In addition to the gages recommended for more comprehensive upgrades listed above, it is recommended that all gages in high-priority areas have temperature sensors. There are 364 active-high quality and 139 active-limited use gages that are recommended for temperature only sensors at an approximate total cost of approximately $5,030,000 with a 5-year timeline. Operation and maintenance for these gages is not expected to add additional cost.

The total number of stream gages recommended to be upgraded is 542 (39 multi-parameters and 503 are temperature only).

- **Install New Stream Gages.** Table A-4 in Appendix A identifies the top locations to install new stream gages. The table identifies watersheds that have high-priority water management needs, including multi-benefit locations. New stream gaging locations are identified and prioritized by their water management categories (i.e., water supply, flood, water quality, and ecosystem) separately so that parties with a specific interest (e.g., flood) can identify which watersheds are prioritized for that water management category. Tier 1 watersheds in Table A-4 should be prioritized for installation if a qualified gage operator (most likely DWR, USGS, or local water managers) and funding source can be identified to support their installation and long-term operation. Because of the variability and scale of potential deployment, timeline parameters are provided for reference in future planning efforts. Depending on the site location and gaging needs, deployment can take as little as 3–4 months and as long as a few years to install. 436 out of 4469 watersheds are recommended for new gage installation at an approximate capital cost of $15,696,000. The approximate annual operations and maintenance cost to sustain this recommendation is $13,080,000.
- **Improve Gage Data Quality and Management**. Establish minimum operation and maintenance standards for stream gages that provide for the incorporation of private gage information into the statewide system. This effort would include education and outreach, including the development of tools and information to support reliable data through improved gage operation and maintenance of gages operated by external entities. This effort would also include the development of visualization tools to improve access to gage information to better support State and local decision-making. An approximate timeline to develop this program is approximately two years, with ongoing facilitation and activity. An approximate cost to fulfill this recommendation for the development and implementation of the improvements is an appropriation of $600,000 annually for three years. To continue the maintenance of the data tools, an annual appropriation of $280,000 would be needed.

Table 1 Summary of Recommendations and Associated Costs

	Reactivation Gages	Upgrade Gages	Watershed with New Gages	Total
Recommended Count	156	39	436	631
Capital Unit Cost	$33,000	$33,000	$36,000	
Subtotal Capital Cost	$5,148,000	$1,287,000	$15,696,000	$22,131,000
Annual O&M Unit Cost	$30,000	$30,000	$30,000	
Annual O&M Cost	$4,680,000	$1,170,000	$13,080,000	$18,930,000

Note: Costs provided are estimated in early 2022 and do not account for escalation.

- **Prioritize Funding.** Funding and associated resources are needed to implement the recommendations outlined in this report. Reliable and sufficient funding are key elements of the state's stream gage deficit. In general, there are two costs associated with a stream gage: (1) initial capital cost for installation of the stream gage; and (2) annual cost for operation and maintenance of a stream gage.
    - **At the state level.** Long-term funding sources are needed to support the installation of new gages, re-activation of historic gage sites, and upgrade of existing gages using the prioritized lists provided in Recommendation 2.
    - **At the local or private level.** Additionally, funding should be provided to incentivize local agencies to install and operate new gages or upgrade existing gages to meet established standards and share their data publicly. For example, a grant program could be established where local agencies could apply for funding to install and operate stream gages for a limited number of years (e.g., five years), whereafter the local agencies agree to operate the gage for an additional time (e.g., 15 years).

Potential funding sources at the State level are the Environmental License Plate Fund, Greenhouse Gas Reduction Funds, Wildlife Conservation Funds, the establishment of water use fees, and the General Fund. Without additional stable funding, critical gaps in the stream gage network will continue to expand, further limiting water managers' ability to effectively manage the state's limited water resources.

- **Streamline Regulatory Permitting.** In November 2020, the California Natural Resources Agency (CNRA) released the Cutting Green Tape — Regulatory Efficiencies for a Resilient Environment. The "Cutting Green Tape" is an effort to increase the pace and scale of environmental restoration (California Landscape Stewardship Network November 2020). Stream gaging is a vital tool to protect the environment and should be included in the Cutting Green Tape effort.

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Acronyms and Abbreviations

API — Application Programming Interface

BIA — Bureau of Indian Affairs

BMI — Benthic macroinvertebrate

CDEC — California Data Exchange Center

CDFW — California Department of Fish and Wildlife

CFS — Cubic Feet Per Second

CGS — California Geological Survey

CMF — Cooperative Matching Fund

CSCI — California Stream Condition Index

CSV — Comma Separated Value

DOC — Department of Conservation

DWR — Department of Water Resources

ELPF — Environmental License Plate Fund

FIRO — Forecast-Informed Reservoir Operations

Flood-MAR — Flood Managed Aquifer Recharge

GIS — Geographic information system

GOES — Geostationary Operational Environmental Satellites

GSA — Groundwater Sustainability Agencies

GWSIP — Groundwater and Stream flow Information Program

HUC — Hydrologic Unit Code

IOW — Internet of Water

NGWOS — Next Generation Water Observing System

NID — National Inventory of Dams

NOAA — National Oceanic and Atmospheric Administration

NWIS — National Water Information System

QA/QC — Quality Assurance and Quality Control

SGMA — Sustainable Groundwater Management Act

SB 19 — Senate Bill 19

State Water Board — State Water Resources Control Board

SWAMP — Surface Water Ambient Monitoring Program

TAC — Technical advisory committee

TSV — Tab Separated Value

TNC — The Nature Conservancy

USGS — United States Geological Survey

WDL — Water Data Library

Introduction

Over the past two decades, California's climate has experienced drastic changes in precipitation, resulting in longer droughts and record-breaking rainfall. The statewide water system is highly engineered, moving millions of gallons of water for almost forty million people. The state's economy is highly dependent on our water systems. The state's $47 billion agriculture industry, local governments, private industry, and hydropower facilities all depend on reliable water supplies. Our vital ecosystems are heavily dependent on the magnitude, timing, and duration of water availability, and the ability to recreate in and around water is a way of life for many Californians. In addition to water availability needs, a significant portion of the state is at risk of flooding. With changes in precipitation patterns, volume, and intensity associated with climate change, the need to collect and use streamflow data for emergency preparedness and flood management is critical.

Although the state's ecosystems, public safety, human right to water, and economy are directly affected by water availability, we have surprisingly little data about how water is moving through our streams at a resolution and time scale needed for water management. At one time, there were over 3,600 active stream gages throughout the state, but less than half of that number are active today and even fewer provide the level of real-time data needed to manage our most precious resource. The purpose of the California Stream Gaging Prioritization Plan (SB 19 Plan) is to identify significant gaps in the stream gage network and to develop a framework to efficiently bridge the gap in surface water information for water management and the conservation of freshwater species.

Importance of Real-Time Monitoring

A portion of the state's stream gage network continuously monitors streamflow year-round and computes daily mean statistics that are made available online. Real-time data collected at stream gages serves several important functions (including flood warning/forecasting, water allocation, fish and wildlife protection, and recreation) and can be used by anyone. The data are typically transmitted to data sharing platforms within one hour of a measurement being taken. Data users include emergency responders, water managers, environmental and transportation agencies, universities, utilities, recreational enthusiasts, and consulting firms. Specific uses of the data include the following:

- Planning, forecasting, and warning about floods and droughts.
- Managing water rights and State and federal transboundary water issues.
- Operating waterways for power production and navigation.

- Monitoring environmental conditions to protect aquatic habitats.
- Assessing water quality and regulating pollutant discharges.
- Planning for safe and enjoyable recreational activities.
- Analysis of groundwater recharge and streamflow depletion.
- Describing impacts to streamflow from changing land and water uses.
- Designing reservoirs, roads, bridges, and drinking water and wastewater facilities.

The State recognizes the importance of data collected through stream gaging for the management and protection of California's water resources and the human and natural environment. A robust and reliable stream gage network is essential for State, federal, and local agencies to manage water resources and conserve freshwater species more effectively for multiple benefits and to help avoid conflicts. It has become apparent that the existing stream gage network could be strengthened to assist and facilitate water management decisions (i.e., water supply management, flood management, water quality management, and ecosystem management). To make informed decisions, water managers and emergency operations need both real-time (or near-real-time) data and long-term records to evaluate current water management needs and variability over time because of climate change.

There are approximately 1,500 inactive stream gages in California, and additional gages are slated to be discontinued, primarily from lack of funding. Some of these inactive gages are not good candidates for reactivation, but approximately 1,200 gages have potential for reactivation. Some of the gages slated to be discontinued, and those that were discontinued in prior years, provided the only real-time streamflow information in a watershed. Additionally, many discontinued gages provided long-term continuous data that would be helpful for comparison across water year types, which is important for water management decisions. In addition to the challenges created by the trend in discontinued gages, 86 percent of California watersheds do not have a federally or State-operated stream gage, and the majority (64 percent) of these ungaged watersheds have surface water diversions. The 2012–2016 drought and the ongoing 2019–2022 drought have clearly illustrated that the decommissioning of gages and lack of gages in priority watersheds results in data gaps that hamper effective management of California's limited water resources. In turn, State and local agencies are forced to spend extra resources on field investigations or other less accurate means to obtain needed data or to forgo timely and effective action because the data do not exist.

It is the State's responsibility to manage and protect California's water while also protecting, restoring, and enhancing the natural and human environment. A comprehensive stream gage network is essential for effective water management. The lack of comprehensive streamflow information impacts the State's ability to make the most efficient and effective water management decisions, especially during critically dry periods when limited water supplies must be managed to meet multiple needs, such as the protection of senior water rights, water transfers, and threatened and endangered aquatic species.

State and local agencies rely on stream gages to assess risks to public safety, property, infrastructure, and the environment from floods, debris flows, landslides, and sedimentation. The California Department of Water Resources (DWR) relies on stream gages to assist with early flood warnings and manage flood events, surface water reservoir operations, and water supply forecasting throughout the state. Deficiencies in the stream gage network negatively impact an agency's capacity to conduct hazard analyses, which can leave public safety, private property, infrastructure, and the environment at risk.

The State agencies responsible for protecting water resources for water quality, beneficial use, and aquatic species are also heavily dependent on streamflow monitoring data. California Department of Fish and Wildlife (CDFW) programs regularly rely on monitoring data from stream gages to inform hydrology for instream flow study planning, implementation, and analysis. Additionally, with the legalization of commercial cannabis cultivation, CDFW and State Water Resources Control Board (State Water Board) cannabis programs rely on this gage information to evaluate effects of stream diversions on aquatic habitat and implement programs to ensure minimum flows remain instream (i.e., limit diversions). In the Sacramento-San Joaquin Delta, CDFW and the State Water Board routinely use gage information to evaluate surface water outflow and its effect on key Delta species. Gaging information allows CDFW and the State Water Board to use the best available scientific data to increase their understanding of the functions that flows provide to native species, to manage flows for the greatest benefit to native species, and for other beneficial uses of water.

The integrated nature of the planning process associated with the development and implementation of the SB 19 Plan will help to strengthen existing interagency partnerships and develop relationships among State and local entities and other partners who operate or rely on stream gage data to manage water in their local watersheds. By working collaboratively, a more efficient stream gage network can be designed and implemented to meet the State's water data needs and inform key water resource management decisions.

Senate Bill 19 Scope

SB 19 (Statutes of 2019, Chapter 361, Dodd) directs DWR and the State Water Board to develop a plan (SB 19 Plan) to deploy a network of stream gages that address significant gaps in the current gage network, help inform water management, and support the conservation of freshwater species. The bill directs DWR and the State Water Board to develop the SB 19 Plan in consultation with CDFW, the Department of Conservation, the Central Valley Flood Protection Board, interested parties, and local agencies. The SB 19 Plan should consider opportunities for:

- Modernizing existing stream gages.
- Reactivating old stream gages.
- Deploying new gages.
- Determining funding needs.

In addition, stream gage data management and public data access are important issues that need to be addressed and integrated with the Open and Transparent Water Data Act (AB 1755, Dodd 2016) where possible.

The following Water Management Criteria were provided in SB 19 to help prioritize and address the gaging gaps that impact water management and the conservation of freshwater species:

- Areas with conflicts in water management.
- Areas where water can be managed for multiple benefits.
- Presence of historic gage data.
- Reference gage locations.
- Water supply management.
- Flood management.
- Water quality management.
- Ecosystem management.
- Additional consideration of temperature, water quality, cannabis, or groundwater management issues.

Integration with the Open and Transparent Data Act and the existing network calls for addressing data management, public data access, and transparency. The following issues have been previously noted:

- Data on existing gages are difficult to find.

- Data are not accessible to the public promptly.
- Information on funding, location, and operating condition are lacking and would be useful to water managers and the public.
- Many gages lack information on flow, water temperature, and watershed characteristics.
- Data from stream gages must be of high quality to be useful to water managers.

Modernization involves a wide array of important elements. Summarized below are elements of the current system where modernizations to gages are warranted, starting with the most rudimentary. More detailed information on this topic is provided in the Modernization and Emerging Technologies section.

- Aging software platforms.
- Keeping pace with improvements to telemetry communications equipment and technology.
- Antiquated Infrastructure.
- Enhanced instrumentation.

Outreach

The SB 19 legislation stated that the SB 19 Plan shall be developed in consultation with CDFW, Department of Conservation, Central Valley Flood Protection Board, interested partners, and local agencies. A Core Team was created to develop the SB 19 Plan, which included representatives from the State Water Board, DWR, CDFW, and the Department of Conservation's California Geological Survey (CGS). The Core Team established a Technical Advisory Committee (TAC) consisting of interested partners. The Core Team also held two public meetings to seek input from other interested parties.

Technical Advisory Committee

A TAC was formed to allow for various organizations and agencies to provide input and recommendations on the development of the SB 19 Plan. The TAC also played a key role in outreach with their constituents. Approximately 20 water-focused entities were contacted to seek their interest in joining the TAC. Ultimately, the TAC consisted of 10 entities representing a wide spectrum of water management interests (water supply, water management, public safety, water quality, ecosystem management, and academia).

The TAC comprises the following entities:

- Association of California Water Agencies.
- California State Association of Counties.
- Central Valley Flood Protection Board.
- National Oceanic and Atmospheric Administration (NOAA) — California-Nevada River Forecast Center.
- Northern California Water Association.
- The Nature Conservancy (TNC).
- Trout Unlimited.
- United States Geological Survey (USGS) — Water Science Center.
- Internet of Water.
- California Water Data Consortium.

The Core Team met with the TAC bi-monthly to review the development of the analysis, inform outreach efforts, and solicit input on the SB 19 Plan Technical Report. The TAC members also participated in several technical workgroups throughout the planning process.

Public Outreach

An SB 19 web page[1] was developed to provide information to and engage the public. Two public meetings were scheduled to allow for interested parties to provide input on the development of the SB 19 Plan. Both meetings were held virtually because of the COVID 19 pandemic.

The initial meeting was held on February 4, 2021, and approximately 200 people attended. The purpose of the initial meeting was to answer general questions and provide a background on the SB 19 bill and an overview of:

- The roles and responsibilities of the participating agencies.
- The Core Team's efforts.
- Ways interested parties could provide input and answer any questions.

[1] https://www.waterboards.ca.gov/waterrights/water_issues/programs/stream_gaging_plan/

The second public meeting was held on May 19th, 2022. The purpose of the second meeting was to answer questions and provide an overview of:

- The stream gage gap analysis process and results.
- The prioritization process and results.
- The summary and recommendations outlined in the SB 19 Plan.
- How interested parties can provide input on the SB 19 Plan.

Background

Stream Gaging in California

Historical

In the late 1800s, California's first state engineer had a permanent system of 200 stream gages installed along various rivers to help with flood control. The gage network expanded significantly from the late 1800s up until the 1960s in response to California's expanding water needs and the construction of water infrastructure projects. During this time, the diversity in gage operators and the funding sources for gage operation also increased. In June 1920, the Federal Water Power Act was passed, which provided the status of water power as an alternative source of energy and established the Federal Power Commission to issue licenses for the development of water power on federal lands.

Construction of large dams to impound water to meet demands for irrigation, power development, flood control, and industrial use focused attention on the need for more information on streamflow and sediment load, the effect of water loss by evaporation, and limitations to the useful life of reservoirs because of deposition of sediment. The heavy drain on groundwater resources during World War II resulted in critical conditions in many areas; groundwater recharge and saltwater encroachment was a subject of special concern in some coastal areas. Efforts to upgrade the nation's highways also required hydrologic data and flood studies to aid highway infrastructure and drainage design (U.S. Geological Survey Circular 1050).

Current — Declining System

In the 1940s through the 1960s, there were over 3,600 locations in California where stream gages were, at some point, operating and reporting to the California Data Exchange Center (CDEC). Since 1970, the number of stream gages has dwindled to only a fraction of the historical numbers owing to a reduction in available funding sources for the maintenance and operation of gages. Today, only approximately 1,000 gages are currently operating and reporting data publicly.

This decline in stream gage sites can be attributed primarily to reductions in funding for gage operations. Installation and maintenance of new stream gages are currently driven by specific programs or project needs, typically with more short-term funding allocations. Despite modern advances and improved capabilities of stream gages, the number of gages continues to decline because of the long-term effort and funding required to operate gages and maintain an accurate hydrologic record. Additionally, for locations that require more technical and complex gaging, such as tailwater and return flow systems, the high relative cost to operate and maintain these specialized sites significantly impacts the long-term viability of these gages. Other factors that have contributed to the decrease in active stream gage sites over time include challenges in real property access and permissions for sites and increased costs to permit and develop stream gaging sites.

Water managers have resorted to installing shorter-duration, project-specific gages in locations where funding is available rather than placing them in areas more suitable for the collection of long-term data. These short-duration stream gages also lack the fidelity that longer-duration gages have, with respect to comparing current streamflow to historical streamflow characteristics and patterns.

Stream Gaging Overview

This section provides a high-level overview of stream gage operations, from measurements to resulting user data, and briefly describes the methods and standards DWR requires to provide near-real-time and certified stream gage data.

A stream gage is an instrument that measures water conditions (such as pressure or velocity) to calculate a river's surface height, called *stage*, and/or the volume of water flowing by, called *discharge* or *streamflow*. The term "streamflow" will be used primarily in this document. An image of a stream gage with telemetry equipment is shown below in Figure 1. The common unit of measure for streamflow in the United States is cubic feet per second, or "CFS." Other types of stream instruments measure different parameters such as temperature or water quality, but for this plan, the term *stream gage* refers to the stage and/or streamflow gages.

Figure 1 Image of a telemetered stream gage installed by DWR and operated by Montague Water Conservation District on the Parks Creek Diversion Channel in Siskiyou County

Image by DWR, Northern Region Office.

Temperature and other water quality measurements can be co-located with stream gages and use existing infrastructure and communications. Certain water quality parameters, such as temperature, turbidity, and dissolved oxygen, are relatively simple to measure and report on a real-time basis. Measurement of water quality elements are addressed in this SB 19 Plan as part of the prioritization and stream gage upgrades sections.

The operation of streamflow gages can be described in four key elements: gage establishment, sustained gage maintenance, data quality control/quality assurance, and gage operators and data repositories. The following references are common in the industry and are used to guide standard operating procedures involved in collecting and computing accurate reliable streamflow using stream gages:

- General Procedure for Gaging Streams (Carter Davidian 1968).
- Measurement and Computation of Streamflow, Water Supply Paper 2175 (Rantz 1982).
- Techniques and Methods 3-A8 Discharge Measurements at Gaging Stations (Turnipseed and Sauer 2010).

- Measuring Discharge with Acoustic Doppler Current Profilers from a Moving Boat (Mueller et al. 2013).
- Stage Measurement at Gaging Stations, Chapter 7 of Book 3, Section A (Sauer and Turnipseed 2010).
- Computing Discharge Using the Index Velocity Method (Levesque and Oberg 2012).

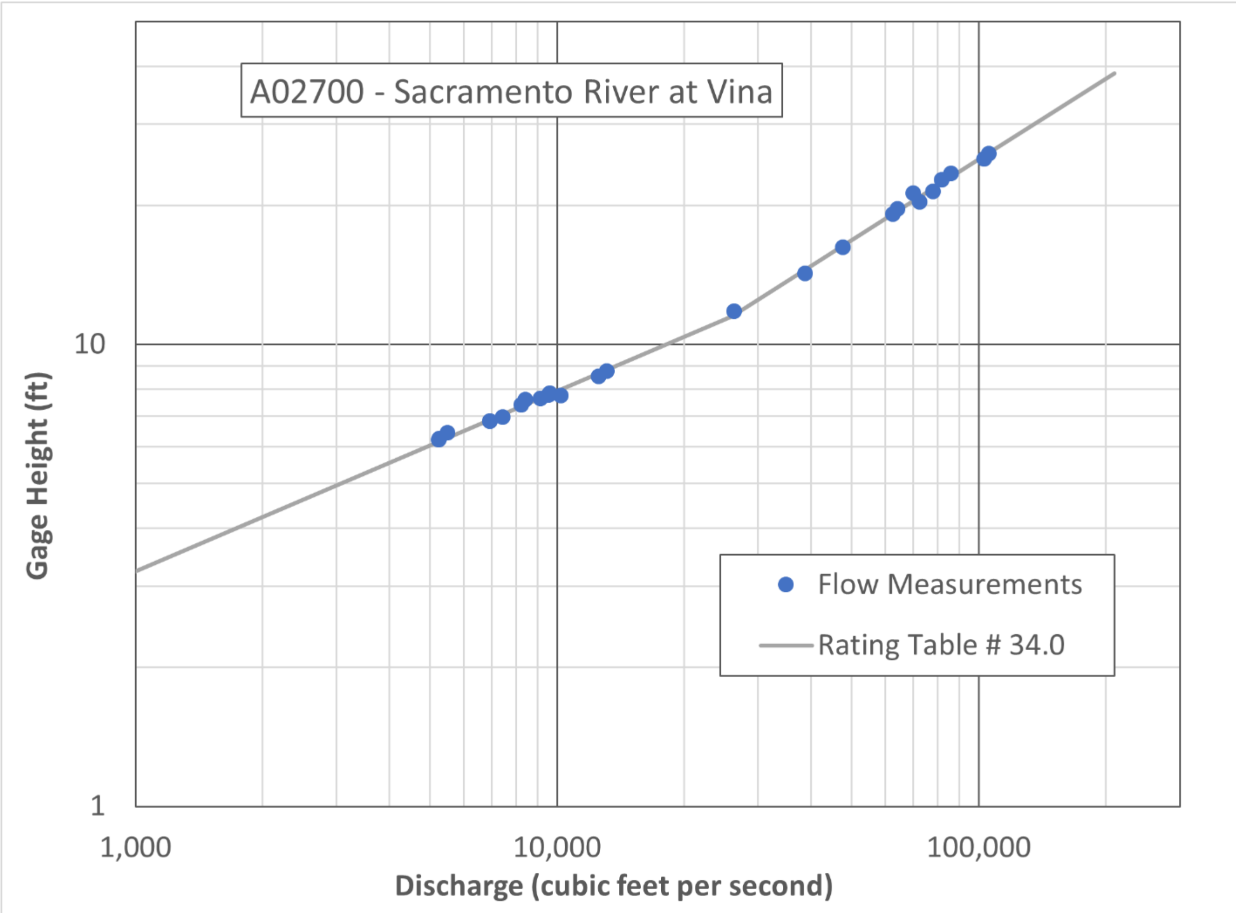
Gage Establishment

The establishment of a stream gage starts with strategic site selection that considers favorable streamflow conditions for measurement, accessibility, proximity to existing communications infrastructure, and minimization of environmental impacts. The establishment also requires equipment procurement, addressing potential real property rights, and compliance with environmental regulatory permits for gage installation and maintenance. This process typically requires notable time and resources, depending on the complexity of the gage site. Frequently, gage sites are on property that requires the acquisition of rights to access, place, and operate a gage. Most stream gages will involve a certain amount of land disturbance and therefore trigger regulatory permitting. Most gages have minimal impacts, but certain equipment requires more disturbance in the stream channel and therefore require more extensive measures to minimize or mitigate impacts. Over 4 percent of the land in California is a designated wilderness area, which prohibits the installation of mechanized or technological equipment.

Once installed, the gage needs to be calibrated by establishing a relationship between gage readings of stage or velocity and streamflow. Historically, measuring stage has been the most feasible and consistent measurement and is appropriate for most stream gage sites throughout the state. The most common method for collecting and computing streamflow using stage measurements is to develop a stage-discharge curve. Sites affected by lake or tidal influence may require measurement of velocity (instead of stage) for accurate streamflow measurement.

A stage-discharge curve is a key aspect of stream gage operations for both the establishment of the gage and long-term routine maintenance. An example curve is shown in Figure 2. Developing a stage-discharge curve involves the physical measurement of velocity and depth over a cross-section of the river by field staff using hand-held instruments or remote-controlled boats with onboard sensors. This measurement is done many times on different dates and with different flow rates to establish a correlation between the instrument's stage and the calculated streamflow. USGS recommends 8–12 streamflow measurements at different flows to establish a stage-discharge curve and routine measurements as part of annual ongoing maintenance. The resulting stage-discharge curve allows streamflow to be estimated remotely with a telemetered stage recording device.

Figure 2 Example stage-discharge rating curve



Sustained Gage Maintenance

Sustained gage maintenance and communication include the essential elements of routine gage calibration and maintenance of telemetry systems to maintain accurate and reliable results. Frequently, ongoing maintenance is not included in program and budget appropriation considerations and ongoing maintenance is often overlooked. All gages require routine maintenance to ensure the stage-discharge curve is accurate and to confirm that the site remains suitable for streamflow measurement. High streamflow events can result in accumulation of sediment or debris and other changes to stream channel geometry that can impact the calibration of the stage-discharge relationship or render a site unsuitable for streamflow measurement, even when the instrumentation, telemetry communication hardware, and software are operating correctly. Simply put, without sustained maintenance, reported data from stream gages lack the accuracy and consistency for reliable use by end-users.

Data Quality Control/Quality Assurance

Once the stage is measured, the streamflow is commonly reported as near-real-time "preliminary" data based on the gage-specific stage-discharge curve. In addition, a robust quality control and quality assurance process is performed to validate the reported values. For example, during a high flow event, debris or sediment movement can change the stage-discharge curve; following a site visit and recalibration, those preliminary data are adjusted appropriately based on the recalibrated curve. More context on this process is provided in the Data Management section of this document.

Overview of Gage Operators and Data Repositories

There are several agencies and private entities that operate permanent and temporary stream gages in the state. Some of these agencies and entities include:

- The United States Geological Survey (USGS).
- State of California — Department of Water Resources (DWR).
- The Army Corps of Engineers (USACE).
- Bureau of Indian Affairs (BIA).
- Private Electric Utilities (e.g., Pacific Gas and Electric, Los Angeles Water and Power, etc.).
- Local Water and Irrigation Agencies.
- The Bureau of Reclamation (BOR).
- The US Forest Service (USFS).
- California Geological Survey (CGS).
- Local Agencies (Cities and Counties).
- Community Groups, Academia, Non-Government Agencies (NGOs).
- Native American Tribes.

Most publicly available data originates from USGS- or DWR-operated gages. The State's CDEC; however, can report third-party (non-DWR) operated data if the data are formatted correctly and are near real-time with satellite telemetry. These data are frequently preliminary, which means the data have not been validated for accuracy. The entities listed above contribute at least some data to the CDEC repository. The State's Water Data Library (WDL) only reports data from DWR-operated gages and is the repository for validated data. Local agencies, utility companies, and private entities also have a significant amount of gage data; however, the majority of that data are not publicly available or are only available through local data repositories.

Gage Inventory and Stream Coverage (Gage) Gaps

An assessment of the existing gage network and coverage of the state's stream systems was an integral part of evaluating California's current stream gage network. This assessment is referred to as the Gage Gap Analysis. The University of California Berkeley's Stream Network Analysis for Gages (SNAG) tool was used to complete the Gage Gap Analysis, which includes:

- Evaluation of the existing gage inventory (of gages that share their data publicly).
- The network of stream and surface waters of the State (stream network).
- An assessment of existing gage coverage in the stream network.
- Identification of stream reaches throughout the network that are well gaged, almost well gaged, or ungaged.
- A summary of the analysis at the local sub-watershed level (i.e., Hydrological Unit Code 12 [HUC12]), which typically range in size from 40 to 150 square kilometers.
- Identification of current and historic stream gages that should be prioritized for upgrades or reactivation.

The Gage Gap Analysis focuses on physical and spatial elements of the stream network and existing gage locations and does not include an assessment of priority locations for gage reactivation or installation to meet management objectives. Incorporation of management objectives is addressed in a secondary assessment which is discussed in the Management Criteria and Prioritization section.

This analysis process was surprisingly complex and provides insight for future data management improvements. Gages are managed by several different entities, and there is not a single standardized gage inventory or accepted base layer dataset that includes all publicly available gages in California. As a result, defining gage activity and functions across multiple datasets is difficult. Similarly, while there is a single data source for the stream gage network, it includes both natural streams and infrastructure such as canals and pipelines. This is complicated further since there is not currently a differentiation between canals that lead into a pumphouses (not relevant) and canals that convey stream water across urban areas (highly relevant).

Development of the gage inventory and hydrography base-layers is described in detail in the sections below.

Gage Inventory

The process and decisions used to develop an existing gage inventory for the purposes of this plan are provided below. Existing gages were identified and separated into two broad categories:

1. **SB 19 gage inventory**. Gages that report validated and high-quality data from the USGS National Water Information System (NWIS), the CDEC, or the WDL. Existing gages in this category comprise the base dataset for the Gage Gap Analysis.

2. **Third-party operated gages**. This category consists of an incomplete catalog of known third-party gages and gage operators that were not included in the Gage Gap Analysis. Because of the time and resource limitations of this planning effort, completing a gage inventory and analysis of data quality for this category was unattainable. Gages operated by local entities and small projects that are not already part of a statewide database are also in this category. In part, this is to avoid inadvertently *excluding* high-value locations for permanent gage installation or upgrades because a locally operated temporary or seasonal gage exists at that location. The gages in this category, though, could be used to validate prioritization and potentially collaborate future gaging or data management efforts.

The SB 19 gage inventory consists of gages and metadata from 6,500 NWIS (United States Geological Survey 2020) stations nationwide, approximately 2,800 (California Data Exchange Center 2021) stations, and more than 100 (Water Data Library 2021) potential gaging stations. At first glance, this appears to be a large gage network; however, there is substantial overlap between the three databases, many inactive gages, and stations that are calculated from models or collect data other than streamflow. The inventory was pared down after defining the following parameters from gage metadata:

- Flow, stage data, water quality and/or water temperature data.
- Active or inactive status.
- Permanent gaging station or sampling location.
- Geographic Information System (GIS) stream segment assignment.
- Infrastructure assessment.
- Redundancy.

The analysis of historical and active gages in this report focuses on gages that collected regular stage or flow reports. Of the 3,600 total historical and active gages, approximately 2,600 met these requirements and are classified below; the gages that were not included in this analysis primarily collected water quality data or intermittent measurements that were not consistently collected and reported. The gage sites are classified into four categories for the Gage Gap Analysis and prioritization:

1. **Active — High Quality** (Active-HQ): Flow measurement is active, real-time, sampled daily, and located on either a stream segment or infrastructure connecting natural stream segments.
2. **Active — Limited Use** (Active-LU): Similar to Active-HQ except not real-time and/or stage-only. Site is a good candidate for an upgrade.
3. **Inactive:** Defined inactive by gage operator or, if undefined, no data collected later than 2019. This may include sites that are active but have inactive, irregular, or infrequent flow and stage measurements, or active water quality sites with a history of flow or stage gaging. Site is a good candidate for reactivation.
4. **Excluded:** Excluded from the analysis because of one or more of the following: history has irregular flow and stage measurements, calculated flow measurements (e.g., not actually measured by a gage at the site), located on infrastructure not connecting natural stream segments, inactive because of reservoir inundation, or insufficient data. Calculated flow measurements include model outputs, summing multiple upstream gages at a downstream point, and monthly reservoir volume changes divided by time.

There are approximately 662 Active-HQ and 359 Active-LU out of a dataset of 2,597 potential gaging stations. The remaining 1,576 gaging stations were identified as inactive (1,196) or excluded (380) in the Gage Gap Analysis. Redundant and non-streamflow “gages” were eliminated from the dataset, which accounts for the higher numbers in CDEC and WDL described above versus those shown below.

Table 2 SB 19 gage inventory and classification by primary source

Primary Source	Total Gages	*Active - HQ*	*Active - LU*	*Inactive flow/stage, reactivation candidate*	*Active, excluded*	*Inactive, excluded*
NWIS	2080	460	174	1126	33	287
CDEC	442	197	182	34	22	7
WDL	75	5	3	36	4	27
Total	2597	662	359	1196	59	321

Note: NWIS is the default primary source and CDEC second; redundant gages were eliminated from WDL and CDEC.

Stream Network Hydrography

The second core dataset in the Gage Gap Analysis is the stream and surface water network. Development of a statewide stream and surface water network began with the National Hydrography Dataset Plus Version 2.1 (NHDPlusV2.1) (Get NHDPlus 2021) and associated Value-Added Attributes (VAA) base datasets, which were clipped to the California state boundary. Initial efforts were made to filter the dataset to remove infrastructure and to set it for minimum drainage area size, but too many stream segments with gages on them were eliminated. The dataset was therefore only filtered to remove stream segments that did not have a drainage area attribute associated with them, since the Gage Gap Analysis requires drainage area. Gages located on stream segments that were filtered out were moved to an adjacent stream segment when appropriate, and a small number of gages, primarily inactive, were not analyzed.

Gage Gap Analysis Methodologies

A gage gap analysis is an inventory of the existing gage network and how well it covers the stream network. Gage gap analyses may be based on hydrography or on management objectives. For clarity and objectivity, this analysis considered only physical hydrography. Consideration of management objectives is discussed in the Management Criteria and Prioritization Analysis section.

Analysis of gage gaps is relatively complex, and there have been considerable research and prior efforts that provide insight into the efficacy of different approaches. Several different gage gap analysis methodologies were reviewed, and four were considered as candidates for this project. The candidate analyses were the TNC Gage Gap (TNCGG)[2]

[2] https://gagegap.codefornature.org/

; University of California, Berkeley Stream Network Analysis for Gages (SNAG); USGS National Stream flow Network Gap Analysis[3]) (NSNG) (Kiang et al. 2013); and the Network Analysis of USGS Stream flow Gages[4] (NASG) (Konrad et al 2021).

The TNCGG and SNAG approaches are based on a change in watershed area upstream and downstream of a gage. The primary advantage of the watershed drainage area method is that it is simple, flexible, and easy to implement. For the TNCGG method, a well-gaged stream segment is any segment with an active gage plus stream segments upstream that have a watershed drainage area that is greater than 50 percent of the watershed drainage area at the stream gage and less than 150 percent of the watershed drainage area downstream of the stream gage. The thresholds of 50 percent and 150 percent are cited as a maximum or recommended starting value by the USGS (Ries et al. 2008; Ries et al. 2017). The SNAG method is identical to the TNCGG method except that, with SNAG, the tool is written in R programming language, which allows for any configuration of gages and stream network, changes to watershed drainage area thresholds, and integration with a visualization tool or broader analysis.

The NSNG and NASG methods assess how easily streamflow statistics for ungaged locations can be estimated based on the gage network. Various statistics are calculated for the entire dataset of gages, and the priorities for new gages are areas where the watershed statistics are poorly correlated and therefore unsuitable for statistical flow prediction (or other metrics). NSNG predicts at several scales with a minimum size of 500 square kilometers (km^2), and the NASG works at the HUC12 watershed scale. The predictions are based on physical parameters such as watershed area, precipitation, snow, soils, elevation, geology, land cover, land fragmentation, water storage, road density, pollutants, canals, water diversions, etc. The primary advantage of this method is that it is correlated with multiple parameters and adjusted based on watershed characteristics. A disadvantage is that it requires an intensive effort using multiple parameters and regression equations to derive a high enough resolution to support the management priorities identified in SB 19. Additionally, for applications such as providing flood warnings, measuring real-time changes in stream flow from diversions, and monitoring real-time ecological low-flow stream conditions, actual gage measurements are important. Thus, the gage gap analysis for the purposes of this project serves to answer the question of how much of the stream system is actually gaged, not how well flows can be broadly estimated in ungaged watersheds.

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[3] https://pubs.usgs.gov/sir/2013/5013/

[4] https://www.sciencebase.gov/catalog/item/5f6b982482ce38aaa2454dc3

SNAG was chosen as the primary gage gap method (Gage Gap Analysis) because of its simplicity and flexibility and the time and resource constraints of this project. Statistical and machine learning methods are further discussed in the Emerging Technologies section of the Modernization and Emerging Technologies Chapter, and a statistical predictive flow model was used for the Reference Gage Network Analysis in the Management Criteria and Prioritization Chapter.

Gage Reactivation and Upgrade Analysis

The prioritization of gages to reactivate or upgrade (candidate gages) is based on historic gage record, location relative to other gages, and management priorities. Gage history and location are addressed here, but final prioritization that incorporates management considerations is discussed in later sections. Good candidate gages are those with decades-long flow records located away from other active gages. Conversely, temporary gages, intermittent sampling sites, or gages that are near active gages are not good candidates.

Spatial marginal benefit is how much additional spatial coverage would be gained by adding or upgrading a candidate gage. A simple analysis would rank sites by the candidate gages' additional well-gaged stream length, as calculated in the Gage Gap Analysis. For example, a gage that adds 50 stream kilometers (km) would rank higher than one that adds only 40 km; however, the pitfalls of a simple analysis are that it prioritizes downstream over headwaters gages and is blind to the total stream length within a watershed. For example, the additional 40 km may represent the entire stream length in a watershed while the additional 50 km may only be 20 percent of a larger, wetter watershed that already has several gages. Spatial marginal benefit could instead be determined by additional drainage area, although the pitfall is that large, desert watersheds and watersheds with large lakes or wetlands areas would always rank higher than smaller, steeper watersheds with many tributaries. Consequently, using proportional additional stream length or drainage area is a better indicator than just the absolute values.

Some candidate gages are located on well-gaged stream segments but not near the active gage, and thus may still be good candidates. A metric is therefore needed to determine where the candidate gage is located relative to the active gage. As downstream gages are likely to cover longer stream lengths, length-metrics may end up prioritizing downstream gages over headwaters gages even when the downstream gage has greater overlap with the active gage. In this case, it was determined that drainage area ratios work best to indicate the amount of overlap while removing downstream bias.

The sections below discuss the technical details of the analysis, including presence or absence of other gages in the same watershed, and the historic gage record.

Spatial Marginal Benefit

Spatial marginal benefit analysis is a multi-step process that eliminates redundant gages and uses the Gage Gap Analysis to assign a score. The score is a reflection of the level of marginal benefit (low, medium, or high) and the presence (or not) of an Active-HQ gage in the same watershed (referred to as “nearby” gages in this paragraph). Scores range from 1 to 5, with 1 being the best score and those gages with scores of 4 and 5 being eliminated (i.e., not recommended for reactivation or upgrade).

Gages were first evaluated for spatial redundancy by evaluating whether they occupied the same stream segment as another gage (active or inactive). Redundant gages were eliminated based on the gage gap classification status. Active-LU were eliminated if redundant with an Active-HQ gage, and inactive gages were eliminated if redundant with any active gage. In those cases where redundant gages were of equal classification, one of the gages was randomly selected while the others were eliminated. Redundant gages received the lowest score of 5.

A small number of candidate gages lack data because they are located off the stream network. These gages were given a score of 4 unless they were the only gage in their watershed, in which case they were given a score of 2.

Next, gages that are located on well-gaged stream segments were evaluated for redundancy, e.g., how close they are to the edge of the well-gaged area. The normalized drainage area difference is used for this calculation. The normalized drainage area difference is the absolute value of the difference between the drainage areas of the candidate gage and the active gage, divided by the mean drainage area threshold times the active gage drainage area (

Equation 1).

Equation 1. Normalized Drainage Area Difference Equation. DA = drainage area.

$$\Delta DA_{norm} = abs(DA - DA_{active})/(mean(threshold) * DA_{active})$$

$\Delta DA_{norm} = normalized\ drainage\ area\ difference$
$DA_{active} = drainage\ area\ of\ active\ gage$
$DA = drainage\ area\ of\ candidate\ gage$

The drainage area threshold is the maximum change in drainage area between the gage and a particular stream segment while still considered to be well-gaged; in this project, stream segments of 50 percent and 150 percent drainage area change are used, which is a threshold of 0.5 (50 percent upstream and 50 percent downstream). The classification is as follows: a drainage area threshold greater than or equal to 0.5 is not redundant (and analyzed further), a drainage area threshold greater than or equal to 0.2 and less than 0.5 is medium marginal benefit, and a drainage area threshold less than that is low marginal benefit.

The remaining gages and those classified as "not redundant" are further analyzed for proportional additional gaged length (PAGL), which is the candidate gage's additional gaged length (as calculated in the Gage Gap Analysis) divided by the total length of stream segments in the watershed. PAGL greater than or equal to 25 percent of the entire HUC12 watershed is high marginal benefit, PAGL greater than or equal to 10 percent and less than 25 percent is medium marginal benefit, and less than 10 percent is low marginal benefit.

The spatial marginal benefits score is a function of classification (low, medium, high) and nearby gages. Candidate gages are scored as follows:
5 = redundant; 4 = no data or low marginal benefit with nearby gages;
3 = low marginal benefit without nearby gages or medium marginal benefit with nearby gages; 2 = medium marginal benefit, no data without nearby gages, or high marginal benefit with nearby gages; and 1 = high marginal benefit without nearby gages.
Candidate gages scoring 4 and 5 were eliminated from further review and are not recommended for reactivation or upgrade.

Historic Gage Record

Historic gage record was scored on a scale of 1 to 3 for inactive gages based on the period of record (POR) conditions shown in Table 3 below. Gages in the Active-LU category were not scored for historic gage record since they are currently active.

Table 3 Historic Gage Record Score priority and conditions.

Historic Gage Record Score	Condition
1	POR > 25 years, or POR > 10 years and end-date > 2000, or active water quality or temperature monitoring.
2	POR > 10 years; or POR > 1 year and end-date > 2000, or POR > 1 year with temperature or water quality monitoring.
3	POR > 1 year but does not meet additional conditions in score category 2.
Not recommended	POR < 1 year, off-channel infrastructure, intermittent sampling sites, or calculated sites.

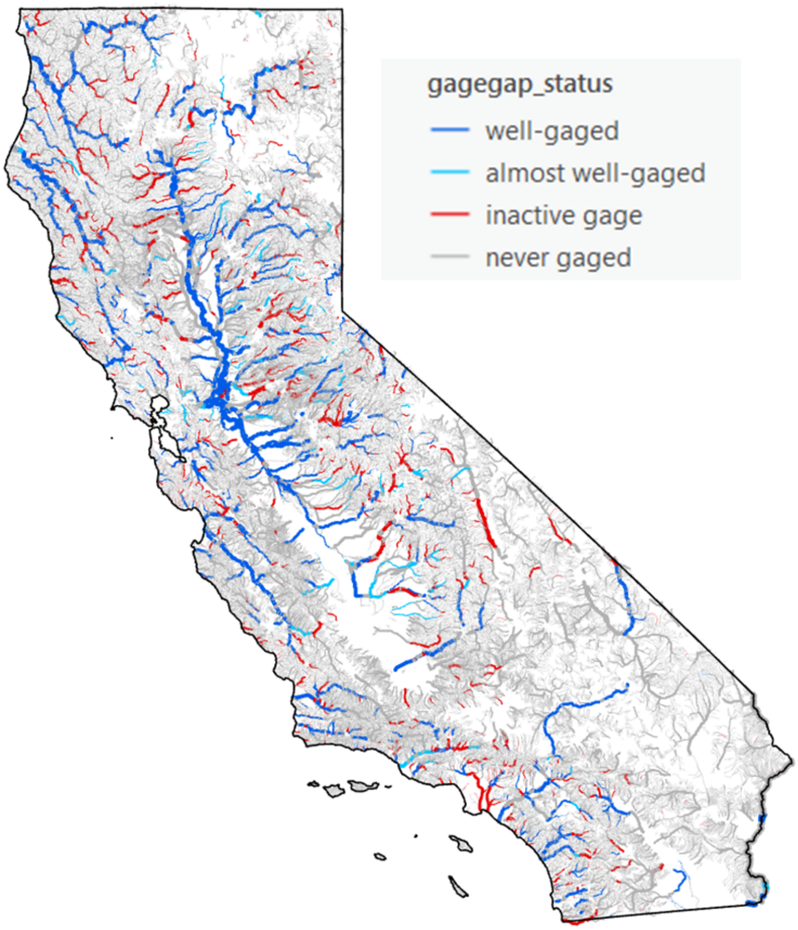
Final Scoring

The spatial marginal benefits score is the final gage gap score for Active-LU. For inactive gages, the history and spatial marginal benefits scores were combined and evaluated on the same 1–5 scale discussed above in the Spatial Marginal Benefits section. For inactive gages, if the historic gage record score was greater than or equal to the spatial marginal benefits score, the overall score remained the same. If the historic gage record score was lower than the spatial marginal benefits score by 1 point, the combined score was lowered by 0.5 points, and if the gage history score was more than 1 point lower, the combined score was lowered by 1 point.

Results

The SNAG Gage Gap analysis determines whether any given stream segment is well-gaged, almost well-gaged, excluded (covered by an inactive gage), or not gaged (no gage history). The results from the SNAG analysis can be summarized by any size of watershed (e.g., HUC12), used to identify the marginal benefit of reactivating or upgrading any given gage, and can help determine the best candidates for upgrade or reactivation in any given watershed. The results (Figure 3) show that many gages are located on downstream stream segments with large drainage areas, and that some areas lack stream segments because they are in the desert or because the natural stream has been channelized into irrigation ditches (southern Central Valley).

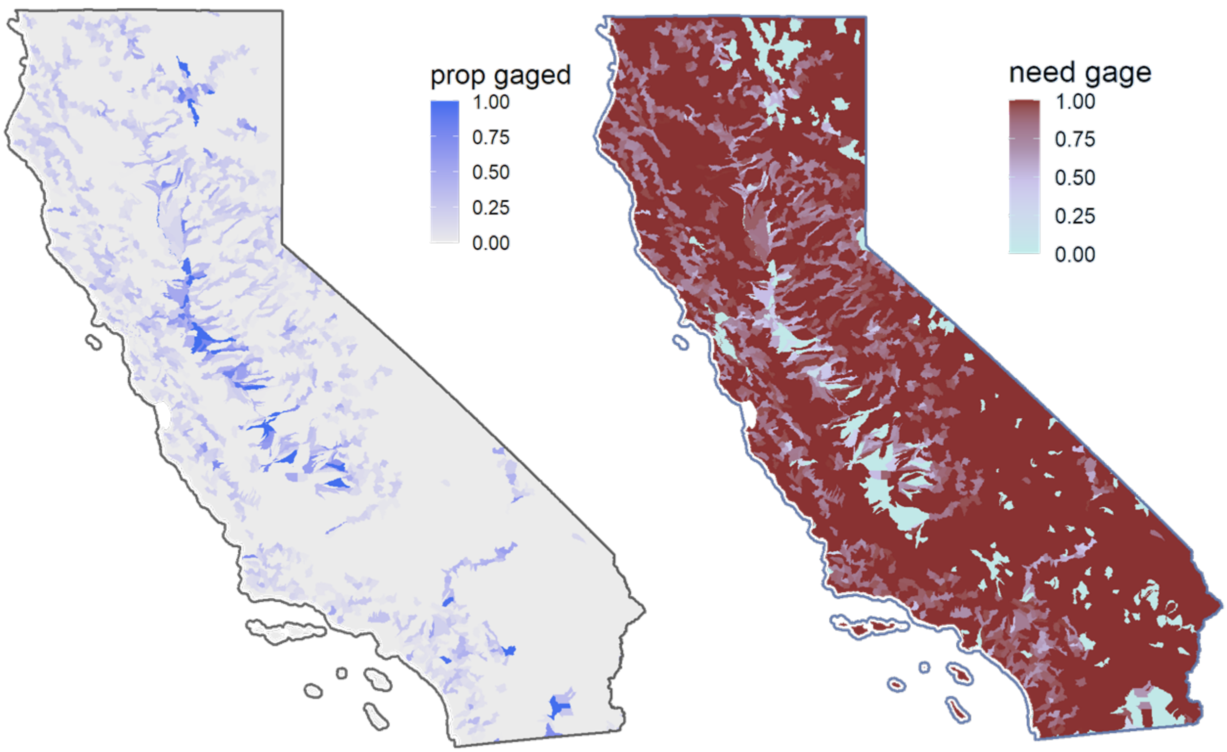
Figure 3 Gage gap analysis results from SNAG using 50% and 150% drainage area thresholds



Note: Thicker lines correspond to stream segments that are farther downstream, also called "stream order."

Another way of viewing the results is to summarize the proportion of each watershed that is gaged, by stream segment length, as is done for HUC12 watershed in Figure 4. The actively gaged proportion includes both well-gaged and almost well-gaged stream segments, while the gage need shows the opposite. The gage need is also referred to as a *gage gap* and is analyzed in the analysis and represented by the gage gap score. Viewed by watershed, most streams in California are ungaged and, proportionally, most watersheds lack gages. This is unsurprising: there are 4469 HUC12 watersheds in California, and only 1021 active stream gages.

Figure 4 Proportion of HUC12 watersheds that are actively gaged (prop gaged, left). The proportion of watersheds that need a gage, also called the gage gap score, is shown on the right (need gage). Blank areas on both maps lack flowlines or were eliminated because most of the watershed area is a lake (e.g., Lake Tahoe).

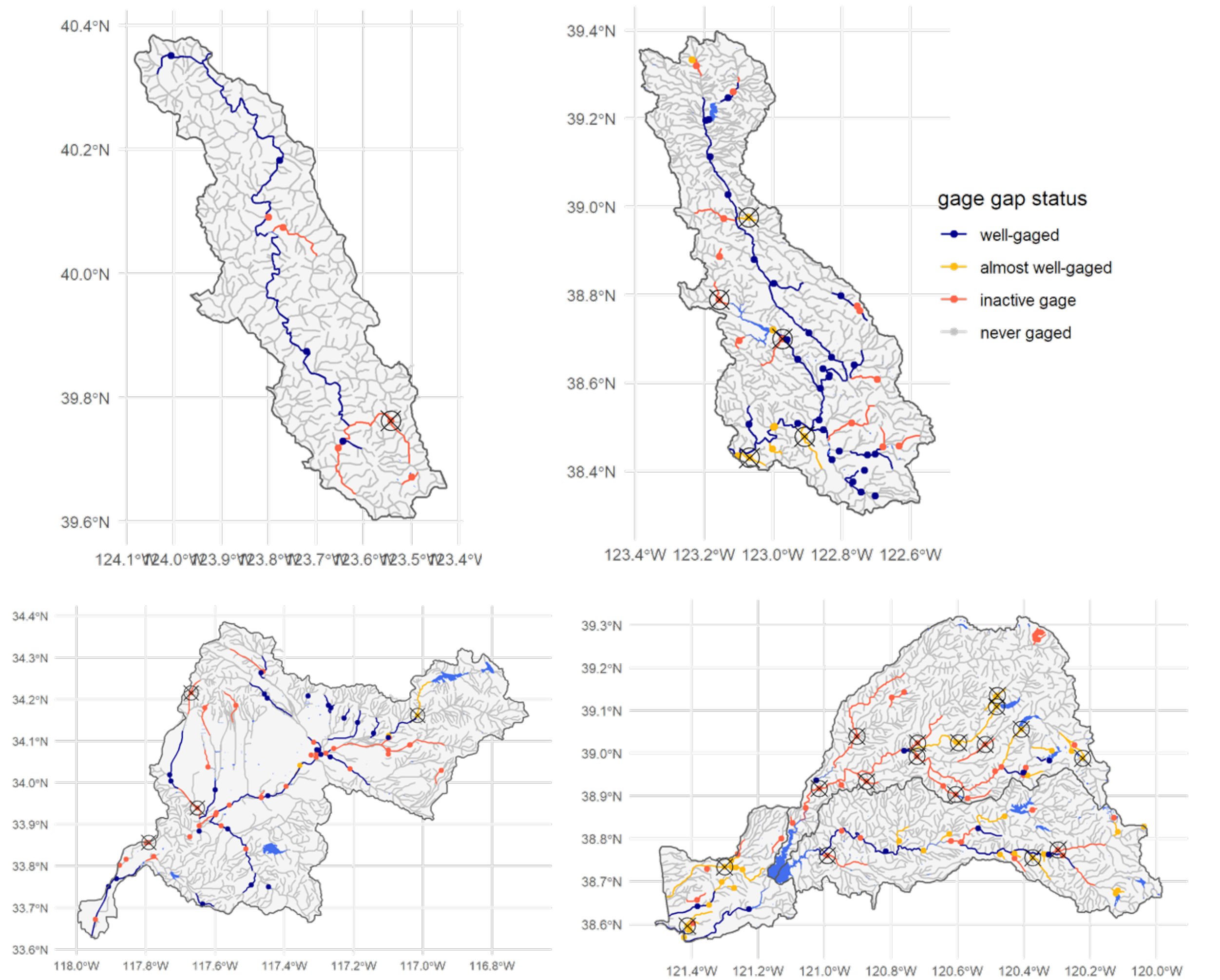


The combined historic gage record and spatial marginal benefits score are tallied in Table 4. This tally is generated prior to applying management priorities and represents a filtering step to remove less suitable gages and target the best candidates. There are 359 Active-LU gages and 1196 inactive gages, but they are not all good candidates since some are redundant, have poor spatial marginal benefit, or too short a historic record.

Gages with a score of 1 or 2 are generally good candidates for upgrades or reactivation: there are 109 Active-LU (30 percent) and 340 inactive gages (28 percent) scoring 2 or better. There are 4469 HUC12 watersheds in California, of which 3237 (72 percent) have no history of gaging (active or inactive). 592 watersheds (13 percent) with a candidate gage have no current active gages. For watersheds with candidate gages flagged for reactivation or upgrades, there are 413 watersheds (9 percent) with candidate gages scoring 1 or 2, and 811 (18 percent) scoring 1, 2, or 3.

The candidate gages can be mapped alongside the Gage Gap Analysis results. Zooming in to specific watersheds helps to visualize the results on a local level (Figure 5). The propensity of active stream gages to be located on mainstem rivers is obvious, but there are many stream reaches that could be added by upgrading or reactivating a gage. In Figure 5 below, the bullseye gages have a minimum score of 2 or better and are the best score in their respective HUC12s.

Figure 5 Gage gap and gage analysis results from SNAG for the South Fork Eel (top left), Russian (top right), Santa Ana (bottom left), and American (bottom right) river watersheds



Note: Gages with a bullseye have minimum score of 2 and are identified as the best gage to upgrade in their respective HUC12. There are multiple HUC12s in each watershed shown.

Management Criteria and Prioritization

One of the main goals of the SB 19 Plan is to address significant gaps in information necessary for effective water management and the conservation of freshwater species. The SB 19 Plan prioritizes modernizing, reactivating, or placing new gages in locations that best meet the needs for water supply, flood, water quality, and ecosystem management. These specific management needs or categories are referred to as *Management Criteria*. Additional management needs identified in SB 19 (e.g., groundwater management, water temperature management, cannabis, etc.) are also addressed within the Management Criteria except for the reference gage network, which was analyzed separately.

The prioritization effort combines the Management Criteria, Gage Gap Analysis, and Gage Inventory to identify: (1) watersheds that have the highest need of new or reactivated gages, (2) the best candidate gages for reactivation and upgrades, and (3) areas where water can be managed for multiple benefits.

This effort involved identifying the highest priority needs within each management category and evaluating and choosing datasets that best represent those priority needs. We recognize that there are a large number of datasets that could be used to represent priority needs within each management category. Datasets were chosen that were reviewed by experts in their field, often comprising several smaller datasets, and that fully represent the highest priorities in each of the Management Criteria while minimizing internal redundancy.

It is also important to recognize that there is some overlap between the different management categories. For example, groundwater (and surface water-groundwater interaction) is addressed in water supply but also with groundwater-dependent ecosystems (GDE) under ecosystem management. Surface water storage is addressed in both flood and water supply management as reservoirs serve both functions. Datasets that had crossover potential were placed in a single management category that best represented the purpose of the dataset and gaging needs of the management category.

Combining all the datasets and management criteria categories into a single recommendation score was considered, but this approach was decided against in recognition of the limitations of the individual datasets, transparency in the analysis, and acknowledgment that future stream gaging may choose to target areas suited for managing multiple benefits as well as high-priority areas in each of the individual management categories. As such, we primarily considered each of the Management Criteria separately and then evaluated for multi-benefit overlap in the top-ranking results.

For each management category, a management prioritization score was assigned by assigning a watershed score for each individual dataset (usually between 0 and 1), weighting each of the input datasets by relative importance or value, and then summing the weighted input scores (Equation 2) in each watershed. It should be noted that even valuing each input dataset equally is in itself a value-judgement, and that there are many valid reasons for unequal weighting, which will be discussed for each case.

Equation 2. Equation used to weight and sum the input datasets.

$$\sum_{m=1}^{M} dataset\_score_m * weight_m = management\_criteria\_score$$

The gage gap score represents the proportion of each watershed in need of a gage, which is calculated by summing the proportion of the watershed that is well gaged and almost well-gaged (by stream length) and subtracting from 1. Note that Active-LU gages are, for the purposes of management criteria prioritization, considered equal to Active-HQ gages, as these two categories are both active and used for water management. In addition, watersheds with less than 5 km of total stream length or whose area overlapped with a waterbody by more than 50 percent (e.g., Lake Tahoe, Goose Lake, Clear Lake, Mono Lake, etc.) were assigned a score of 0, since there are few or no appropriate places for stream gages.

The final prioritization score was calculated by multiplying the management criteria score and gage gap score (higher score equals higher priority).

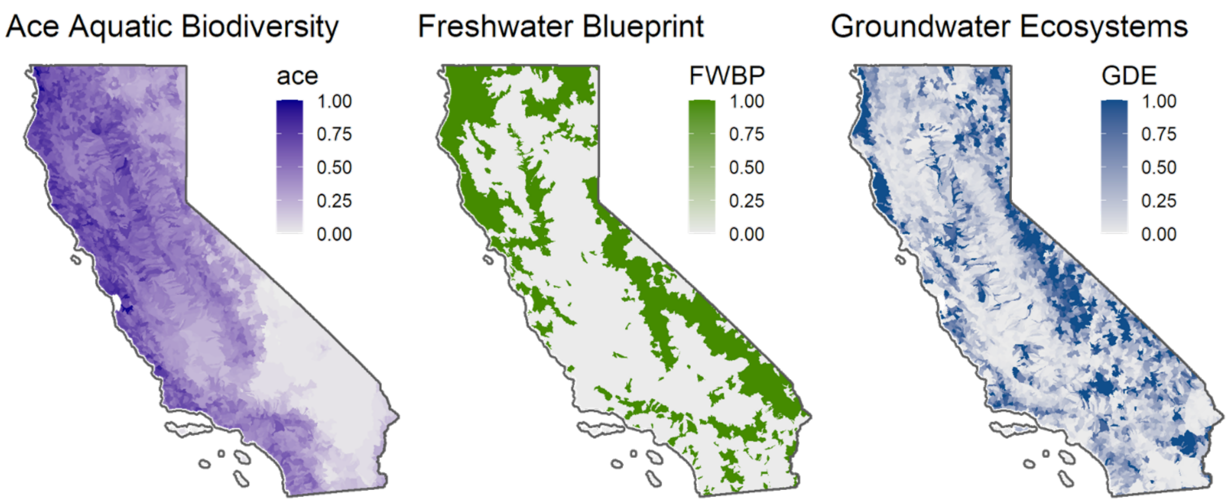
Ecosystem Management

The most important concerns identified for ecosystem management were threatened and endangered aquatic species, groundwater-dependent ecosystems, and a holistic approach for ecosystems in terms of taxa and spatial distribution. It should be noted that surface water and groundwater interaction are both indirectly addressed, here through groundwater dependent ecosystems and later in the Water Supply Management section, to inform potential gaging needs related to the Sustainable Groundwater Management Act (SGMA).

Datasets

Three datasets (Figure 6) were chosen to represent the ecosystem concerns identified above: (1) CDFW Areas of Conservation Emphasis, Aquatic Biodiversity Summary (ACE Aquatic Biodiversity) (California Department of Fish and Wildlife 2015 and California Department of Fish and Wildlife 2019); (2) TNC Freshwater Conservation Blueprint (Freshwater Blueprint) (The Nature Conservancy 2018); and (3) TNC Natural Communities Associated with Groundwater, version 2.0 (Natural Communities Commonly Associated with Groundwater 2.0) dataset (The Nature Conservancy 2021).

Figure 6 Ecosystem input datasets for prioritization



ACE Aquatic Biodiversity

The ACE Aquatic Biodiversity dataset synthesizes spatial data on wildlife, vegetation, and habitats into thematic maps by HUC12 watershed, drawing from multiple sources of vetted species occurrence data as well as predictive species modelling efforts. ACE Aquatic Biodiversity is an index that combines three measures of biodiversity: (1) aquatic native species richness, which represents overall native diversity of all species, both common and rare, in the state; (2) aquatic rare species richness, which represents diversity of rare species; and (3) aquatic irreplaceability, which is a weighted measure of rarity and endemism. The included taxa are aquatic amphibians, fish, aquatic invertebrates, and aquatic reptiles. This dataset was chosen because it combines native, rare, and endemic species richness into a single metric and is published and vetted by CDFW.

Freshwater Blueprint

The freshwater conservation blueprint dataset (FWBP) (Howard et al. 2018 and The Nature Conservancy 2018) was developed by TNC by analyzing species distribution data to identify areas of high freshwater conservation value that optimized representation of target taxa on the landscape and leveraged existing protected areas. For each watershed, they compiled data on the presence/absence of herpetofauna and fishes; observations of freshwater-dependent mammals, selected invertebrates, and plants; maps of freshwater habitat types; measures of habitat condition and vulnerability; and current management status. The data can be symbolized according to many attributes; however, the recommended usage of this dataset is to include all of the watersheds with equal rank, as they have already been chosen as conservation priority areas in California, based on species, current protective status, and in groups of contiguous watersheds. This dataset, representing 34 percent of California, complements the other datasets by considering habitat and existing conservation status and weights contiguous areas as priorities for conservation. The overlap with public lands and protected areas helps to ensure that stream gaging will have a direct and useful benefit to areas already managed for biodiversity.

Natural Communities Commonly Associated with Groundwater

The Natural Communities Commonly Associated with Groundwater (NCCAG) 2.0 dataset is a compilation of 48 publicly available State and federal agency datasets (published between 1984–2016) that map vegetation, wetlands, springs, and seeps in California, which represent indicators of groundwater dependent ecosystems (GDEs). GDEs are ecological communities or species that depend on groundwater emerging from aquifers or on groundwater occurring near the ground surface. (California Code of Regulations, Title 23, section 351(m)) This dataset addresses ecosystem response to groundwater diversion. Surface water-groundwater interactions are a high concern for many environmental managers, including those that are working on SGMA efforts.

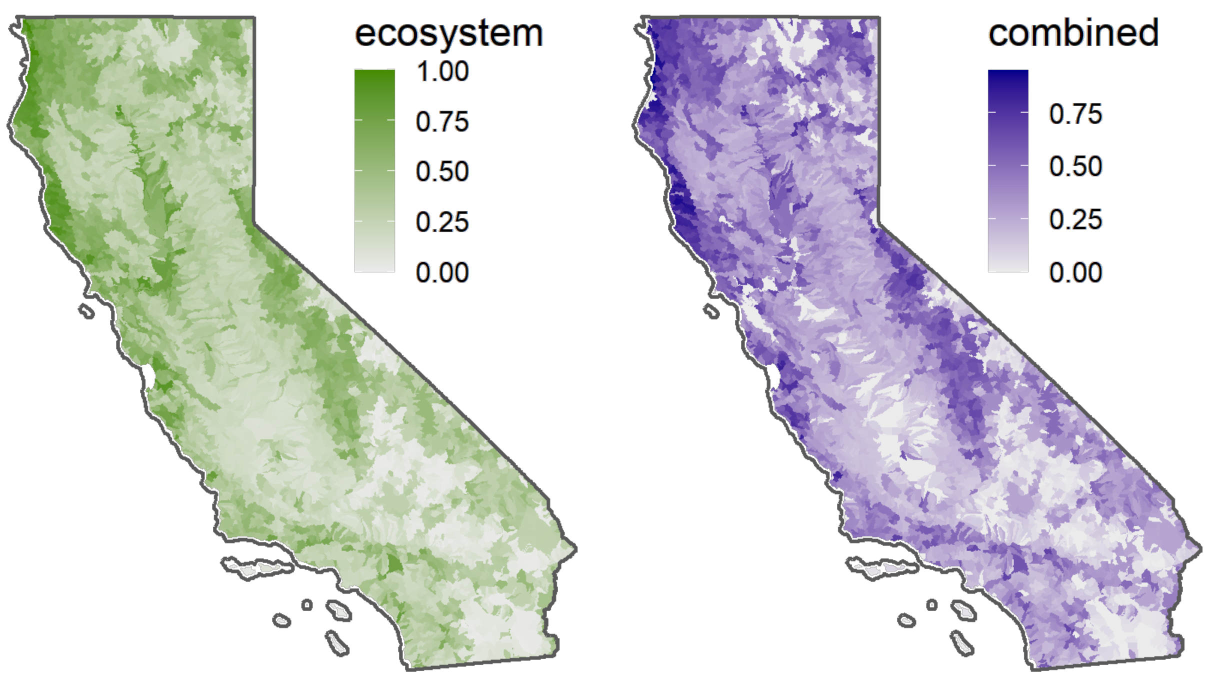
Prioritization Ranking

The three input layers were scored between 0 and 1, weighted to provide relative value between the input datasets, and summed to produce a final score. The ACE Biodiversity score is the raw score used to create the index, which ranges between 0 and 1. Freshwater blueprint scored either 1 (in-network) or 0 (not-in network). The NCCAG v02 dataset comprises roughly 500,000 vegetation and wetlands polygons; the areas from the two datasets were first summed for each HUC12, and then divided by the total area of the HUC12. There is overlap between the vegetation and wetlands polygons, such that some areas are double-counted, but these areas also represent the highest likelihood of near-surface groundwater, so the double-counting serves to weight the most likely areas. Thus, the result (Figure 6) is not a true percentage of the watershed area.

The three input layers were then weighted with ACE scores given a weighting of twice that of the other two layers. This helps to ensure that areas with high biodiversity that are not included in the freshwater blueprint or that have little groundwater interaction are still prioritized for stream gaging. Locations benefiting from more emphasis on biodiversity include the southern and central coast. The locations that scored well with equal weighting across all three datasets still scored high with the additional ACE weighting (high scoring locations are relatively insensitive).

Finally, the ecosystem score was multiplied with the gage gap score to produce a final ecosystem gage gap priority score (Figure 7).

Figure 7 Ecosystem prioritization showing raw prioritization score (left) and ecosystem combined with gage gap score (right)



Discussion

The three input layers are weighted such that the ACE Biodiversity comprises half of the score and the GDE layer plus FWBP comprise the other half. A high-scoring ACE biodiversity watershed may only receive a score of, for example, 0.75, while all FWBP watersheds receive a score of 1 because there is no differentiation in priority level. In short, the ACE biodiversity dataset receives an inadvertent penalty for being a higher resolution analysis in comparison to the FWBP, and thus, needs addressing in the weighting. The addition of the GDE layer places emphasis on areas with widespread wetlands areas, including tidal marshes and flat river bottoms, over steeper headwater streams that may have narrower riparian corridors, which arguably is a problem, and is partially addressed with a lower weighting than the ACE biodiversity layer. The final result shows a strong signal on the North Coast, northern Central Valley, and Sierra Nevada.

Water Supply Management

Water supply management is a large category that encompasses surface water diversions, reservoirs, groundwater pumping, aquifer management, and water transfers. Some of these areas are best managed with methods that do not rely heavily on stream gaging; in other cases, there is considerable overlap with another management criteria area.

The areas for which stream gages are most likely to enhance Water Supply Management are surface water diversions and groundwater basin management, especially pertaining to surface water-groundwater interaction and potential for managed aquifer recharge. Surface water diversions are regulated under the California water rights system. Areas where surface water is limited may be deemed fully appropriated or adjudicated, limiting future water rights and allocated diversions between existing water rights holders. Instream flow recommendations are being developed for many streams in California to protect aquatic ecosystems from the effects of excessive diversions. Water rights may be subject to seasonal allowances, curtailments, instream flow requirements, and other actions. Stream gages can help monitor real-time flow conditions and are key to understanding the impact of surface water diversions.

Forecast-informed reservoir operations (FIRO) is a reservoir-operations practice that uses enhanced monitoring and improved weather and water forecasts to inform reservoir operations that strategically retain or release water from reservoirs to optimize water supply, reduce flood-risk, and enhance environmental co-benefits. The FIRO program is currently a pilot project for key large reservoirs and is discussed in more detail and prioritized under the Flood and Emergency Management section. Furthermore, FIRO may expand to include other watersheds and reservoirs over time as resources and management objectives dictate.

Groundwater resources in California are important for current and future water supply, groundwater-dependent ecosystems, and interconnected surface water. Groundwater basins are facing increasing regulation and management in the form of adjudications and SGMA. Groundwater also offers a potential powerful alternative to surface water reservoirs through flood managed aquifer recharge (Flood-MAR), which would divert high surface water flows to intentionally flood an area conducive to the percolation and recharge of the surface water to the shallow underlying aquifer. Where percolation or recharge is not feasible, the surface water could be conveyed down to the aquifer(s) by using injection wells. Suitable locations for a Flood-MAR project depend on a combination of water availability, water rights considerations, soil and aquifer characteristics, land use, crop suitability (if using agricultural lands), conveyance infrastructure, and other criteria (California Department of Water Resources 2018). Stream gaging could benefit groundwater management when there is a connection between the stream and aquifer or to assess water availability for groundwater recharge.

Water transfers can be one of the water management tools used to enhance flexibility in the allocation and use of water in California. Transfers are particularly useful for meeting critical needs during drought periods. Water transfers can occur when willing sellers (surface water rights holders) enter into an agreement with buyers (entities willing to purchase the seller’s surface water); these agreements are facilitated by State and federal agencies. There are three types of water transfers: (1) Cropland Idling/Crop Shifting; (2) Groundwater Substitution; and (3) Reservoir Release. Cropland idling requires the seller to idle or fallow land that would have been planted during the transfer period in the absence of the transfer. Crop shifting requires the seller to shift from historically planted higher-water-intensive crops to lower-water-using crops. Groundwater substitution transfers require the seller to make surface water available for transfer by reducing or forgoing their surface water diversions and replace that water with groundwater pumping to meet the seller’s needs. Reservoir release transfers make surface water available for transfer when the seller releases water from their reservoir in excess of what would be released annually under normal operations; the water must also be released at a time when it can be captured and/or diverted downstream after conveyance loss. Transfers must be carried out in a responsible manner to ensure that they do not result in adverse impacts to other water users, including the State Water Project and the Central Valley Project, or the environment. While stream gages can be an important tool in accessing the affects and the routing of the amount of water transferred, water transfers are project specific and are not included in this statewide analysis.

It is understood that large surface water reservoirs and conveyance systems are a major part of the California water supply that is not directly included as an explicit data set in the water supply management criteria. This is largely because most of these reservoirs and conveyances already have stream gages, reservoir volume measurements, or controlled stream releases. Furthermore, flood hazard is the primary way stream gages could be helpful for large reservoir management, as such, large reservoirs are included in the flood management category. Forecasting of water supply for the upcoming season is best done with precipitation, air temperature, solar radiation, and snow level measurements, not necessarily stream gages. Finally, managing a few large reservoirs is, in many ways, less challenging than managing hundreds of smaller diversions. Stream gages have high potential to help assess and manage the large numbers of small diversions that can contribute to intra-basin water supply conflict as well as conflict with ecosystem and water quality.

Datasets

Seven datasets were chosen to represent surface water diversions and areas of conflict, groundwater priority basins with interconnected surface water, and Flood-MAR.

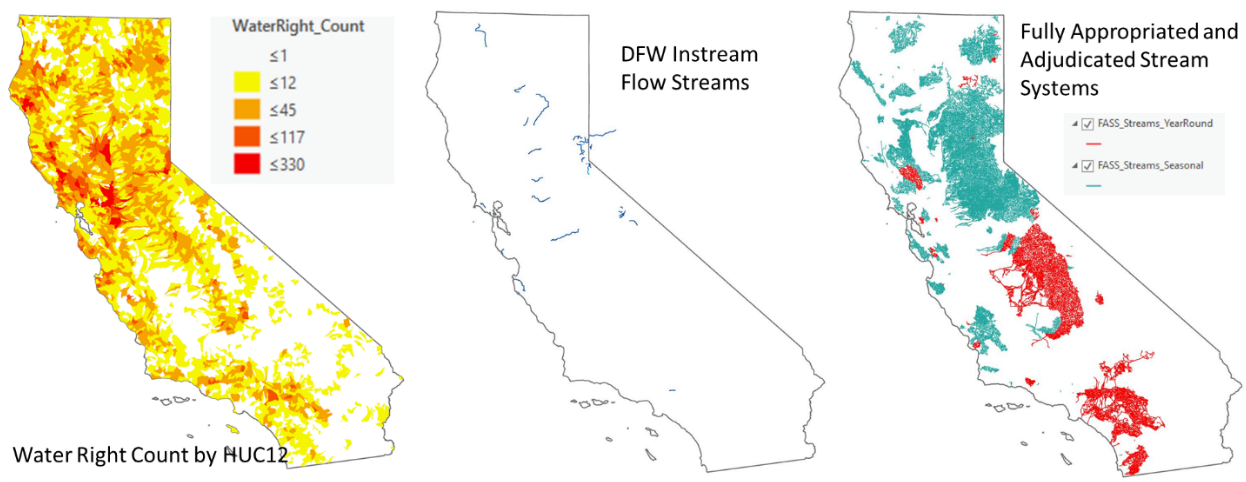
CDFW Instream Flow Recommendations (IFR)

CDFW has developed Instream Flow Recommendations[5] (California Department of Fish and Wildlife n.d.) for a number of streams, including the Scott River, Battle Creek, North Fork Feather River, Butte Creek, the Lower Yuba River, the Truckee River and several Tahoe-area streams, the Lower American River, the Lower Mokelumne River, Lagunitas Creek, the Merced River, Scott Creek, the West Fork San Gabriel River, Redwood Creek (Marin), and several creeks flowing into Mono Lake (Figure 8). This layer represents areas with available instream flow recommendations that were prepared and submitted by CDFW[6] to the State Water Board pursuant to Public Resources Code Section 10002 (California Department of Fish and Game 2008). We are using this layer to show areas of conflict by assuming that these streams have been identified as areas of high aquatic resource value that have the potential to be impacted by water diversions. Streams may be added to this layer as additional instream flow recommendations are submitted.

[5] https://wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/Recommendations

[6] https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=14489

Figure 8 Surface water data layers to generate a surface water priority score



Fully Appropriated and Adjudicated Stream Systems

Fully appropriated stream systems[7] (FASS) (Figure 8) are those where there is insufficient supply for new water right applications (State Water Resources Control Board n.d.). The FASS dataset includes seasonal and year-round diversion limitations, relevant court references, and State Water Board decisions and orders, but excludes State and federal Wild and Scenic Rivers (which also have limitations on new water right applications).

Surface Water Diversion Locations

Surface water diversion (SWD) locations are legal water rights that are tracked and permitted by the State Water Board. This dataset is a bulk download of the Electronic Water Rights Information System surface water points of diversion (PODs) that was filtered to remove inactive water rights and modified to select a single POD to represent each water right to remove density bias for water rights that have multiple closely spaced diversion points and storage locations (State Water Resources Control Board 2021).

While it is possible to estimate diversion volumes as well, volume is heavily biased toward large reservoir and water systems. In addition, large reservoir and water systems are well-monitored through regulation or necessity, and additional gaging needs for reservoirs are evaluated under the flood management category. Individual points of diversion locations are a distributed dataset that can help inform which areas

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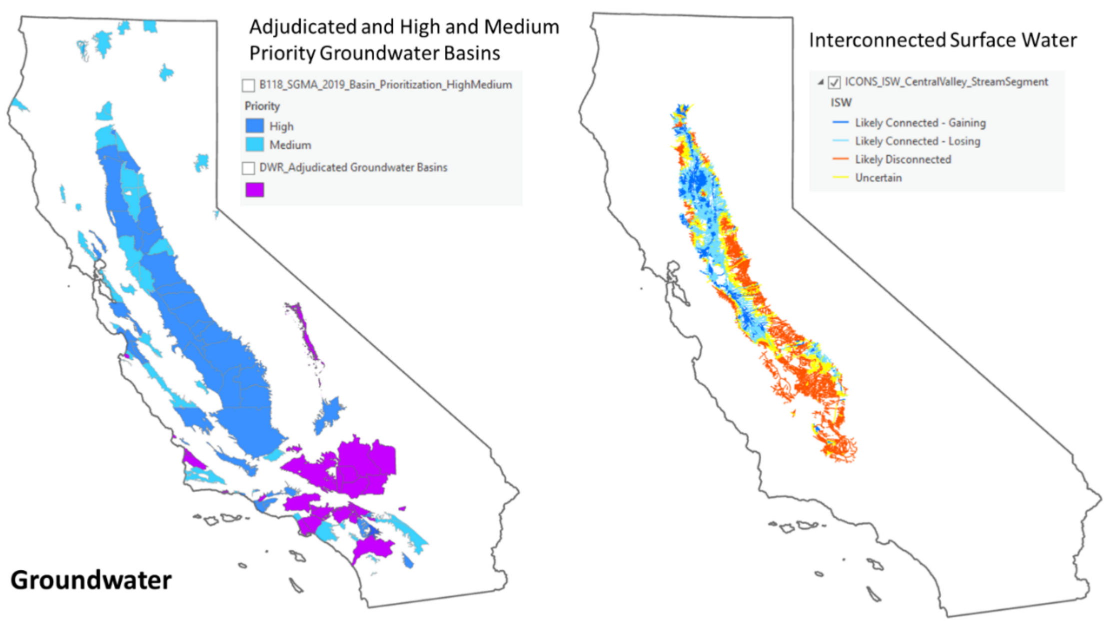
7 https://www.waterboards.ca.gov/waterrights/water_issues/programs/fully_appropriated_streams/

have a large number of water rights holders and surface water diversions (Figure 8). This dataset is also simpler and does not require the pre-processing and judgment required for volume estimates. The number of SWD ranges from 0 to 330 in a HUC12 watershed, with an average of 10 and median of 3, reflecting the large number of watersheds with no surface water diversions at all.

SGMA Bulletin 118 Groundwater Basins

SGMA requires local agencies to develop and implement [groundwater sustainability plans](https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management)[8] to avoid undesirable results and mitigate overdraft within 20 years in high- and medium-priority groundwater basins (California Department of Water Resources n.d.). This dataset represents areas of conflict between water users and SGMA undesirable result objectives and is an important water supply management area of current interest in California.

Figure 9 Groundwater Basins and Interconnected Surface Water Layers



Adjudicated Groundwater Basins

Court-ordered adjudications happen when water users are in dispute over legal rights to the water and the court is brought in to settle the dispute by determining the legal rights of all diverters, including how much groundwater may be pumped in a given management area. The adjudication can cover an entire basin, a portion of a basin, or a

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[8] https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management

group of basins and all non-basin locations between. The 27 adjudicated basins[9] are required to report under SGMA (California Department of Water Resources n.d.). Adjudicated basin management predates SGMA and represents areas of conflict between water users.

Interconnected Surface Water in the Central Valley

Stream gaging is only useful to support groundwater management if the surface water and groundwater are interconnected. This layer provides a method to filter for interconnected surface water in groundwater basins. The ICONS dataset[10] (Groundwater Resource Hub 2021) shows the likely presence of interconnected surface water (ISW) in the Central Valley (Figure 9). Interconnected surface water is stream water that is connected to groundwater through a saturated zone. Stream volumes increasing from groundwater interaction is called "gaining," while decreasing from losses to groundwater is called "losing" or "being disconnected." Groundwater pumping can cause gaining streams to become losing streams or increase the rate or volume of surface water loss in losing streams, thereby depleting vegetation and the stream ecosystem of water.

Unfortunately, this layer only covers the Central Valley. The methodology could, in theory, be applied to groundwater basins statewide, and some Groundwater Sustainability Agencies (GSAs) may have already done so. However, the SB 19 team does not have the resources to conduct an independent analysis or to collect and analyze potential studies by individual GSAs.

UC Davis Soil Agricultural Groundwater Banking Index

The Soil Agricultural Groundwater Banking Index (SAGBI) (University of California 2015) is a suitability index for groundwater recharge on agricultural land. The SAGBI is a weighted score based on five major factors that are critical to successful agricultural groundwater banking: deep percolation rates, root zone residence time, topographic limitations, chemical limitations, and soil surface conditions (Figure 10). The Moderately Good, Good, and Excellent categories (score ≥ 50) are suitable for Flood-MAR projects. Agricultural lands with a high SAGBI score may be quite removed from the stream(s) or river(s) that may serve as the water source; however, we found that the input streams are either entirely contained within a HUC10 watershed that also contains a SAGBI basin or are blocked by a large reservoir, such that that water would be

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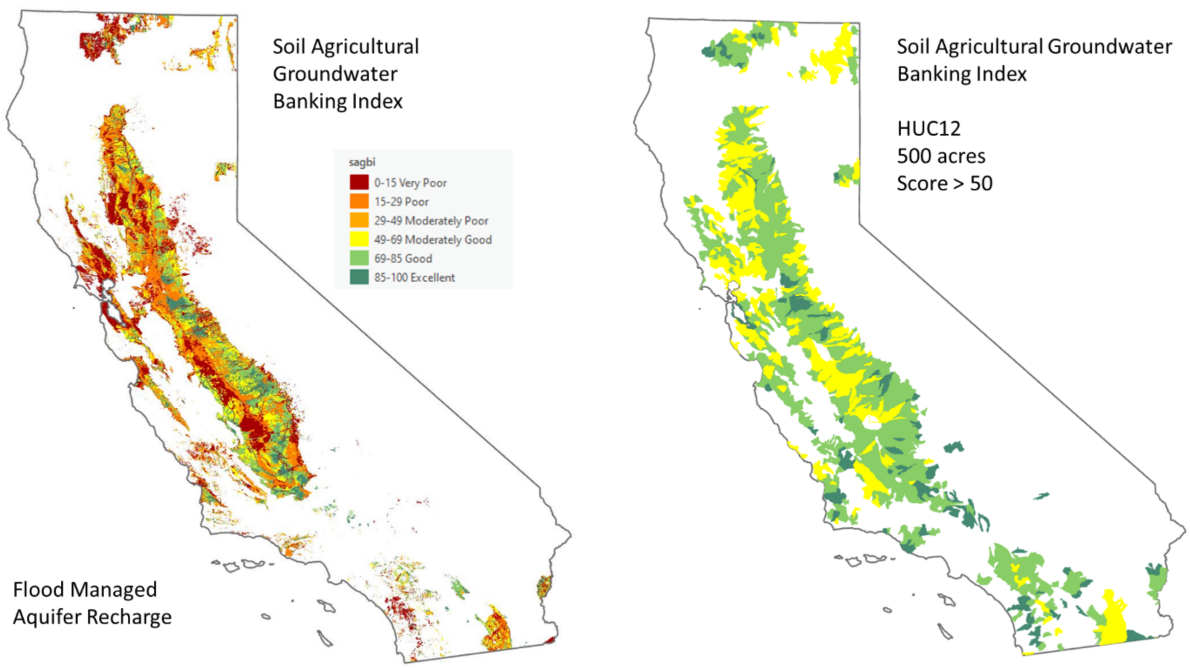
[9] https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management/Adjudicated-Areas

[10] https://icons.codefornature.org/

passing through the reservoir and consequently be part of the gage network supporting the reservoir operations.

While the SAGBI does not address all the issues related to siting a potential Flood-MAR project, it does address some of the fundamental physical and agricultural cropping considerations, such as the capacity of agricultural land to accept recharge, and the possible limitations of existing perennial crops to tolerate prolonged root zone saturation. Lands currently cultivated with annual crops are assumed to have no limitation in this regard, since they would likely be fallow during the period of high flood-water availability in the winter.

Figure 10 Modified SAGBI Flood-MAR areas (left) and HUC12 watersheds with SAGBI potential (right)



Prioritization Ranking

The water supply dataset was first grouped into three categories: surface water, groundwater, and Flood-MAR potential. Each category was scored and then added together to calculate the overall score.

The surface water score is a combination of the IFR, FASS, and SWD layers. IFR watersheds are scored 1 if there are any instream flow recommendations present and 0 if there are none. FASS watersheds are scored 1 if they contain FASS and 0 if they do not contain FASS (although streams with less than 5 percent of stream segments, because of minor spillover of FASS systems into adjacent watersheds, are given a score of 0). The SWD score is the logarithmic (base 10) value of the total number of water rights diversions in the watershed. The logarithmic value is exponential and used because of the large variation in total water rights in any given watershed. For example, 50 and 250 SWDs are both significant (logarithmic scores = 1.7 and 2.4, respectively), while < 3 SWDs are not significant (logarithmic score = 0.5). Thus, the water rights score ranges from 0 to 2.5, reflecting a range of SWD from 0 to 330. The three datasets are summed and normalized for a score between 0 and 1.

The groundwater score was generated by first selecting all watersheds with at least 10 km^2 or at least 10 percent of watershed area underlain by medium- to high-priority SGMA basins and DWR-adjudicated basins. All other watersheds not meeting the minimum area criteria were automatically scored zero. Next, the groundwater basins were assigned a score based on ISW. ISW stream segments were scored as follows: 4 = Likely Connected, Gaining; 3 = Likely Connected, Losing; 2 = Uncertain; 1 = Likely Disconnected. The watershed ISW score was generated by first calculating the mean and standard deviation of stream segment ISW scores, and then adding one standard deviation to the mean to help highlight the portion of streams with interconnected groundwater in each basin. Basins outside of the Central Valley do not have ISW stream segments, so the likelihood of connection was estimated based on geographic location and score of adjacent areas as follows: 3.5 = Northern California; 2.5 = Eastern Sierra, Western Slope Sierra, and Central Coast; 1.5 = Southern California. Finally, all basins were assigned a raw score equal to the ISW score, and all raw scores were normalized between 0 and 1 by dividing by 4, setting the maximum value to 1 if the normalized score exceeded 1. This analysis could be improved by a more comprehensive ISW layer.

Equation 3. Calculating watershed ISW score by adding mean and standard deviation of the ISW from stream segments.

$$ISW_{HUC} = mean(ISW_{ss}) + \sigma$$

$ISW_{HUC} = ISW\ for\ the\ HUC12\ watershed$
$ISW_{ss} = ISW\ of\ the\ stream\ segment$
$\sigma = standard\ deviation$

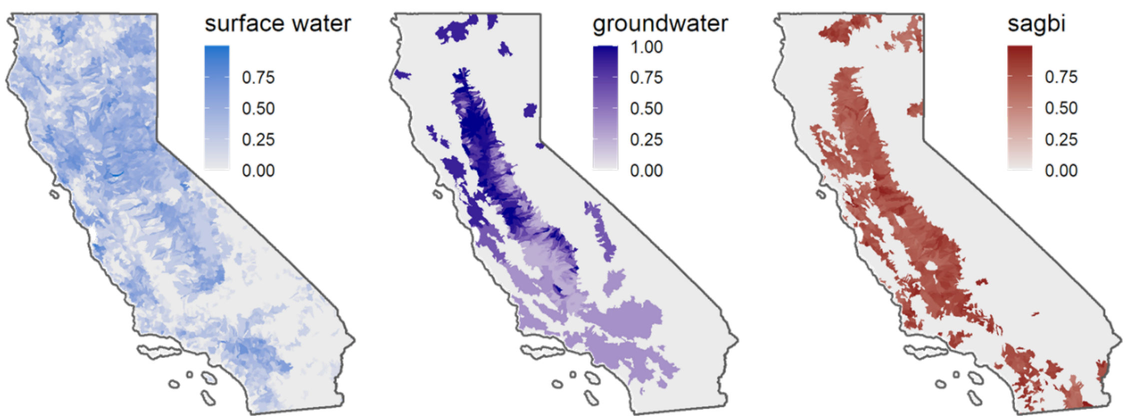
The SAGBI score was used to represent Flood-MAR potential. The SAGBI score was generated by first selecting only basins with a score greater than 50 (e.g., selecting only suitable basins and eliminating unsuitable basins), splitting those basins into HUC12 watersheds, limiting the analysis to watersheds with at least 500 acres of SAGBI basins, and then calculating a mean normalized SAGBI score, as described in Equation 4.

Equation 4. Calculation of mean normalized SAGBI score in each watershed.

$$Mean\ Normalized\ SAGBI_{HUC} = \sum_{i=1}^{N} area_i * sagbi_i \Big/ area_{total}$$

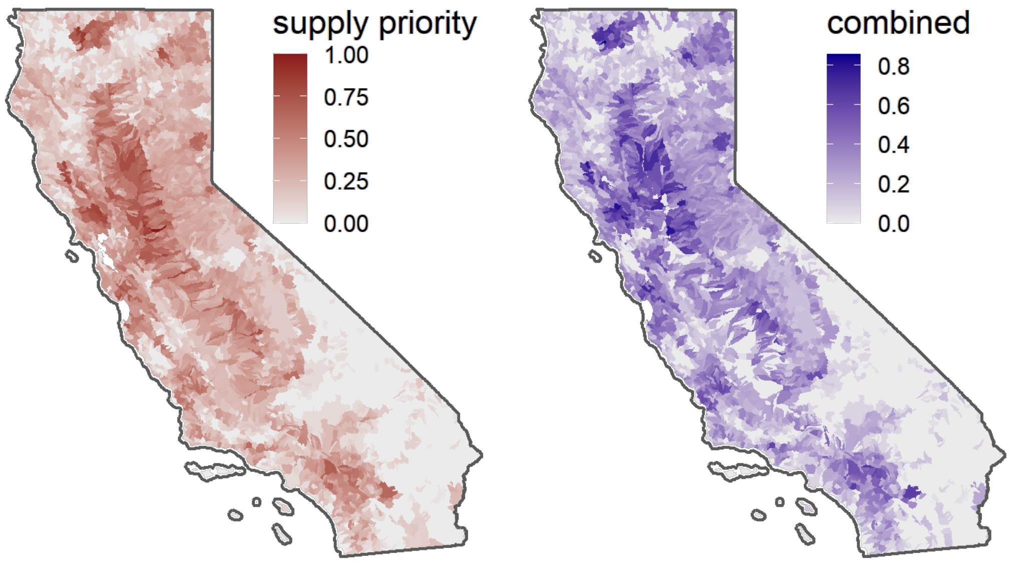
The surface water, groundwater, and SAGBI scores (Figure 11) were then weighted and summed. Surface water diversions are a high management priority that will likely benefit directly from additional stream gages and was therefore given three times the weight of the groundwater and SAGBI scores. Finally, the water supply score was multiplied with the gage gap score to produce a final water supply gage gap priority score (Figure 12).

Figure 11 The surface water (left) combined score, groundwater (middle) combined score, and Flood-Mar score (right)



Note: Surface water was weighted 3x as much as the other two inputs and comprised sixty percent of the final score.

Figure 12 Water supply prioritization showing raw prioritization score (left) and water supply combined with gage gap score (right).



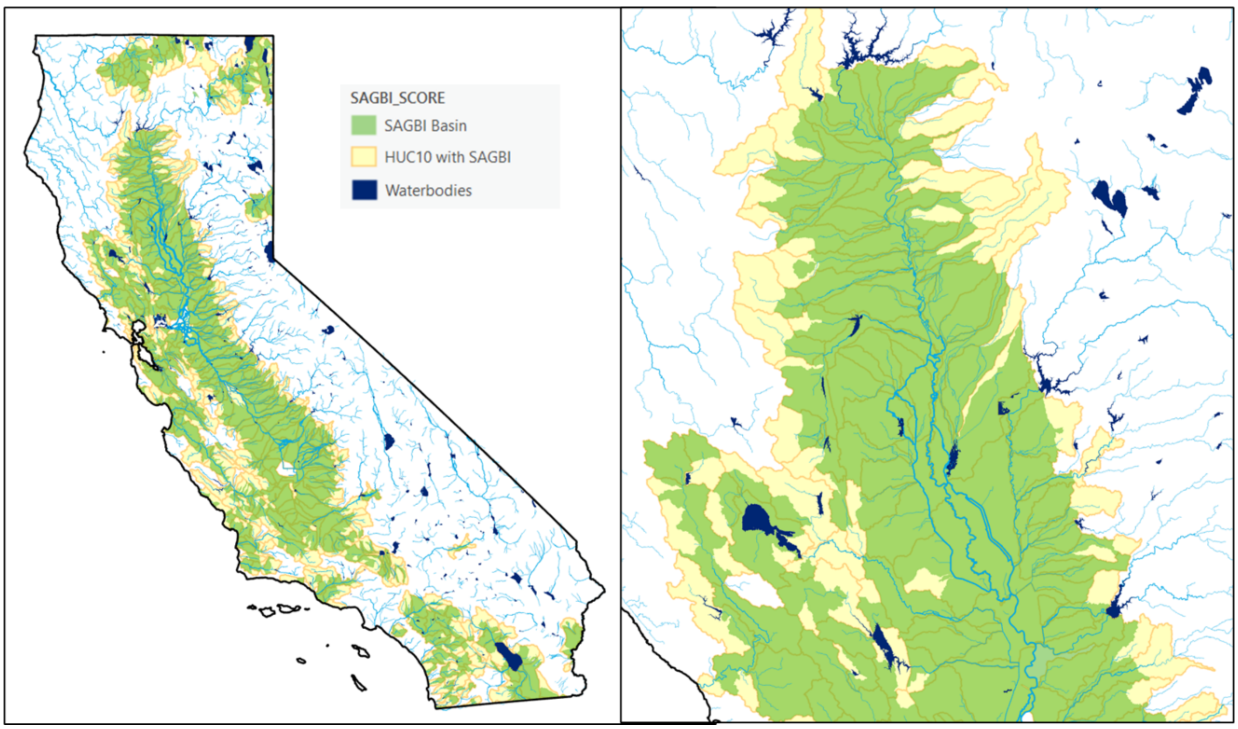
Discussion

The question as to where to place stream gages in support of Water Supply Management is difficult, because the most important sources of water supply are large reservoirs and conveyance systems, many of which are monitored and controlled. Furthermore, the management of these systems is a function of weather and snowpack (during the wet season) and reservoir levels and water demand (during the dry season), neither of which points to the need for a stream gage for water supply management. Stream gages are useful for reservoir operations during the wet season, but that is largely for flood management and is addressed elsewhere in this plan.

Projects that enhance water supply, such as water transfers and Flood-MAR, could potentially benefit from stream gages, although exactly where the stream gage should be located is difficult to resolve. Water transfers are project-specific, and at this time, we have not identified a data layer that could reasonably be interpreted to forecast gage needs for water transfers. Flood-MAR projects may receive their water supply from locations far removed from the storage aquifer, and the SAGBI layer does not highlight the primary water source. Nevertheless, we find that for locations outside the Central Valley, the source of water is likely to be within the same HUC10 watershed, and possibly HUC12 watershed, in the absence of a water transfer. For locations within the Central Valley, the HUC10 and HUC12 watersheds containing suitable Flood-MAR basins tend to end at the same location as a major surface water reservoir (Figure 13).

Thus, any stream gages monitoring Flood-MAR source water would have to be located upstream of an already-managed reservoir. SAGBI is given a score separate from groundwater because SAGBI does not require that a given basin is a high management priority; it is more analogous to a reservoir. SGMA basins alone are not necessarily priorities for surface water gages; there needs to be a surface water connection. This area is one that deserves a closer review before stream gages are installed and improvements are made in future updates to this analysis. Consequently, the issues surrounding potential beneficial gage location for SAGBI and the high degree of overlap of SAGBI and SGMA basins led to the decision to double the weight of the surface water score relative to the groundwater and Flood-MAR scores.

Figure 13 SAGBI basins (green) and HUC10 watershed boundaries (yellow) showing the entire state (left) and the Sacramento River valley



Note: This figure shows that most streams above SAGBI basins are either contained entirely in HUC10s containing SAGBI basins or are blocked by a reservoir (dark blue) at the upper end of the HUC10 watershed.

The results show a statewide distribution of water supply priorities with emphasis on the Russian River, Scott River, and Sacramento River Valley. Additional analysis is needed to better support large volume reservoir operations; however, many already have a stream gaging network, in contrast to areas with many small diversions. There may be a need for other types of gaging, such as snowpack and temperature monitoring, to help predict spring recession and other climate-related gaging needs.

Water Quality Management

Streamflow (timing, magnitude, and duration of different flow events) strongly affects water quality, the condition of physical habitat, and ultimately, the biology of a stream (Yarnell et al. 2015). Not only does streamflow play a critical role maintaining adequate water quality conditions for beneficial uses, but its spatial and temporal variation also affect the movement of energy and nutrients through a stream system (Power et al. 1988; Humphries et al. 2014) and influence the community structure of aquatic and riparian ecosystems (Poff et al. 1997; Bunn and Arthington 2002), especially during disturbances such as droughts and floods (Resh et al. 1988; Poff and Ward 1989; Lytle and Poff 2004). Long timeseries of flow data are particularly helpful in characterizing the variability in components of a stream's flow regime (i.e., rate of change, duration, frequency, magnitude, and timing) (Poff et al. 1997), which provides context for understanding ecosystem processes and can help guide management actions to mitigate water quality impairments.

The variation in water quality impairments and water quality parameters monitored statewide makes it difficult to comprehensively assess the priorities that should inform the siting of stream gages for the SB 19 effort. Water quality data is collected by a mix of entities and programs such as local watershed groups, Tribes, federal and State agencies, and the State Water Board's Surface Water Ambient Monitoring Program (SWAMP). These data include water quality parameters ranging from specific nutrients, bacteria, and ions to physical parameters, such as temperature and specific conductance (commonly used to estimate salinity). Accessing and retrieving water quality information that could support the SB 19 effort, such as data from repositories like the State Water Board's California Environmental Data Exchange Network, proved to be cumbersome and time consuming given the scope of data needed to inform the statewide analysis. Moreover, the breadth of measured parameters and the sizable number of monitoring sites statewide also made it challenging to identify priority areas for monitoring.

Apart from temperature, the SB 19 bill text does not explicitly mention which water quality parameters should be considered in the analysis. Given this, and the previously mentioned challenges, we chose to prioritize locations that can provide streamflow data where there are existing temperature or dissolved oxygen water quality monitoring efforts because those parameters are directly affected by natural variation and anthropogenic alteration of streamflow. In addition to sites specifically monitoring these two parameters, locations of aquatic biological assessment (bioassessment) monitoring sites, which are monitoring sites where instream habitat assessments and benthic macroinvertebrate (BMI) samples are collected, are also considered in the analysis because they contribute to a better understanding of the habitat and biological conditions of a stream or watershed and offer a tool to indirectly assess water quality health. Because these conditions are impacted by streamflow and are often used to inform water resources permitting and other management actions (e.g., as a line of evidence to support a Section 303(d) listing decision) (State Water Resources Control Board 2015), having accessible flow data plays a critical role ensuring that the best science is being applied during the decision-making processes.

Datasets

Water Quality Impairments

Given that streamflow magnitude impacts both surface water dissolved oxygen concentration and temperature, this analysis aims to identify priority watersheds for new and/or reactivated stream gages using the locations of surface waters that have water quality impairments for those parameters. Under section 303(d) of the Clean Water Act, states and Tribes are required to identify and develop lists of impaired and threatened water bodies, which are surface waters that fail to meet, or are at risk of not meeting, established water quality standards. Using a stream gage to monitor streamflow in, or upstream of, an impaired water body can provide important information to guide water quality management actions. For the SB 19 effort, we used geospatial data from the State Water Board's 2020–2022 Integrated Report for Clean Water Act Sections 303(d) and 305(b) database to prioritize areas for stream gage consideration. These water quality impairment data are categorized by, and presented using, the National Hydrography Dataset (NHDPlus) of stream reaches and water bodies (e.g., lakes).

Water Quality Monitoring Sites

Similar to impaired water bodies, the locations of dissolved oxygen and temperature monitoring sites can be used to inform the siting of stream gages to help support water quality management. Stream gages provide important information to relate flow and observed water quality conditions at monitoring stations. For this analysis, we used geospatial data from two sources: the California Water Indicators Portal[11] and the USGS National Water Information System[12]. The California Water Indicators Portal is a data repository that provides access to water quality indicator measurements throughout California and includes data from both individual monitoring locations and composite assessments. The National Water Information System is a nationwide data

[11] https://indicators.ucdavis.edu/cwip/data/download

[12] https://nwis.waterdata.usgs.gov/nwis

portal that provides access to streamflow and water quality monitoring data collected by the USGS and other partners. Unlike the impairment layer analysis which identifies impaired broad areas such as stream segments or water bodies, both of these databases present water quality monitoring stations as specific point locations.

Bioassessment Monitoring Sites

Stream gages that are co-located with, or nearby to, bioassessment monitoring sites provide important data to better understand the relationships between streamflow, habitat conditions, and biological indicators. Understanding these relationships and characterizing flow patterns can help inform water management for environmental flow needs in a watershed or stream system with a similar stream classification type (Lane et al. 2018), which is especially relevant for management considerations in a changing climate with more frequent drought conditions. For example, alteration to the natural flow regime (Poff et al. 1997), such as changes in streamflow timing or magnitude, can have negative ecological impacts to fish and BMI communities (Poff and Zimmerman 2010; Carlisle et al. 2011). While this generally holds true, developing broadly applicable environmental flow needs throughout California is challenging because of the state's extreme hydrologic variation (both spatial and temporal) and high degree of flow alteration at existing stream gages (Zimmerman et al. 2017). Furthermore, it is often difficult to link observations from bioassessment monitoring sites with flow data from these stream gage locations because the sites are not close enough to provide meaningful relationships. A study conducted by Peek et al. (2022) determined that only ten percent of the bioassessment sites in the state were within ten river kilometers (~6.2 miles) of a long-term USGS stream gage location. Given the importance of drawing connections between streamflow and ecological responses (Zimmerman et al. 2017; Peek et al. 2022), this effort aims to identify priority watersheds for new and/or reactivated stream gages using the existing bioassessment sites in the statewide monitoring network.

Measurements of physical habitat characteristics and observations of BMI at bioassessment sites, such as those monitored through SWAMP, provide a snapshot of overall stream condition and ecosystem health. Scientists draw upon modeling and the characteristics of reference sites (Ode et al. 2016), which are sites that maintain high relative stream health and minimal anthropogenic disturbance (e.g., dams, roads), to predict expected biological conditions at environmentally similar non-reference sites. A monitoring site's field-collected BMI samples and habitat characterization can then be compared against the expected reference conditions to develop an indicator score known as the California Stream Condition Index (CSCI) score (Mazor et al. 2016; Ode et al. 2016). These scores are calculated for monitoring sites on streams throughout the state and help water resource managers protect water quality and prioritize degraded streams in need of habitat restoration or additional water quality monitoring.

The existing SWAMP bioassessment monitoring network serves as a helpful spatial framework to guide the prioritization of stream gage locations for the SB 19 effort. The majority of the bioassessment sites used in this analysis came from the *Bioassessment Scores Map* (Fetscher et al. 2014; Rehn et al. 2015), available from the State Water Board's SWAMP website[13]. This statewide dataset incorporates bioassessment sites that have CSCI scores (Mazor et al. 2016) and were monitored between 1999 and 2015, including sites from the Perennial Streams Assessment and the Reference Condition Management Program. These sites are monitored through a variety of entities such as the state Regional Water Quality Control Boards, the U.S. Forest Service, and the Southern Stormwater Monitoring Coalition. This dataset was supplemented with an additional inventory of long-term and frequently visited reference sites.

Ranking Methodology

Watershed Ranking for Water Quality Impairments

To inform the SB 19 prioritization, watersheds were ranked based on whether they contain listed water bodies for either dissolved oxygen, salinity, or temperature impairment. Watersheds received a rank score of 0 if they contain no listed water bodies for those water quality parameters, or a rank score of 1 if they contain at least one impaired water body (Figure 14). Because water bodies are connected within a drainage basin, adjacent sections of stream are often also listed as impaired, and as a result, the statewide distribution is biased. For example, in the north coast region, we can see that much of the lower Eel River and its tributaries are impaired (in this case, for temperature). Additionally, when looking at a statewide scale, very few watersheds (< 5%) have a dissolved oxygen, salinity, or temperature impairment, based on the dataset used in this analysis. For these reasons, we did not want to assign watershed ranks based on the density of impaired water bodies. The 0 (no) or 1 (yes) ranking score based on the presence of only one impaired water body simplified the analysis and allowed for a fair comparison between watersheds at the statewide level.

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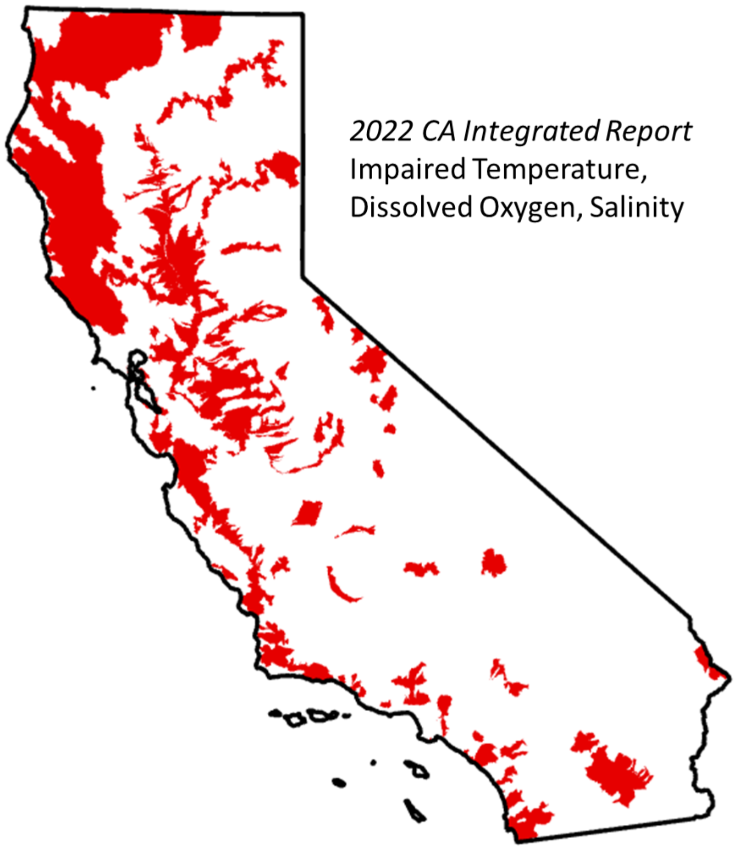
[13] State Water Boards' SWAMP website:
https://www.waterboards.ca.gov/water_issues/programs/swamp/bioassessment/csci_scores_map.html

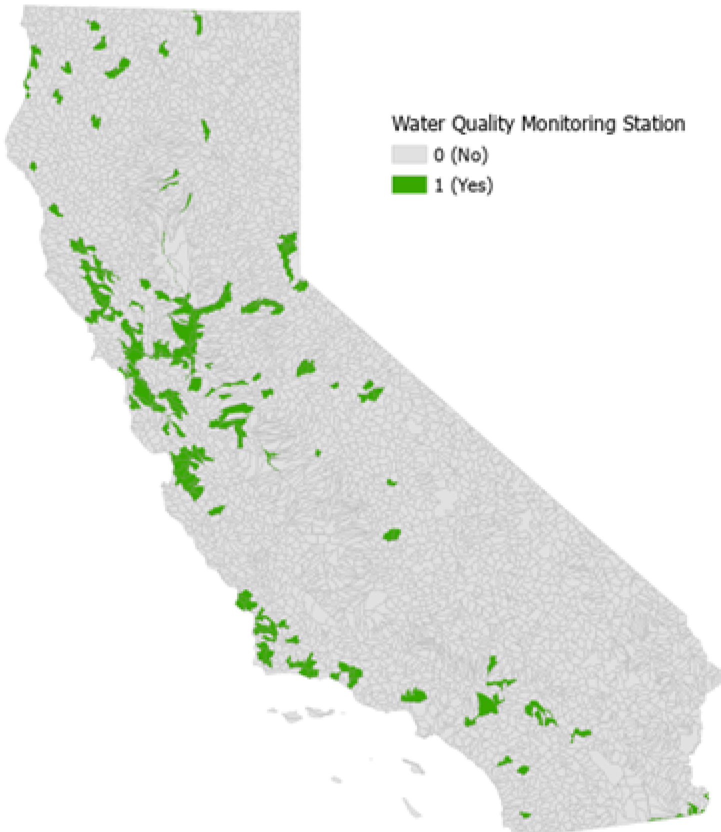
Figure 14 Map of California showing ranked watersheds based on the presence of a waterbody listed as impaired for either dissolved oxygen or temperature



Watershed Ranking for Water Quality Monitoring Sites

For water quality monitoring, watersheds were ranked based on whether they contain water quality monitoring stations that measure dissolved oxygen or temperature. Watersheds received a rank score of 0 if they contain no stations monitoring for those water quality parameters or a rank score of 1 if they contain at least one monitoring station (Figure 15). When compared to the water quality impairment analysis, monitoring stations are distributed more evenly throughout the state in the north-south direction, but there is a large cluster of watersheds with monitoring stations around the Bay-Delta region. Similar to the impairment analysis, less than 1 percent of the watersheds in the state have a station monitoring for these water quality impairments based on the datasets used in this analysis.

Figure 15 Map of California showing ranked watersheds based on the presence of a dissolved oxygen or temperature water quality monitoring station



Watershed Ranking for Bioassessment Monitoring Sites

To identify and prioritize watersheds where co-located stream gages could be helpful to support bioassessment monitoring, the sites first needed to be assigned a rank score. In consultation with the statewide Bioassessment Monitoring Group, we developed a ranking scheme to prioritize the 3,042 monitoring sites around the state into five categories based on a set of criteria (Table 5).

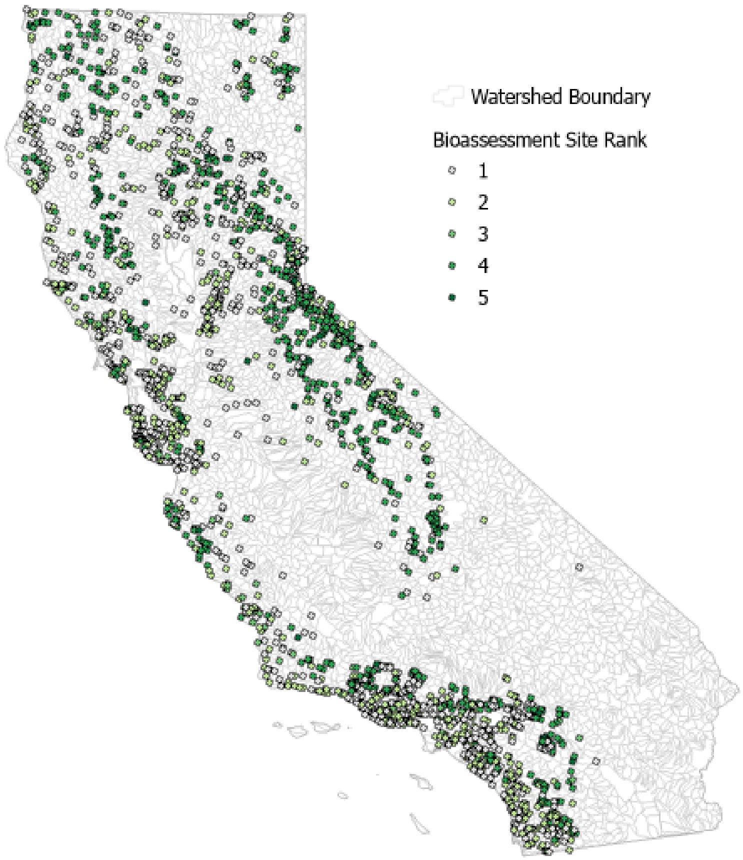
Table 4 Criteria used to rank bioassessment monitoring sites for prioritization according to their sampling history and/or site characteristics

Criterion	Rank	# of Sites
Site meets no other criterion	1	1,133
Non-reference site with more than two samples *or* at least one recent site visit (since 1 January 2010)	2	880

Criterion	Rank	# of Sites
Non-reference site with more than two samples *and* at least one recent site visit (since 1 January 2010)	3	92
Reference site (not in long-term and/or frequently visited site inventory)	4	900
Long-term non-reference site and/or frequently visited reference site	5	37

The highest rank was applied to reference sites because they are used in the calculation of CSCI scores to set expected conditions (Mazor et al. 2016). Given that reference-condition bioassessment sites are found in watersheds with minimal flow alteration and few anthropogenic impacts (Ode et al. 2016), it is not surprising to see the majority of these sites in the mountainous regions such as the Transverse and Sierra Nevada ranges (Figure 16). In cases where monitoring sites had multiple sampling visits, the most recent site visit was used for the analysis and the site was given extra weight in the ranking scheme. Just over two-thirds of the monitoring sites were not characterized as reference condition and were assigned ranks of 1, 2, 3, or 5 as noted in Table 5 above. Sites that have not been visited recently or did not have more than one site visit were given the lowest rank of one. One important limitation of this analysis to note is that, while the inventory of reference sites has been updated, the 2015 SWAMP dataset does not reflect recent non-reference site additions or site visits. The statewide Bioassessment Monitoring Group is currently updating this dataset and it can be incorporated into future prioritization efforts when it becomes available.

Figure 16 **Map of California showing the statewide spatial distribution of ranked bioassessment monitoring sites (n = 3,042) used in the prioritization analysis**



Once sites were ranked according to the criteria found in Table 5, HUC12 watersheds were prioritized to identify where co-located stream gages could provide the most benefit for bioassessment monitoring programs and water quality management. Watersheds were prioritized by applying additional criteria to the bioassessment sites that were ranked in the previous step of the analysis. Based on the criteria found in Table 6, watersheds that contain reference-condition sites were given the highest priority, and those that contain multiple sites, of any rank, received more weight.

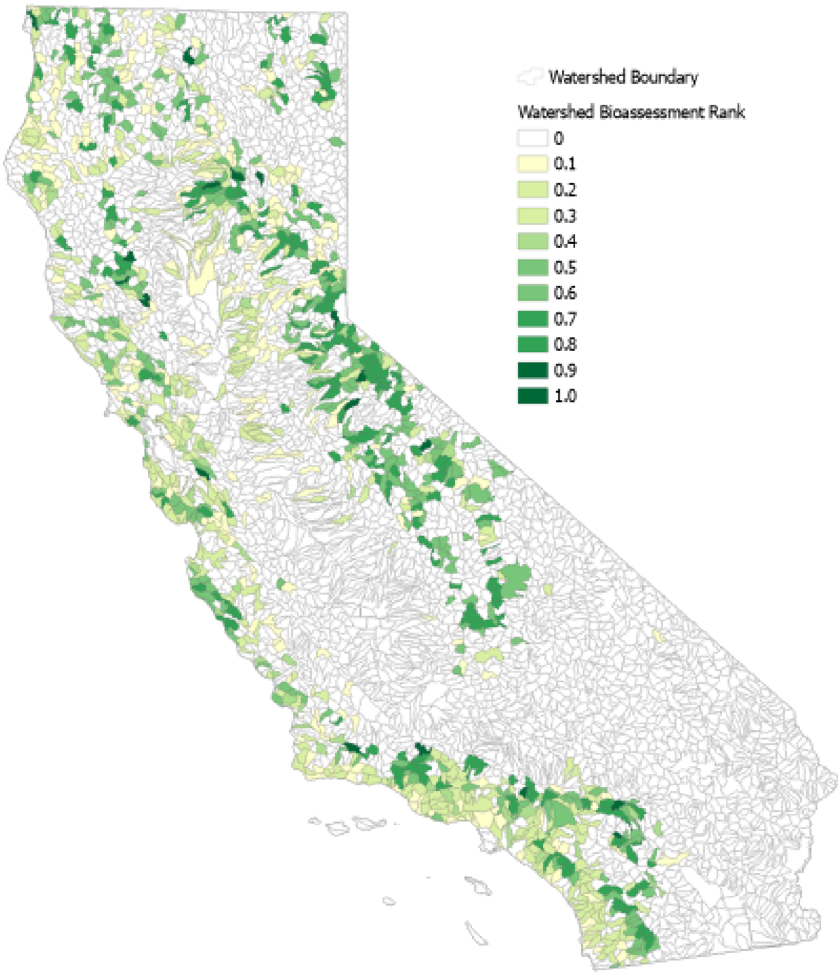
Table 5 **Criteria used to identify priority watersheds for co-location of stream gages based on the bioassessment monitoring site ranks**

Watershed Rank	Criterion	# of Watersheds
0	No bioassessment sites	3,350
0.1	Non-reference site; meets no other criterion (i.e., Rank 1 sites)	360

Watershed Rank	Criterion	# of Watersheds
0.2	One non-reference site; must have recent site visit *or* more than one sample (i.e., Rank 2 site)	219
0.3	Multiple non-reference sites; must have recent site visits *or* more than one sample (i.e., Rank 2 sites)	110
0.4	One non-reference site; must have recent site visit *and* more than one sample (i.e., Rank 3 site)	44
0.5	Multiple non-reference sites; must have recent site visits *and* more than one sample (i.e., Rank 3 sites)	11
0.6	One reference site (i.e., Rank 4 site)	250
0.7	Multiple reference sites (i.e., Rank 4 sites)	194
0.8	One frequently visited/long-term reference site (i.e., Rank 5 site)	17
0.9	At least one frequently visited/long-term reference site *and* one regular reference site (i.e., Rank 5 and Rank 4 site)	17
1.0	Multiple frequently visited/long-term reference sites (i.e., Rank 5 sites)	1

The vast majority (~75 percent) of watersheds do not contain any bioassessment sites, while approximately 10 percent of the watersheds contain at least one reference site (Table 6; Figure 16).

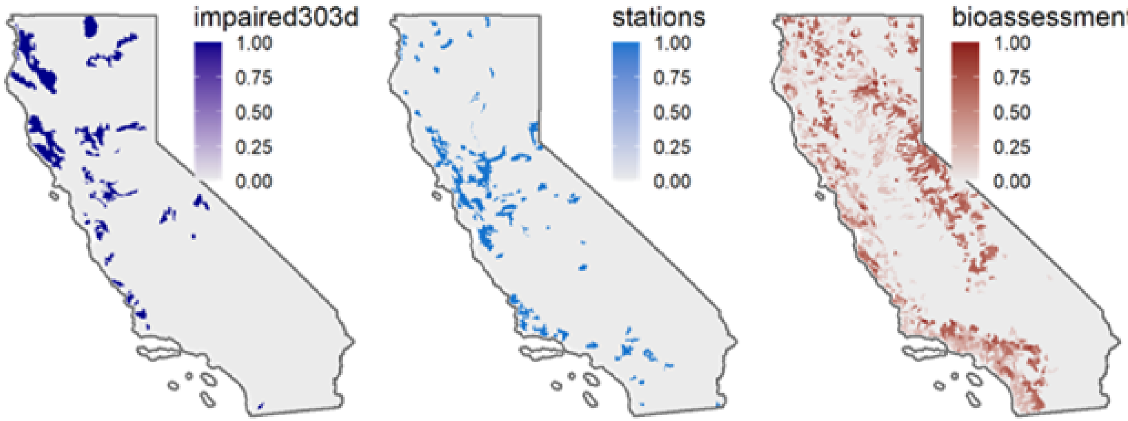
Figure 17 **Map of California showing ranked watersheds for bioassessment monitoring sites**



Watershed Prioritization

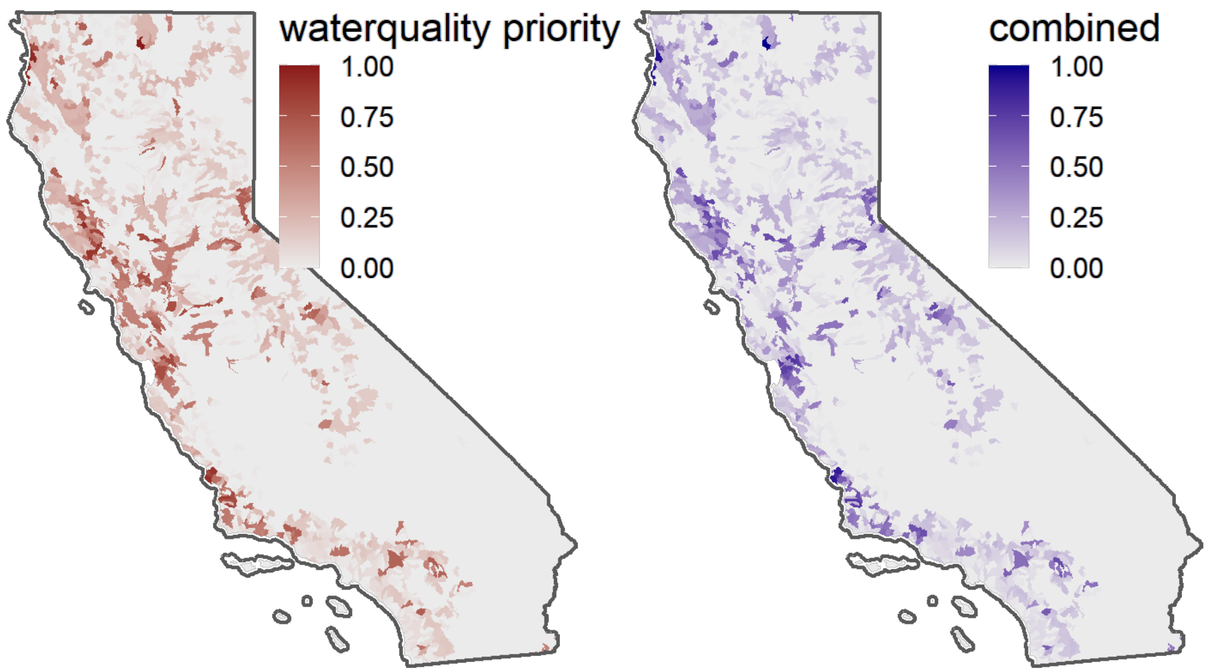
This analysis produces a rank score that highlights which watersheds are priority areas to co-locate stream gages based on existing water quality monitoring efforts and impaired listing status. The three datasets used in this prioritization analysis are the temperature, salinity, and dissolved oxygen impairment layer; the temperature and dissolved oxygen monitoring layer; and the bioassessment monitoring site layer (Figure 18).

Figure 18 Watershed priority scores for each of the three input layers used in the water quality prioritization analysis



The temperature, salinity, and dissolved oxygen impairment layer (score 0 or 1); the temperature and dissolved oxygen monitoring layer (score 0 or 1); and the bioassessment monitoring site layer (score range 0–1) were summed to produce a final score with a maximum possible value of 3 and then normalized to the maximum possible score, which in this case was approximately 2.5 out of 3. Therefore, the final priority scores range from 0 to 1 (Figure 19). A higher score indicates a greater degree of water quality monitoring activity that could be supported by additional streamflow data. Watersheds that have a score of 0, or very low scores, have little to no active or recent water quality monitoring data based on the station information used in the analysis.

Figure 19 Water quality prioritization showing raw prioritization score (left) and water quality combined with gage gap score (right)



Discussion

The spatial distribution of scores derived from this prioritization analysis varied throughout the state. In general, watersheds along the central coast, in the southern Transverse Mountain Ranges, and in some areas of the Sierra Nevada Mountain Range received the highest priority scores, while watersheds in the Central Valley and the inland desert areas tended to receive lower priority scores. These results align with expectations given that this analysis prioritized dissolved oxygen and temperature water quality monitoring stations, which are largely in coastal watersheds, and reference-condition bioassessment sites, which are often located in less-disturbed mountainous areas. While the bioassessment monitoring site analysis assesses the density of sites in a watershed, where a watershed with multiple sites receives a higher score, the temperature and dissolved oxygen monitoring station and impairment analysis was simplified to where watersheds only received a score based on whether there is at least one station or impairment in the watershed. This means that, in a few cases, watersheds could be further prioritized based on a water quality parameter of interest.

This prioritization analysis highlights areas where there are existing or recent water quality monitoring sites. Therefore, the results of this analysis are dependent on the monitoring network used to apply the preliminary ranking criteria to the watersheds. Given the challenges of identifying the most comprehensive, up-to-date inventory of water quality monitoring sites, this analysis does not include all current and recent monitoring locations. The analysis could be strengthened with additional tools and information, such as more accessible and user-friendly water quality management databases from which to download data and a more robust inventory of monitoring locations that reflects sites that were not captured in this analysis.

Flood and Emergency Management

Stream gages provide critical data needed to respond to flood events and design infrastructure to reduce future flood risk. Even though most major streams and rivers posing the highest flood risk for infrastructure and public safety have stream gages, flood hazard is increasing and becoming less predictable under a changing climate. Additional gages are needed to help improve and expand the State's flood risk assessment, monitoring, warning, and forecasting capabilities as well as infrastructure planning and preparation for hazardous flash floods following wildfire.

Stream gages provide real-time monitoring and forecasting of stream flows, including forecasting floods. State-of-the-art weather forecasts are coupled with a large network of stream gages, real-time weather gages, and runoff forecast models to predict stream flows and provide real-time flood warnings. Stream gages also provide forecast model verification for critical public safety and emergency response systems. Large water storage reservoirs are primarily operated for both flood safety and water supply management, although there are ecosystem (e.g., temperature management), recreational (e.g., flow releases, fishing, camping, etc.), and other operational considerations. Reservoir operations and storage are identified as key multi-benefit management actions in the updated California Water Plan, Flood Management Resource Strategy Report (California Department of Water Resources 2016). Stream gage forecasts are used to inform reservoir operations for both flood mitigation and water supply. Reservoirs that are intended to manage floods do so by reserving volume for capturing runoff during the rainy season (the "flood control" pool). Reservoirs are operated under strict flood management guidelines that historically have not allowed for the retention of early season storm flows in order to mitigate against later season floods. Atmospheric rivers account for 90 percent of flood damage and forecasting these events has improved since the initial reservoir flood management guidelines were developed.

Forecast Informed Reservoir Operations (FIRO) is changing the way flood pools are managed to maximize water available for the dry season. FIRO is a reservoir-operations practice that uses enhanced monitoring and improved weather and water forecasts to inform reservoir operations that strategically retain or release water from reservoirs to optimize water supply, reduce flood-risk, and enhance environmental co-benefits. FIRO reservoirs release extra water only when a catastrophic storm is forecasted, as long as there is adequate spillway capacity.

FIRO projects depend on real-time streamflow monitoring upstream of the reservoir to manage and forecast upstream surface water runoff and ensure reservoirs are operated as efficiently as possible to maximize water supply and mitigate downstream risks of catastrophic flooding. FIRO is included here instead of Water Supply Management since the reservoir operations are primarily dictated by public safety and flood risk.

Many reservoir and dam spillway structures in the state do not have comprehensive flood management capabilities, lacking a gate control system that allows for regulated release of stored waters. “Fill and spill” reservoirs collect runoff until the reservoir is full and spill excess water over a weir or spillway in an uncontrolled fashion. A significant portion of these ungated spillways do not have stream gages or telemetered reservoir depth and outflow monitoring, which reduces the ability to inform downstream areas of a potential flood risk.

Climate change is causing an increase in wildfire susceptibility and more frequent destructive atmospheric rivers. The increase in magnitude and severity of wildland fires in recent years has increased the risk of flash floods and debris flows. Catastrophic debris flows pose a serious risk to communities downstream, but even small debris flows increase sediment in streams, which degrades aquatic habitat and domestic water supply. Fire-related erosion is predicted to increase by 10–100 percent in the forested mountains of California through 2050, and even higher in a few basins (Sankey et. al. 2017). Streamflow and sediment yield in the Sacramento River basin are projected through 2099 to increase by over 50 percent and over 38 percent respectively (Stern et. al. 2020). Researchers have interpreted that the frequency of post-fire debris flows in southern California will increase 110 percent (Kean and Staley 2021). Stream gaging and precipitation sensors play a critical role in monitoring potential risks of post-wildfire floods and debris flows and informing emergency response actions. The current stream gage network was not designed to account for wildfires and intense precipitation exacerbated by climate change.

Streamflow data are essential for planning and to better understand flood and debris flow hazards that may arise in the future. Infrastructure is designed to withstand flood events based on exceedance probabilities (i.e., “100-year flood event”). Additional gages will help to provide a better understanding of conditions which may result in higher hazards to communities, aquatic habitat, and domestic water supply and help inform planning and design of future infrastructure to reduce or avoid future risk.

Flood-MAR is an innovative water supply flood-capture project type; however, it is primarily a water supply operation. Flood-MAR does not have a strong correlation with the public safety or the operational side of flood management, so it is analyzed in the Water Supply Management section.

Additionally, there are flood management and stormwater drainage systems at a community or local scale. Unfortunately, evaluation of stream gage needs to support local community small flood control channels or community storm drain systems is at a scale too refined for this statewide evaluation but should be considered when choosing specific stream gage site locations.

Datasets

Five datasets were selected to prioritize watersheds for flood and emergency management elements: (1) flood forecasting, (2) FIRO projects, (3) non-FIRO reservoir tributary watersheds, (4) ungated spillways, and (5) post wildland-fire flood risks.

Stream Gaging for Flood Forecasting

One of the primary flood management strategies is forecasting flood flows in real-time. The California-Nevada River Forecast Center[14] is the primary entity responsible for providing river and flood forecasts for the protection of lives and property. Currently, CNRFC relies on 124 forecasting gages and 101 modeling gages (Figure 20) for their ensemble streamflow prediction products. The streamflow predictions include both deterministic (single value) and short-term (5 days) forecasts based on current weather forecasts as well as probabilistic long-term (1 year) forecasts based on current conditions and historical data.

CNRFC and DWR also assess additional gaging needs to improve streamflow and reservoir inflow forecasting; however, assessments were difficult to locate or are in draft form. In addition, many of the recommendations are for weather, precipitation, radiation, soil moisture, and snow gages. Private and unpublished gages may also be present but not available for forecasting, modeling, or analysis because of limited data access.

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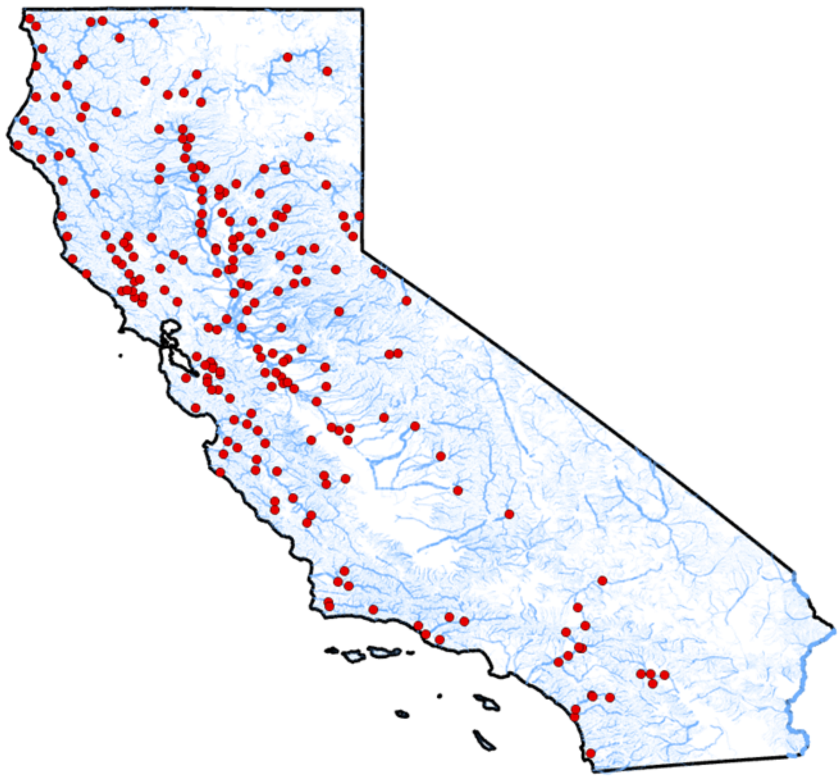
[14] https://www.cnrfc.noaa.gov/

Figure 20 CNRFC forecast and model gages (red dots)

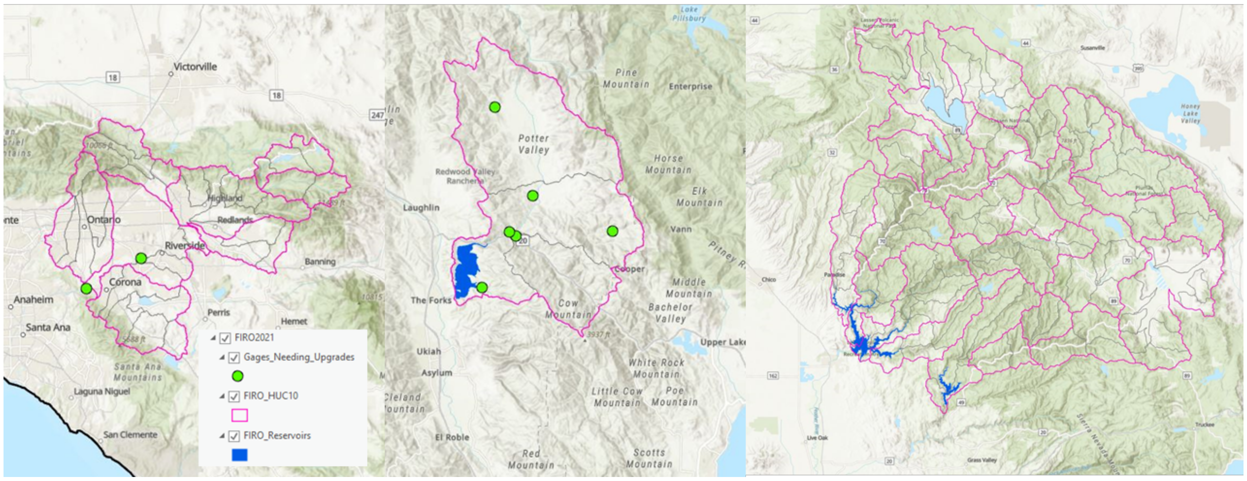


Forecast-Informed Reservoir Operations (FIRO)

The FIRO program is currently a pilot project on four large reservoirs, but it may expand to include other reservoirs as resources and management objectives dictate. FIRO projects are changing the way flood pools are managed to maximize water available for the dry season: stream gages are critical for maintaining the balance between supply and safety.

California's current FIRO projects are Prado Dam, Lake Mendocino, New Bullard's Bar Reservoir, and Lake Oroville (Figure 21), which have a total of 162 HUC12 watersheds and 36 HUC10 watersheds upstream of the reservoirs. Additional stream gaging upstream of the projects is needed to improve and build upon the FIRO pilot projects and support both the operations and the development of flood management guidelines for additional reservoirs throughout the state. Of the four pilot projects, two (Lake Mendocino on the Russian River and Prado Dam on the Santa Ana River) have installed new stream gages, improved existing stream gages, and released a preliminary viability assessment. The remaining two FIRO projects, New Bullard's Bar and Oroville, are in a joint Yuba/Feather FIRO project that is still in the planning phase.

Figure 21 FIRO pilot projects in California, 2021



Note: From left to right: Prado Dam, Lake Mendocino, and Lake Oroville/New Bullards Bar.

Ungaged Hazardous Reservoirs

Watersheds upstream of 145 reservoirs are classified by the California Division of Safety of Dams (DSOD) as High or Extremely High Downstream Hazard reservoirs. Approximately 101 out of 231 HUC-12 watersheds upstream of these hazardous reservoirs are ungaged: these watersheds are high priority for future stream gaging.

Ungated Spillways

There are over 2,300 regulated dams and reservoirs in the state, and approximately 2,000 of those have ungated (uncontrolled) dams. A significant portion of these ungated spillways do not have telemetry that can report reservoir depth and outflow. Prioritization for recommending gage placement downstream of dams with ungated spillways has been coordinated through the Head Water to Floodplain Flood Safety Partnerships preliminary assessment efforts. These assessments reviewed a small number of ungated dams and reservoirs selected on the following criteria:

- Absence of existing telemetry at the dam or the reach downstream is poorly gaged or ungaged.
- Dam is rated as significant, high, or extremely high hazard dam.
- Drainage area/watershed size.
- Presence of populated area downstream at flood risk.

Based on the above prioritization process, there are 22 high-priority stream locations in 20 HUC-12 watersheds in need of stream gaging.

Emerging Wildfire-Related Flood and Debris Flow Hazards

Climate change is causing an increase in wildfire susceptibility and more frequent destructive atmospheric rivers. Post-fire landslide hazards increase because of a combination of increased runoff and debris potential. Higher runoff yields higher magnitude and flashier stream flows with more capacity to transport sediment and debris downstream into populated areas with residential, transportation, and water supply infrastructure.

The CGS conducted a data-driven analysis to identify and prioritize stream gage data to help manage risk to water resources, infrastructure, and the public from increased runoff following wildfires, which results in flooding, debris flows, and erosion (Fuller 2021, in prep), referred to as *CGS Fire*. CGS Fire combined risk factors (fire, flood, and landslides) and showed that the risks are most profound in the headwaters of the forested, mountainous areas of the Sierra Nevada, the Transverse Ranges, and the Coast Ranges where there are few active gages (Figure 22). This dataset combines fire risk maps from the United States Forest Service[15] (USFS) and a CGS Deep-seated Landslide Susceptibility map[16].

[15] USGS Fire Probability Map for CONUS https://usfs.maps.arcgis.com/home/webmap/viewer.html?useExisting=1&layers=623bf8b1e1d34d63beb42bce3a9f5b08

[16] CGS (2011), Deep-seated Landslide Susceptibility Map (Map Sheet 48) https://maps.conservation.ca.gov/cgs/metadata/MS58.html

Figure 22 Combined fire probability and landslide susceptibility. Brighter colors indicate higher combined susceptibility for post-fire landslides

Prioritization Ranking

The datasets were separated into qualitative and quantitative prioritization assessments. Qualitative prioritization data were not input into the statewide prioritization model and instead recommends that stream gaging actions be coordinated with specific project needs. Thirty new stream gages have been assigned to the qualitative projects, but the specific locations are still to be determined. Quantitative prioritization refers to adding the input datasets to a statewide model and assigning stream gage actions to the highest scoring watersheds, as has been done with the other management criteria analyses.

Flood Forecasting and FIRO, Qualitative Assessment

Watersheds with FIRO projects and CNRFC flood forecasting gages are high priority for stream gaging but are not included in the prioritization model because of ongoing planning and an uncertainty of future needs. Thus, the inclusion of these criteria is a qualitative assessment. These programs support multiple objectives beyond flood management, such as water supply, and represent a strategic step in a more resilient management of surface water resources. Recommended actions are continued operation of flood forecasting gages and addition of new gages based on future planning and site-specific needs.

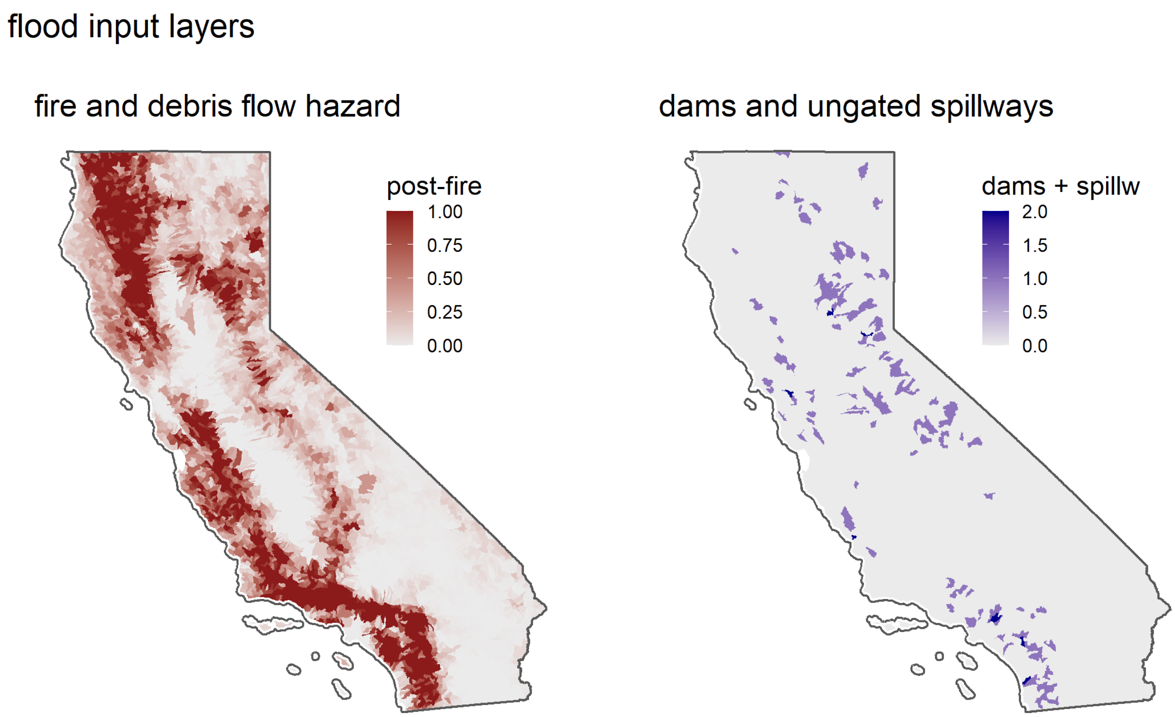
The existing CNRFC gages are active and serve a critical role in protecting people and property. There are 225 gages in operation for current forecasting and modeling, representing 214 HUC12 watersheds (out of 4,471, or 4.8 percent) and 180 HUC10 watersheds (out of 1,038, or 17.3 percent). CNRFC gages are relied upon for current and future flood modeling and forecasting and should be prioritized for continued operation. In addition, we recommend five additional watersheds for new stream gages, to be determined based on CNRFC and DWR analyses.

There are currently four pilot FIRO projects and an undetermined number of near-future FIRO projects. Stream gages should be installed upstream of current and future FIRO projects. These programs are currently in the planning phase and have a high potential for relatively rapid deployment. We recommend that 25 new gages be installed in the near future in support of FIRO projects, at locations to be determined based on project-specific needs.

Ungated Spillways, Ungaged Hazardous Reservoirs, and Post Wildfire, Quantitative Assessment

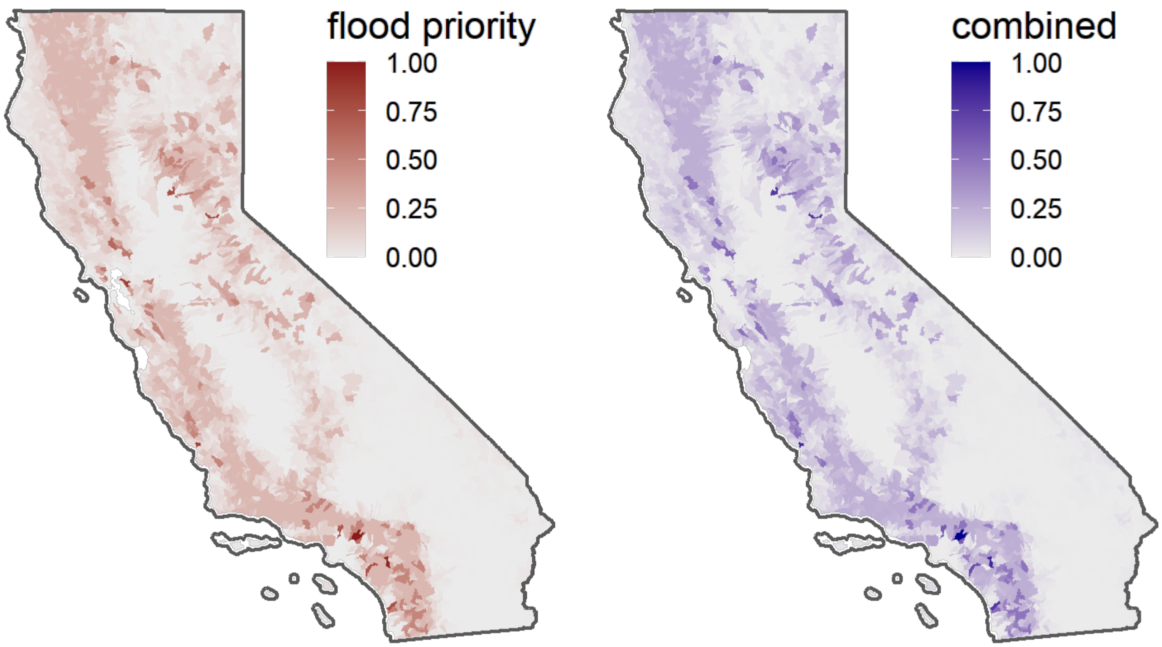
The remaining datasets are Ungaged Hazardous Reservoirs, Ungated Spillways, and CGS Fire. The CGS Fire data is scored with a normalized value ranging between 1 and 0. Ungated spillways and ungaged hazardous dam watersheds were assigned values of 1 while all other watersheds were assigned 0 (Figure 23).

Figure 23 Flood input datasets for prioritization, showing CGS Fire on the left and the combined ungaged hazardous dams and ungated spillways on the right



Datasets were then weighted, with ungated spillways assigned a weight of 2 and the other two datasets a weight of 1. The watershed scores from each dataset were then added to each other and normalized between 0 and 1 (Figure 24).

Figure 24 Flood and emergency prioritization showing raw prioritization score (left) and flood and emergency combined with gage gap score (right)



Discussion

The flood management prioritization is different from the other management prioritization areas in that there are qualitative project-specific recommendations and that some of the input datasets were curated for locations known to lack stream gages. This means that the specific locations are not always known (for qualitative) and that using the raw prioritization results to evaluate the effectiveness of the existing gage networks is not a viable analysis.

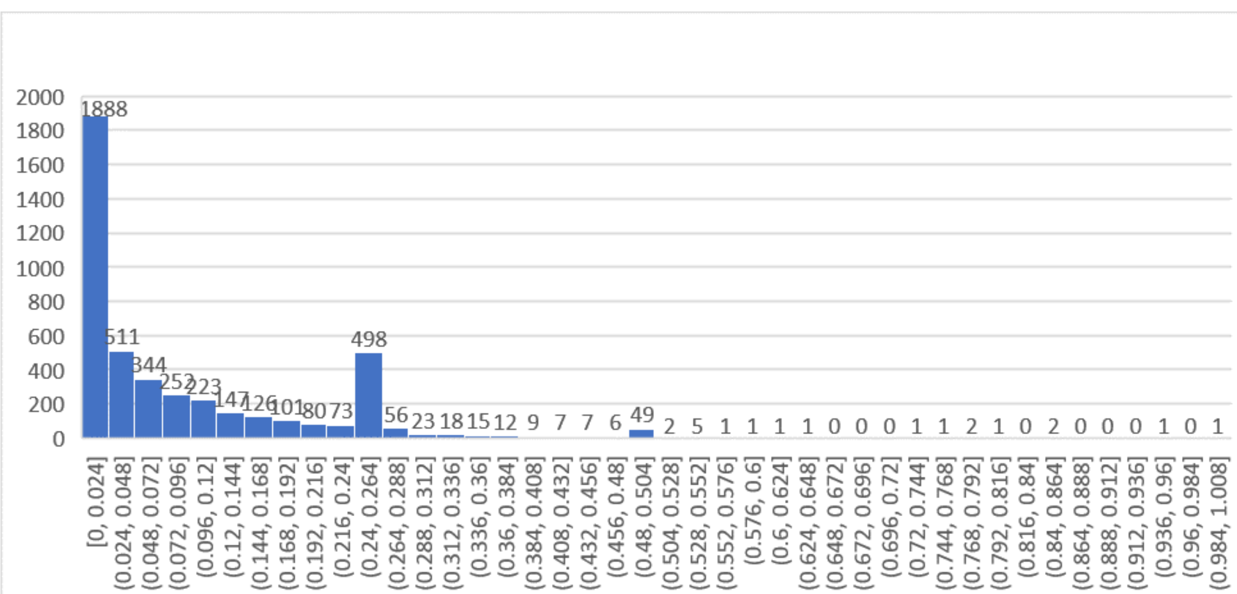
Qualitative prioritizations were made for flood forecasting and FIRO. The Prado Dam project in the Santa Ana River Watershed needs two additional gages and the Lake Mendocino Project on the Russian River needs six additional gages (Figure 21). The New Bollards/Lake Oroville project plans for ten additional gages for the Feather River Watershed and six for the Yuba River Watershed. In total, 25 additional stream gage locations are recommended to support FIRO projects and five stream gages to support CNRFC.

The quantitative prioritization weighted the ungated spillways two times the other two datasets, such that the ungated spillways comprise half of the raw flood prioritization score and are pushed to the top of the ranking. This results in a relatively small percentage of watersheds in the state with high scores, or to put it differently, most of the watersheds in the state received a low score, with nearly 95 percent scoring below 0.25 and 86 percent (3860 of 4467) scoring 0 (Table 7). As noted previously, datasets used in this analysis exclude locations with existing gages; this applies to both the ungated spillways and Ungaged Hazardous Reservoirs datasets and explains the low skewing distribution seen in the Figure 25 histogram. Watershed scores of close to 0.50 are those that either scored high in CGS Fire and are above an ungaged hazardous reservoir or scored zero in those datasets but are associated with an ungated spillway. Similarly, scores close to 0.25 represent watersheds that scored high in a single-weighted dataset.

Table 6 Distribution of Prioritized Flood and Emergency Management Datasets of Post Wildland Fire, Non-FIRO Watersheds, and Ungated Spillways

Watershed Management Prioritization Score Range	Watershed Count	Percentage or Watershed Count in the State
0.50 – 1.0	65	1.5%
0.35 – 0.49	51	1.1%
0.25 – 0.34	128	2.9%
0 – 0.24	4,223	94.5%

Figure 25 Histogram of prioritized watersheds for Flood and Emergency Management Datasets: Post Wildland Fire, Non-FIRO Watersheds, and Ungated Spillways only

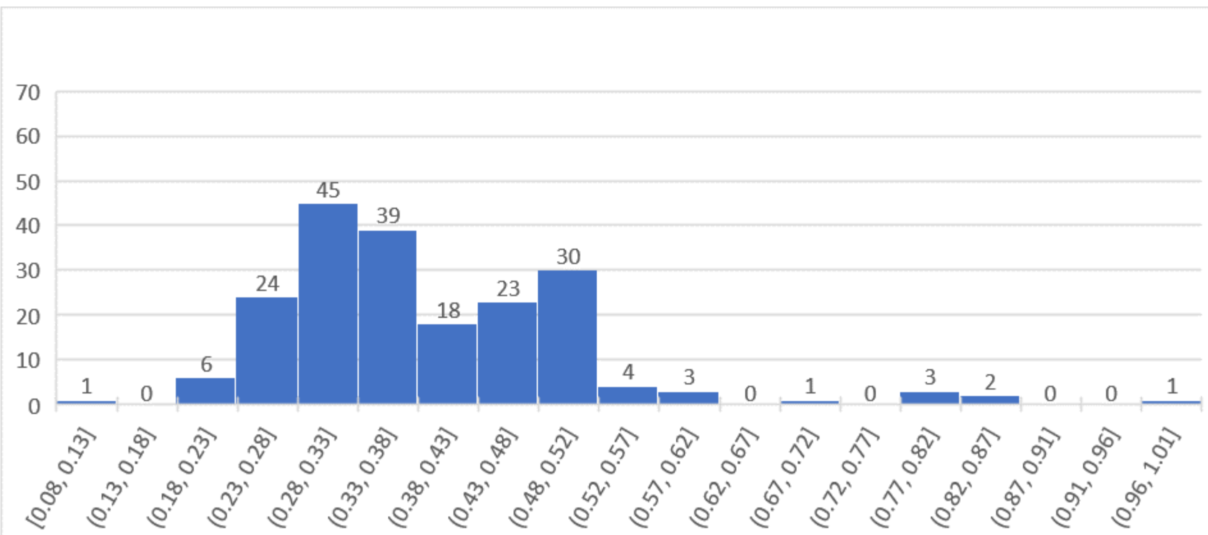


Note: Gage inventory not included.

Comparisons of the raw and combined (with gage gap analysis) prioritization scores (Figure 24) shows that most high-scoring watersheds are not affected by the gage gap analysis (e.g., are priorities for both raw and combined). Out of the top 200 scoring watersheds, only 13 fell out of the top 200 when combined with the gage gap analysis. The combined score distribution is shown in Figure 26.

In the final combined score distribution, the 20 ungated spillways are represented by the top prioritization scores, and the lower scores out of the top 200 represent watersheds with high post-wildfire flood or debris flow risk. The top 200 flood priority watersheds include 187 out of 231 hazardous ungated spillway watersheds and 47 out of 488 CGS Fire watersheds.

Figure 26. Huc-12 prioritization score histogram of top 200 prioritized watersheds for Flood and Emergency Management Datasets following gage inventory analysis



Reference Gage Network Analysis

Reference gages are stream gages used to estimate natural flows (expected streamflow in the absence of human modification) in ungaged and flow impaired watersheds and are critical for calibrating hydrologic models (rainfall-runoff and snowmelt). Reference gages must be sited in areas with full natural flow, defined as flow that is relatively unimpaired by dams, diversions, returns, or imports. The reference gage network should be capable of covering all of California, but unlike the other Management Criteria, ungaged does not necessarily indicate inadequate coverage. Thus, this analysis does not use the Gage Gap Analysis; instead, it assesses gage coverage gaps from statistical similarity, of which one input is a predictive flow model which was briefly discussed in the Gage Gap Analysis methodology section. Here we assess the adequacy of the existing reference gage network and recommend watersheds to target for new reference gages.

Datasets

Datasets were selected to help subset the existing gage network into a reference gage network, analyze the ability of the existing network to support natural flow estimates in ungaged watersheds, and assess the relative impairment level of watersheds to identity their potential to host a new reference gage. Some of the data used for this analysis is already embedded in the gage inventory and gage gap analysis datasets (e.g., gage location, drainage areas of gages and watersheds based on flowline attributes, and flowline spatial representation, which can be used to calculate flow direction [Get NHDPlus 2021]). Additional datasets are described below:

UGSG GAGES-II

USGS has analyzed their gage network for reference sites in a dataset called GAGES-II (Falcone 2011). This effort identified both active and inactive gages with at least 20 years of complete records. For the purposes of identifying the current need and coverage of reference sites though, inactive gages were not included and 20+ years of record was not considered important. The USGS effort did not identify reference gages hosted on agency or State-operated databases, such as CDEC.

California eFlows

The California eFlows[17] effort started with the GAGES-II reference sites and modified them slightly, but only for Hydrologic Unit 18, which does not cover all of California. Some reference sites in the eFlows effort were unimpaired flow locations involving multiple reservoirs and streamflow gages.

Cannabis Cultivation Policy Compliance Gages

The State Water Board included and expanded upon the efforts of GAGES-II and eFlows as part of their Cannabis Cultivation Policy[18] by generating a list of compliance gages to assign to watersheds (State Water Resources Control Board 2019). *Compliance gages* are active gages that are representative of their watersheds and not below any major dams. The compliance gage dataset adds CDEC database gages, and

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[17] https://eflows.ucdavis.edu/

[18] https://www.waterboards.ca.gov/water_issues/programs/cannabis/docs/policy/final_cannabis_policy_with_attach_a.pdf

an analysis of relative impairment based on GAGES-II, eFlows, onstream storage, and diversions, which allows reference gages to be selected from the dataset.

National Inventory of Dams

National Inventory of Dams[19] (NID) is an ongoing effort by the U.S. Army Corps of Engineers to inventory all dams that could pose a hazard to human life or property downstream, including those that do not pose a hazard but meet a minimum size. A low hazard dam is typically included in the NID if it is at least 25 feet in height and over 15 acre-feet in storage, or at least 6 feet in height and over 50 acre-feet in storage. This dataset can be used to estimate dam-related watershed impairment.

Natural Flows Database

The Natural Flows Database (Zimmerman et al. 2017) is a machine learning (statistical) model developed by USGS and TNC. The model provides a statewide set of full natural (unimpaired) monthly flow predictions from 1950 to 2015. The model is calibrated to designated reference gages using physical watershed (e.g., geology, soils, and elevation) and climate characteristics (e.g., air temperature, and runoff) and then applied to all streams within a region. This dataset is used to estimate the hydrologic similarity between ungaged watersheds and reference gages, based on climate, regional weather, elevation, and other physical watershed characteristics.

Methodology

Selecting new reference gage locations requires a different approach than the other management prioritization areas because it is dependent on (1) defining a reference gage subset from the existing gage inventory, (2) analyzing the ability of the reference gage network to support natural flow estimates in ungaged watersheds, and (3) eliminating highly impaired watersheds from consideration for a potential new reference gage.

Reference Gages

Reference gages were identified from the gage database used in the Cannabis Policy Staff Report[20] (State Water Resources Control Board 2019). The gage database contained a thorough analysis of eFlows and GAGES-II reference status as well as notes about impairment and applicability as a compliance gage. Of the 88 GAGES-II

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[19] https://nid.sec.usace.army.mil/

[20] https://www.waterboards.ca.gov/water_issues/programs/cannabis/docs/policy/staff_report_with_appendices.pdf

reference gages in California, 10 were eliminated based on the SWRCB analysis because they were stage-only gages, inactive, or below dams. 68 additional USGS gages were designated as reference based on minimal storage impairment, minor urban diversions and impervious area, and minor agricultural diversions. In addition to these, 34 CDEC-only hosted gages were designated as reference gages based on the same criteria. Many of these CDEC-only gages are privately operated by water contractors. In total there are 180 reference gages considered in this analysis.

Pairing Gage and Watershed

To identify how well the existing reference gage network represents ungaged reference watersheds, a modified version of the pairing algorithm used for the Cannabis Cultivation Policy (State Water Resources Control Board 2019) was developed. The base watershed dataset used is HUC12 watersheds with some additional sub-watersheds delineated to differentiate areas downstream of dams. The general approach was to select a set of pairing factors, generate a watershed-gage pairing score for each factor, calculate a weighted mean for each watershed-gage pairing using all factors, and select the best scoring gage for each watershed. The three primary differences between this and the Cannabis Policy method are that it used different pairing factors, modified the relative factor weighting, and applied a score normalization. These different approaches are discussed in detail in the following paragraphs.

The four factors selected to compare existing reference gages and ungaged watersheds were (1) distance, (2) hydrology, (3) flow direction, and (4) drainage area. Their relative weights (score percentages) are distance 50 percent, hydrology 20 percent, flow direction 20 percent, and drainage area 10 percent. Thus, proximity of the gage to watershed is the most important factor, followed by hydrology and flow direction, with drainage area being least important. Distance is important because nearby gages will experience similar precipitation and climatology patterns. Hydrologic similarity accounts for many physical characteristics such as overall climate, temperature, elevation, topography, geology, etc. Flow direction is important to ensure wet (north facing) or dry (south facing) are not considered a good match. Likewise, it is important that west facing (orographic enhanced) and east facing (rain shadow) watersheds are not considered a good match. Finally, drainage area allows for watersheds of similar size and runoff response to be matched.

Normalization is a data transformation that adjusts the relative values to balance them across a desired range, for example, requiring that all data be scored between 0 and 1 and spreading them out to avoid a large clump at any value, in order to better differentiate the scores (unless intentional, usually to represent a zero value). The Cannabis Cultivation Policy normalized scores *for each watershed* to select the best possible gage to pair for a watershed. Normalizing by watershed avoids score clumping but also means that a score from one watershed is calculated differently than scores from other watersheds, resulting in scores that cannot be compared between watersheds (i.e., 0–1 score range represents 180 gages paired for a watershed). The method used for this project normalized scores *across all watersheds* to compare how well the reference gage network serves each watershed, with relative scores calculated the same way between watersheds (i.e., 0–1 score range represents 813,000+ watershed-gage pairings). The normalization methods are discussed in detail in the following paragraphs.

The distance between the watershed and the gage was calculated using a variation of the inverse-distance formula to assign a proximity score, with scores > 1 (within 10 km) assigned as 1 (the maximum score):

Equation 5. Equation used to calculate distance score.

$$\sqrt{\frac{10}{distance\ (km)}}$$

The normalized annual hydrograph (mean monthly predicted flow, normalized by mean annual flow, plotted over time) was generated for each gage station and ungaged watershed as part of the Cannabis Cultivation Policy (State Water Resources Control Board 2019), using the NHD Plus Enhanced Runoff Method (EROM) (Bondelid 2019).

The difference between the normalized annual hydrograph for each gage-watershed pair was calculated as follows:

Equation 6. Equation used for the normalized annual hydrograph difference between the gage and watershed, which is step 1 for the hydrology score.

$$Normalized\ Annual\ Hydrograph\ Difference\ Score$$
$$= \sqrt{\left(gage_{Jan} - watershed_{Jan}\right)^2 + (gage_{Feb} - watershed_{Feb})^2 + \cdots + (gage_{Dec} - watershed_{Dec})^2}$$

$$gage_{month} = gage\ normalized\ hydrograph\ for\ specified\ month$$
$$watershed_{month} = watershed\ normalized\ hydrograph\ for\ specified\ month$$

Each watershed-gage pair result is then centered by the mean watershed-gage pair value for all watershed-gage pairings and scaled by dividing out the standard deviation.

Equation 7. Equation used to center watershed-gage pairing scores, which is step 2 for the hydrology score.

$$\frac{X - \bar{X}}{\sigma}$$

$X = watershed - gage\ pairing\ result$
$\bar{X} = mean\ of\ all\ watershed - gage\ pairing\ results$
$\sigma = standard\ deviation$

This results in dimensionless, unitless measures of dissimilarity for each pairing. This data is converted to an interval between 0 and 1 and subtracted from 1 using the following formula:

Equation 8. Equation used to convert scores to an interval between 0 and 1, which is the final step (3) for the hydrology score.

$$1 - \frac{X - Xminimum}{Xmaximum - Xminimum}$$

Pairs of gages/watersheds were then assigned a rating (0 to 1) that express how similar they are in terms of the overall flow direction of the watershed. This is calculated using the flow direction raster from NHDPlusV21 (Get NHDPlus 2021) as follows:

Equation 9. Equation used to calculate flow direction score.

$$\frac{\cos\left(gage_{fdr} - watershed_{fdr}\right) + 1}{2}$$

$gage_{fdr} = mean\ flow\ direction\ of\ stream\ segments\ upstream\ of\ the\ gage$
$watershed_{fdr} = mean\ flow\ direction\ of\ stream\ segments\ in\ a\ watershed$

The cosine of the difference between two angles is 1 if the angles are the same, decreasing to zero as the angles are perpendicular, and approaching -1 as the angles are inverse (opposite directions). This formula modifies that relationship so that opposite directions receive a score of zero, perpendicular directions have a score of 0.5, and similar flow directions (less than 90 degrees) have a score better than 0.5.

The drainage area is simply a ratio of the smaller to the larger drainage area. For example, if a watershed is 10 percent of the drainage area upstream of a gage, the score will be 0.1; if a watershed is twice the size of the drainage area upstream of a gage, the score will be 0.5.

Watershed Impairment

The last step is to eliminate highly impaired watersheds from consideration for a potential new reference gage. For the purposes of this analysis, the NID dataset was used to determine which stream segments have dams on them and to calculate the percentage of impairment of every stream segment. Named stream segments with at least a 25 km^2 drainage area, less than 15 percent of that drainage area above dams, and classified as a stream or river were considered candidates for reference gages and not eliminated. Watersheds were then assigned a score of 0 (no suitable stream segment candidates) or 1 (suitable candidates present).

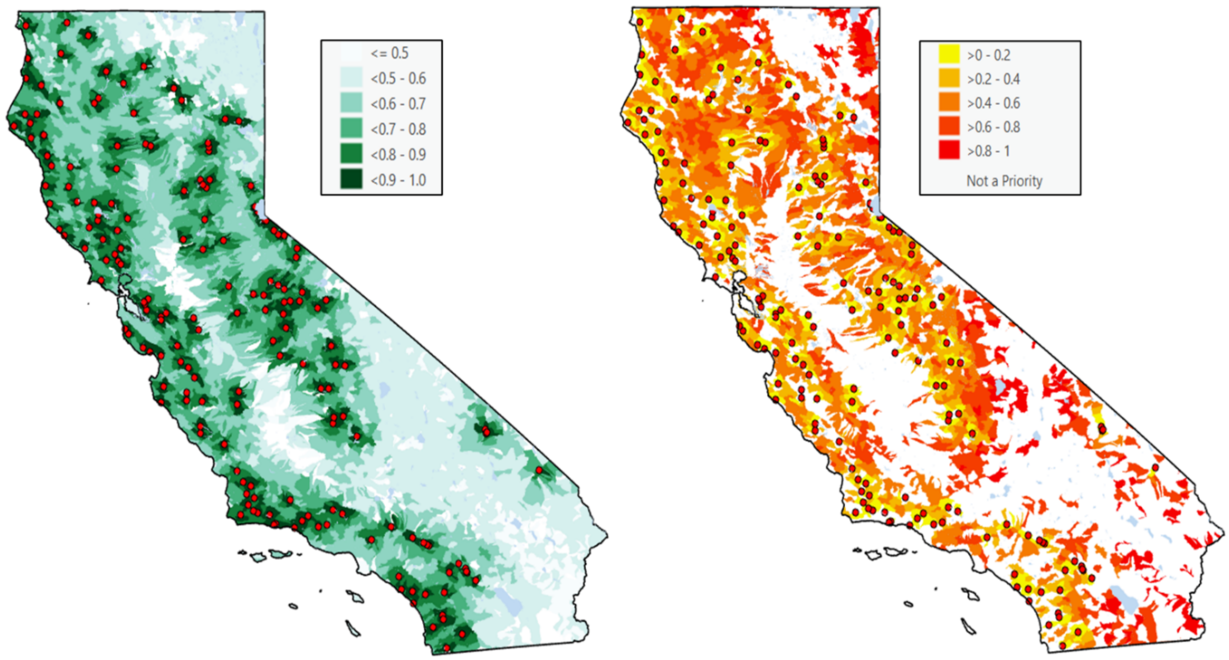
Final Analysis

The gage pairing match score produces a score from 0 to 1 describing how well an area is already represented by nearby reference gages. Consequently, watersheds with the greatest need of new reference gages have the lowest scores. The priority score is generated by subtracting the gage pairing score from 1 and multiplying by the watershed impairment score to eliminate watershed with no potential for new reference gages (the higher the score the higher the priority).

Prioritization Ranking

The analysis produced a gage pairing score as well as a prioritization score (Figure 27). Gage pairing scores show how well each watershed is paired to the best fit gage, while prioritization shows the areas that are priorities for receiving a new reference gage based on the final analysis described above. More than half of all watersheds are poorly represented in the reference gage network, with pairing scores under 0.7, and more than a quarter have a score less than 0.6. In part, this is because of a concentration of reference gages in coastal or mountainous areas. An additional 100 gages are likely necessary to adequately cover the entire state.

Figure 27 **Gage pairing (left) and prioritization (right) scores**



Note that some poorly gaged watersheds do not have any suitable locations for a reference gage and thus also receive a zero-priority score (shown as white for prioritization scores map in Figure 27 above). It is also important to note that any new reference gages will benefit their host watershed as well as nearby watersheds. Thus, watersheds that score poorly on both metrics can still be helped by new reference gages installed nearby.

The areas that have the poorest gage pairing scores are either highly impaired (e.g., the Central Valley) or have flashy, desert hydrology (Modoc, Eastern Sierra, and Mojave). This prioritization analysis provides guidance on areas to target for new reference gages; however, new reference gage locations should be chosen with local expertise and additional data analysis.

Discussion

The Reference Gage Network Analysis assesses how well unimpaired flow can be estimated for ungaged stream segments by the existing reference gage network and provides recommendations for new reference gage locations to improve the network.

The prioritization scores are based on factors of distance, hydrology, flow direction, and drainage area and are weighted based on our assessment of relative importance. We recognize that some of the factors are co-dependent, such as the impact that flow direction has on hydrology and that proximity indicates similar climate which also affects hydrology. The input datasets, methods used to score and normalize, and relative weights are subjective and could be changed, although we are confident that any high-level analysis would yield similar results.

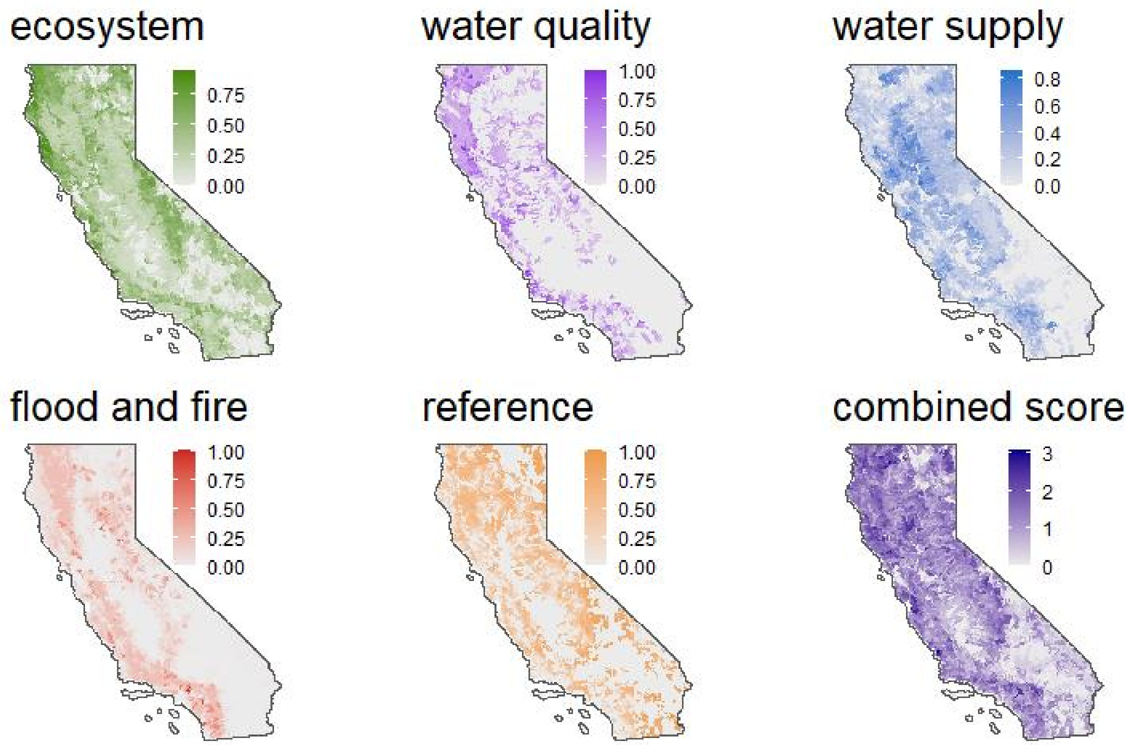
The State Water Board defines unimpaired streams and gages as those with minimal flow impairments but with current land use and geomorphology. This effort seeks to be consistent with the above definition and to use the most inclusive definition of reference gages, not excluding anything attributable to urbanization or land use. Most of California’s rivers and streams are impaired, meaning the water is intercepted or diverted by structures during its natural runoff path. Records for dams and diversions are often incomplete and erroneous, or privately held, which makes it difficult to accurately determine the natural upstream hydrographs. Many USGS gages have comments that describe impairments such as “several small dams and diversions upstream.” This assessment did not include a detailed analysis on diversion storage volumes, seasons of diversion, location of impairments, or proportional volume of diversions relative to the total flow, and therefore overestimates locations that may be useful as a reference gage and therefore is intended to provide a starting point for more site-specific analyses.

This assessment of watersheds which need and are suitable for reference gages does not supersede local knowledge or data collection. There are likely gages operated by smaller entities in ungaged watersheds that would have a more accurate accounting of the hydrology and therefore hydrological similarity between that watershed and a reference gage. There may not be suitable locations for installation of a new gage in prioritized watersheds as we have not analyzed all impairments, such as excessive diversions and agricultural returns, or land access, such as roads and wilderness areas. This analysis is meant to be a high-level assessment of the reference gage network and areas in need of improvement. For the reasons discussed above, we recommend that additional data collection and research be done before specific gage sites are selected.

Results and Limitations of Management Criteria and Prioritization

Prioritization of watersheds and gages for reactivation or upgrades was a multi-step process analyzing statewide gage gaps, reviewing individual gage characteristics, and combining input datasets into a model to prioritize watersheds for management criteria. Each HUC12 watershed was assigned a raw score for each management objective, a gage gap score, and a combined score multiplying each raw score with the gage gap score. High combined scores indicate that the watershed is both a high priority and is not well-gaged, while existing well-gaged watersheds and watersheds with few management criteria priorities have low scores. The results show that management priorities vary across the state and different regions (Figure 28).

Figure 28 Results of the management prioritization and gage gap analysis for each area and combined, bottom right



High rank in multiple management objective categories is a good indicator of multi-benefit priorities and likely water management conflicts. The individual management category rankings better represented the overall priorities than an equally weighted combined score (Figure 28, bottom right). This is because there is relatively little overlap between the highest scores in different categories and also because of large differences in score distribution between categories (e.g., mean, median, the shape of the distribution, and other statistics). Only 30 watersheds scored within the top 100 and only 84 in the top 200 for more than one category, for a total of 922 priority watersheds out of 4469 in California.

The results were reviewed for relative accuracy and trends using local expert knowledge and known locations of management challenges and projects. In addition, an implicit assumption is that existing gage locations were chosen for good management reasons, and thus the raw prioritization analysis should overlap with the existing gage network unless there is a strong alternate explanation. This analysis is imperfect because some of the input data were specifically targeted at places lacking gages, especially flood management and reference gage analysis. These limitations were addressed in this analysis by including CNRFC gages (225), existing reference gages (180), and an earlier gage survey from water managers noting gages serving specific important management needs. In total, 81 percent of active high-quality gages and 69 percent of active limited-use gages are in high-priority watersheds, are critical for forecasting, and/or are reference gages.

The prioritization analysis highlights the subtle differences between watersheds, and are reflective of the input datasets, their data structure, and management-related decisions regarding the highest and lowest priorities. Summing by HUC12 watershed has the potential to reward low resolution datasets and penalize higher resolution datasets because lower resolution priorities all receive the maximum score of 1. In addition, a single watershed may score highly in multiple datasets, but the priority locations may be in different parts of the watershed; for example, salmon rearing habitat may be well upstream of a SGMA basin.

This effort is intended to provide high-level guidance that generally captures the different management priorities but does not supersede local experience and more specific knowledge. Specific locations were not analyzed for access, suitability, roads, permitting conditions, or other impediments. We encourage future water management planners to review the input dataset on their own merit and to conduct more localized analysis to help inform actual gage locations.

Modernization and Emerging Technologies

SB 19 expresses the need to explore modernization of stream gages. The concept of modernization is wide ranging. For clarity, this section summarizes modernization by categories of common upgrades. It is important to recognize that updating and retrofitting of a streamflow gage can be integrated with reactivation in many cases. The elements discussed are all valuable and recommended. Recommendations on how to best implement gage modernization is discussed in the Recommendations section.

Current Software

The software platforms used by some stream gages are relatively old and struggle to function on modern hosting and interface platforms. Recent State drought and proposition funding has updated some of the gage software, but some gages are still running outdated software. Some embedded computers may require a hardware upgrade to support the latest software.

Communication Hardware and Integration

Real-time remote sensing requires a robust communication connection. Most gages are not close to a phone or fiber-optic cable and require a remote connection via satellite or cellular network. The Geostationary Operational Environmental Satellites (GOES) network sponsored and maintained by NOAA has been a reliable and valuable communication network. As satellite and other communication networks advance, gage hardware is required to be upgraded to stay compliant with new systems. Current technology like LoRa radio (short for Long Range), may provide additional opportunities for cost-effective connectivity. While improved performance is expected, the ability to retain connectivity requires upgrades to certain outdated equipment. Antiquated data collection platforms are not being supported by vendors or are unable to communicate with current end user devices, such as 64-bit computers, smart phones, telemetry radios, and portable handheld data collectors.

Enhanced Instrumentation

There are multiple opportunities and benefits in modernization of the physical measuring instruments that ultimately improve accuracy, resiliency, and efficiency. The modernization elements below serve to identify unique benefits. These elements can and should be bundled into one implementation plan to maximize efficacy when feasible.

Modify Existing Gages to Accept Multiple Sensors

The capital cost for modern sensors used in water quality have decreased significantly in the last few years. Many of the existing gage sites would benefit greatly by leveraging the gage system to provide real time data for other parameters other than just stage and streamflow. New data collectors typically have between 4 to 16 input and outputs, and data handling systems which provide opportunity for versatility in gage operation. These data collectors use a common data communications platform and equipment to allow for efficient deployment of sensors.

Adding additional sensors to existing gages is a cost-effective approach to enhancing the network and adding to gage utility. Quantifying water quality parameters, rainfall, soil moisture, and other physical elements will allow managers and users to better inform endangered species management, water supply management, or other critical watershed management elements.

Modify Existing Gages for Power Efficiency

Newer computer systems consume much less power compared to older data collectors, which allows more sensors to run for a longer time without charging. Stage can be recorded by float sensors, bubble gages, pressure transducers, or electronic distance measurement, which all have different power requirements. Most stream gages currently are powered by solar power and backed up with a single car battery. Low-power systems are more likely to provide critical accurate measurement information during weather events and continue to function afterwards because of sensor redundancy and more robust power and data systems.

Replace Hazardous Equipment

Some streamflow gages still use older infrastructure to operate, such as stilling wells and mercury-based sensors, that present unnecessary safety risks to gage operators. Stilling basins can pose a hazard from confined space requirements, while a mercury manometer may expose technicians to a toxic substance. This equipment can be replaced with alternatives like pressure transducers, bubble pressure gages, or radar level sensors to eliminate the hazard.

Remote Communication with Gage

A modern stream gage needs to transmit data in near real-time for water managers and data-critical models, as well as have remote communication between the stream gage operator and the gage site equipment for remote operation and troubleshooting. New data collectors have technology that allows for communications to and from the gage site equipment. Having a means of "rebooting" the site or resetting a sensor is critical in modern stream gaging. This technology allows gage operators to confirm gage operation remotely, connect to the gage and modify settings, and reduce the need to travel to the gage site to ensure the gage is properly functioning. The quicker an operator can identify potential problems and fix it, the better the data will be to the water managers.

Cameras that can pan, tilt, and zoom (PTZ) are now more energy efficient and can be easily powered by a small solar panel and battery system. At priority locations or very remote locations, the ability to see the conditions at a site during a critical event (flood, low-flow fish passage, etc.) is vital to monitor the event and gage status. Frequently, staff are deployed to remote locations to confirm gages are operating correctly during or following a storm. The savings in staff expense can be significant if the need for remote site visits is reduced.

Emerging Technologies

To continuously improve the gaging network, new and unproven technologies must be tested and developed before they can be deployed reliably. Eventually such technologies may be deployed to the broader network or ultimately become industry standard.

Automated Discharge Measurements

In traditional streamflow gages, the stage-discharge relationship (rating curve) requires constant calibration and validation with discharge measurements. These measurements require site visits by hydrologic technicians at varying flow conditions, especially during and following storms. The on-site discharge measurements make up a vast majority of ongoing gage operation costs.

The USGS Next Generation Water Observing System (NGWOS) is evaluating several systems that can estimate discharge without a technician on site. Particle-Image Velocimetry is a technique involving a video camera (sometimes thermal) recording the water surface continuously. With advanced image processing algorithms, the video can be analyzed to calculate the surface velocity across the whole cross-section of a river. These velocity measurements could be used, along with depth, to continuously estimate discharge at the gage site. Ground penetrating radar and bathymetric lidar are also promising technologies which can be used to measure depth and velocity and calculate discharge automatically. A remote and automated discharge measurement, if reliable, could drastically reduce the need for site visits to gages.

Drones

Quadcopter drones are typically flown by a pilot within line-of-sight, but they may offer measurements over a broader area than is possible from a cableway or on foot. Drones can capture ground penetrating radar, particle-image velocimetry, bathymetric lidar, or other information depending on the installed sensors and payload. Drones may also be used to calculate a 3D height surface using a photogrammetric technique called *structure-from-motion*. Drone-based measurements can improve the safety and accessibility for many streamflow measurements.

Ultra-Low-Power Sensor Networks

Advancements in sensor technology have resulted in ultra-low-power and wireless sensors. With a low enough power requirement, a gage could be deployed by foot without the need for a road or vehicle to carry heavy batteries and solar panels. Rather than communicating via satellite, radio, or cellular, which have higher power requirements, sensors could be deployed using LoRa radio in a mesh configuration. For example, an existing streamflow gage could link to several other ultra-low-power sensors miles away up a canyon with no cellular reception. These sensors may be able to operate for months on a single battery charge. Each additional sensor can expand the range and reliability of the lower power radios, forming an off-grid mesh network.

As State and local agencies continue to respond to various natural and climate-related disasters, the need for stream gages to inform emergency response efforts and best allocate resources to reduce risks to life, property, and the supporting environment is paramount. Ultra-low-power devices allow for inexpensive and rapid deployment in response to wildfires, flooding, environmental contamination, or other events that require a temporary expansion of sensors. The USGS NGWOS program has multiple pilot studies, including post-fire rapid deployment of multi-sensor systems (United States Geologic Survey 2021)

Machine Learning

Machine learning is a process that uses existing data and statistical methods to train algorithms capable of learning and making useful predictions based on underlying patterns. Machine learning allows computers to learn and adjust without a human fully specifying the analysis steps or physical processes and is now foundational to the operations of many modern corporations, across sectors, demonstrating its surprising effectiveness at transforming training data sets into useful predictive models (Alpaydin 2021).

Effective machine learning requires robust training datasets and care in applying the process appropriately. Machine learning will not work effectively if the underlying stream gage network is inadequate to train the model. Modern machine learning models can help fill stream gage gaps, using information known about climate, weather, topography, and basin characteristics, etc., to estimate streamflow in ungaged locations that have a nearby gaged watershed with similar characteristics. Both traditional surface water–groundwater (physical) models and data-driven (statistical and machine learning) models are useful, with recent advances suggesting that machine-learning models can perform on par with or outperform physical process models, given suitable training inputs (Kratzert et al. 2019). Recent applications of machine learning for flood management forecasting suggests that a predictive model approach can help fill gaps for locations lacking a stream gage, augmenting existing gage networks.

A machine learning model may work well for one application and poorly in another, even in the same watershed using the same dataset. For example, during low-flow or drought periods, stream ecological conditions are highly sensitive to small changes in surface water diversion, groundwater pumping, and local stream morphology. The same machine learning model may do a good job of predicting overall yearly water volume and spring runoff patterns and a poor job of predicting summer water availability for agriculture and juvenile salmon survival. Even at high flows, this approach may not be sensitive to localized high-intensity rainfall events and resulting localized flood events. For many applications, such as measuring real diversions, providing localized flood alarms, and monitoring real-time ecological low flow stream conditions, actual gage measurements are important.

For this project, we are using a statistical flow modeling tool for reference gage analysis because the ability of the gage network to help assess natural flows in ungaged or gaged-but-impaired basins is the entire purpose of reference gages. The gage-pairing algorithm depends on a USGS and TNC model called the Natural Flows Database[21] (Zimmerman et al. 2017), which predicts natural flows statewide. This project is ongoing, now collaborating with Upstream Tech[22] to add machine learning and dynamic satellite data inputs to predict unimpaired streamflow today and impaired streamflow in the future (Howard et al 2021). This is not the only effort of this kind: there are many efforts outside California that are too numerous to mention and UC Davis research (White 2020 2017) that has similarly applied machine learning to predict streamflow in ungaged basins in California.

Overall, these applications to estimate streamflow and other characteristics at ungaged locations establish machine learning as a viable method of augmenting gage data for areas in appropriate circumstances. Machine learning still needs a robust extensive gage network to train the model. When used in tandem, improvements to the stream gage network and predictive model results could provide an enhanced level of insight to support management decisions in California.

Data Management

Management of streamflow and other surface water data include three primary components: integrity of data, application of universal long-term storage, and data access. Water data management objectives should be based on both the anticipated data use needs as well as the latest recommendations from expert water data managers. For this plan, we reference the Internet of Water (IOW) principles (Internet of Water 2021). Note that recommendations are likely to evolve and thus should always be researched before undertaking a major data management project design.

[21] https://rivers.codefornature.org/

[22] https://www.upstream.tech/hydroforecast

The IOW principles support modernizing the data infrastructure to broaden applications and to ensure data are usable by everyone, including overburdened communities who are addressing water equity issues. Thus, “all water data produced for the public good should, by default, be findable, accessible, interoperable, and reusable (FAIR) for public use or authorized users.” (Wilkenson et al. 2016.) To meet the FAIR Guiding Principles, there needs to be commonly accepted data, metadata, and exchange standards which can help promote interoperability and data-sharing. The IOW principles advocate that control, responsibility, and quality control remain the responsibility of data producers, and that distributed, not centralized, water data systems are preferable because they provide flexibility and scalability as long as data are interoperable between systems.

Objectives and Best Practices

The long-term objectives for managing stream gage data should follow the most current best practices and water data management principles. Current issues specific to California stream gaging data management are:

- Stream gage data in California are collected by dozens of different entities for various purposes. These data are of variable quality, do not have standardized quality control and quality assurance processes, lack standardized data formats or metadata, and are usually not accessible on a public database. Metadata and/or data structure improvements are needed on all gaging efforts, including the highest quality California stream gage data (e.g., USGS and DWR), to differentiate gage status, data type, and applicability.
- Limited resources, especially for smaller organizations, force a choice between more extensive coverage with lower gage quality versus a sparse gage network with high gage quality. Both gaging strategies are useful: highest quality data is needed for applications like flood forecasting or conflicts in water management, while more extensive networks are important for ecosystem and drought monitoring. Limited resources may also mean that small project data are not stored in databases that can be easily accessed.

Both of these issues contribute to a problem where data are hard to integrate and access. Solutions need to be supportive of smaller projects that provide valuable insight into conditions in watersheds that lack permanent, well-funded, high-quality stream gaging stations. A statewide data management strategy should support gage data inputs from many different entities, reconcile gage data of differing quality and longevity, address some of the metadata and data structure needs, and facilitate data access and analysis.

To accomplish these goals and address known issues, we recommend the following objectives:

1. Stream gage data should meet FAIR Guiding Principles.
2. Develop data standards to support accessibility and interoperability, such that data from all sources can be housed, analyzed, and shared on a common interface. Data standards include data formats and data elements (e.g., metadata and data schema).
3. Ensure metadata fields include enough information to determine gage status, data type and status, real-time status, sampling type or interval, location (including watershed and infrastructure), periods-of-operation, site details, funding source and longevity, and quality assurance and quality control (QA/QC) status for each sampling period.
4. Develop QA/QC standards and flags to differentiate the wide ranges of data quality associated with different stream gaging sophistication, equipment, operators, longevity, and maintenance and allow both higher and lower quality data to be shared and hosted on a common interface.
5. Stream gage stations should be assigned and use persistent identifiers, which are a long-lasting reference to a digital resource that includes both a unique identifier and a service that locates the resource over time even when its location changes.
6. The State should develop and maintain a central repository to host and/or access California's stream gage data, including data from independent parties. Smaller entities can opt to upload their data to the central repository, while larger entities may maintain their own data systems, provided those systems are interoperable and accessible.
7. Stream gage data management should be considered a public service. The State should encourage independent parties to share their stream gage data by removing financial or bureaucratic obstacles and requiring data collected under State-funded programs be shared unless an exemption is granted. Anyone should be able to find, access, and download stream gage data or metadata based on time, location, and/or other parameters. Tools facilitating access would ideally provide maps, gage data graphs, and simple statistical analysis for single or multiple gage stations.
8. Gage operators should create and implement data management plans that specify what metadata and data elements are created, how they are stored, and procedures for quality control and revisions. Reported margin of error and QA/QC flags should be provided alongside the dataset, which could be a function of equipment limitations, maintenance, site conditions, and other factors. A

stream gage data management committee should be established to uphold data standards and principles, add depth and detail to the identified issues and objectives, and advise gage operators.

Data Elements

Gage data managers should adopt minimum metadata and data elements. Data elements are unique information about the data, like a category or spreadsheet column name, while schemas are lists of data elements, such as all the named columns of a spreadsheet. Metadata include information about a stream gage and information necessary to interpret the data collected from a gaging station. The data itself would include the gage measurements and timestamps for stage, discharge, and any water quality parameters collected at the site.

Some schemas have been developed to guide data collection and structure for stream gage data, including WaterML2[23], which includes guidance for stream gage metadata and time series as well as specification of rating curves. Common metadata elements should include, but not be limited to:

- Site identifiers and names.
- Location in latitude and longitude and the associated data and locational accuracy.
- Elevation and associated vertical data and accuracy.
- Location expressed as a hydrologic address on the stream network.
- Specific site description, including if the gage is located on a natural channel or part of infrastructure.
- All parameters measured and their periods of record, units, descriptions of measurement methods, and instrumentation.
- Rating curves and their periods of validity.
- Funding source and period of funding, linking to contracts.
- Gage operator(s).
- Equipment types and maintenance records.
- Periods of operation, gaps, and real-time status, such that gage status for any parameter and time could be queried and quickly understood.
- Data sampling type and interval (intermittent or regular).

[23] https://www.ogc.org/standards/waterml

Common data elements should include, but not be limited to:

- The identifier for the gage from which a time series observation comes from.
- Numerical and/or qualitative results, depending on the parameter.
- Timestamps including date, time, and time zone in a standard format, such as ISO 8601[24].
- Data quality codes such as provisional, under review, or final (QA/QC complete).
- Data quality codes derived from data collection conditions, such as equipment type/technology, equipment maintenance, rating curve maintenance, or stability of the site.
- Contextual notes to help interpret data such as low- or high-flow conditions that the gage was not designed to measure accurately.

Data Storage

Metadata and data should be stored in electronic, machine-readable, non-proprietary formats so that they can be easily read and used, including by data users external to the gage operator. It is often useful to store metadata and time series data in separate tables, with gage identifiers linking the metadata with the time series data. Typical machine-readable formats include tables as comma separated value (csv) or tab-separated value (tsv) files which are often produced by data loggers. Large amounts of data may need to be organized into databases (specialized data structures that organize many data tables) to be used and exchanged efficiently. There are several open-source options, as well as commercial/enterprise water data management offerings available that provide such databases. Whether stored as collections of files or databases, data should be routinely backed up in redundant systems to ensure that it is not lost as a result of software or hardware failures. Authoritative versions of the data should be stored in protected systems accessible only to authorized users. However, whichever data storage option is chosen, it should be made as easy as possible to export and provide or send data in a non-proprietary format to other users. This may involve the regular duplication of the authoritative data files or database to a secondary location accessible to external users.

Data Accessibility

Data should be hosted online, in real-time, and easily downloadable by the public in both standard and non-proprietary formats. This should include local downloads, bulk downloads, and an Application Programming Interface (API) to allow automatic access

[24] https://en.wikipedia.org/wiki/ISO_8601

and import of specific subsets of data for visualization and analysis. Data managers should ensure that each station has a persistent identifier, which includes a unique identifier, and a service that stores an updateable web address. Data should be searchable by geographic location, time-of-operation, and metadata parameters including QA/QC flags, operator, data type, site type, status, and more.

The State should facilitate data sharing by standardizing data formats and metadata, offering technical support, and removing barriers, such as fees. All of which should encourage independent gage operators to upload their data. The State should import and link to independent databases through APIs and persistent identifiers to provide the public easy access to stream gage data, no matter where the data are hosted. Finally, data visualizations and interfaces should be easy to use and accessible to the public.

Data Integrity Standards

When a stream gage reports real-time data, this information is considered preliminary. This preliminary caveat is important and identifies the unverified condition of the data. The reported streamflow is based on a rating curve that relates stream stage to flow. To retain accuracy, the rating curve requires adjustment over time to account for physical changes in the stream channel. For example, following a series of high-flow conditions, the channel conditions may change slightly, but be enough to alter the flow-to-depth relationship. Following a routine physical measurement, the curve is adjusted and reported flow data is revised and changed from a “preliminary” condition to “final.” Frequently, these adjustments are minor. However, there are times where the adjustments are significant, particularly when following a substantial high-flow event.

The USGS developed a process that should be performed to validate the accuracy and precision of the streamflow data. This process includes both an accurate measurement of flow to adjust the rating curve and the correct adjustment to the rating curve. DWR has adopted and deployed these USGS processes and standards, and it is recommended that these processes and procedures be the standard operating procedure and common practice for stream-flow gages funded by State funds and reported on the WDL. These processes are listed below with weblinks to the supporting documents that provide detailed information and procedures:

- General Procedure for Gaging Streams (Carter and Davidian 1968).
- Measurement and Computation of Streamflow, Water Supply Paper 2175 (Rantz 1982).
- Techniques and Methods 3-A8 Discharge Measurements at Gaging Stations (Turnipseed and Sauer 2010).

- Measuring Discharge with Acoustic Doppler Current Profilers from a Moving Boat (Mueller et al. 2013).
- Stage Measurement at Gaging Stations, Chapter 7 of Book 3, Section A (Sauer and Turnipseed 2010).
- Computing Discharge Using the Index Velocity Method (Levesque and Oberg 2012).

Stream Gage Funding Cost to install/operate stream gages

The costs for installation and operation of stream gages vary widely depending on whether the costs are for a gage being installed at a new site, upgrading or replacing an existing gage, or adding specific sensors or hardware at an existing gage site.

Estimated New Gage Costs

The cost to install and set up a new stream gage can vary widely based on the number and type of sensors, location and site complexity, and size of the stream. To aid in presenting costs for a wide range of configurations, classes of gages are presented based on practical sensor groupings and are summarized in Table 8. The recommended, or "gold standard" (Class 3) stream gage is one that measures and reports in real-time stage, streamflow, and water temperature. This Class 3 gage uses contemporary data collection platforms, power supply, and telemetry, with costs ranging from $24,000 to $41,000. The highest-class gage (Class 1) reflects a gage with a suite of water quality sensors, cameras, remote access, and streamflow in real-time at a cost of $119,000 to $218,000. This highest-class gage is similar with USGS's "Supergage" and requires more extensive environmental permitting and construction. Between these two gages is a Class 2 gage that provides the same features as the "gold standard" in addition to electric conductivity, pH, precipitation sensors, and remote sensing, with costs ranging from $47,000 to $78,000 depending on site complexity. These additional Class 2 water quality sensors traditionally require similar, low-impact installations as Class 3 and typically don't require extensive permitting.

Elements that are considered in these costs include:

- New equipment and materials.
- Labor to install.
- Labor to calibrate equipment and develop rating curve.

- Regulatory environmental permitting.
- Real property access rights.

Frequently, cost efficiency can be gained in installation labor, permitting, and real-property components when bundling multiple sensors together in a new site. For example, the labor and permitting costs to install a site that only measures streamflow is nearly the same as if the site measures streamflow, pH, temperature, and precipitation. Even though significant improvements in technology and hardware have generally become more affordable, it has not translated into lower installation or annual operation and maintenance costs for a stream gage. The cost to install and operate a stream gage will vary based on the location (access issues), stream geomorphology (changes in stream bed conditions), and the number of streamflow measurements required to develop a reliable rating curve.

Table 7 Summary of stream gage costs for new gages, reactivation, and upgrade of existing gages

Action	Gage Class/Upgrade Package	Cost Range — Low ($/unit)	Cost Range — High ($/unit)	Annual O&M
New Gage	Class 1 "Supergage"	$120,000	$237,000	$50,000
New Gage	Class 2	$55,000	$82,000	$38,000
New Gage	Class 3 "Gold Standard"	$28,000	$43,000	$30,000
Reactivation	Class 1 "Supergage"	$132,000	$196,000	$44,000
Reactivation	Class 2	$42,000	$68,000	$32,000
Reactivation	Class 3 "Gold Standard"	$26,000	$40,000	$30,000
Upgrade	A- Telemetry, stage to flow, data collection, and power supply package	$24,900	$41,100	$30,000
Upgrade	B- Temperature, pH, and precipitation sensors package	$13,800	$23,000	$30,000
Upgrade	C- Safety Instrument replacement package	$66,800	$200,300	$30,000
Upgrade	D- Remote operation and camera package	$17,000	$28,200	$7,000

Note: Unit costs are based on early 2022 estimates and do not account for escalation in labor or material costs.

Estimated Reactivation Costs

Reactivation of a stream gage refers to the deployment of a new stream gage at a discontinued or inactive gage location. Existing infrastructure is expected to vary and will depend on the individual site location. To provide a general scope for reactivation needs, it should be expected that 50–75 percent of previous sites will not have reusable hardware or equipment. The remaining sites may have some hardware that can be reused. Notable savings associated with reactivations are likely if the foundation and base infrastructure remain which could significantly reduce permitting and installation labor costs. The savings that can be reduced from the cost of installing a new gage range from $5,000 to $35,000.

Estimated Modernization Costs

Costs for updating or modernizing a stream gage site can vary significantly based on the type of update and work needed, site conditions, and the potential to bundle work and sensor costs together. To help provide a general sense of potential costs, packages of gage updates were developed based on practical grouping of sensors, upgrades, and efficient deployment. The more rudimentary package includes updates to the data collection platform, telemetry, stage to flow rating table, and power supply, with an average cost of approximately $33,000. Another package includes the addition of temperature, pH, and precipitation sensors to an existing gage; the average cost for these additions is approximately $18,000. A safety-oriented package that replaces a mercury manometer and a stilling well at an existing gage site is approximately $134,000, with the cost fluctuating significantly depending on site conditions. The addition of remote operation and cameras to an existing gage, which can reduce the annual operating costs by avoiding unnecessary site visits to monitor the gage, is approximately $23,000. The addition of a temperature sensor alone costs approximately $10,000 per sensor. Each of these costs represent a typical bundle of work. Costs should be expected to vary if these elements are added together or are broken out by individual sensor.

Operation and Maintenance

Sustained maintenance is critical to stream gaging. The average annual costs vary based on the site location and complexity and by sensor inventory. The average range of annual operation, maintenance, and material costs are $30,000 to $50,000. These costs cover expenses to perform routine gage inspection and flow measurements, replace damaged equipment, and maintain access. The addition of remote access and cameras can significantly reduce the average operation and maintenance cost by reducing the number of trips to remote locations.

Potential Operators

Who else is in the stream gage game? The answer to this question is — a whole lot of folks. Each entity may develop and maintain a gage for specific purposes, which may or may not be adequate to the overall network need. Some examples include:

- Flood Control Agencies.
- Hydroelectric Facility Operators.
- Water Agencies, cities, and counties.
- Local and Project-Specific Owners.
- Nonprofit Organizations.
- Regulatory Agencies.
- Academia.

Electric Utilities Maintaining Hydroelectric Facilities

California is home to over 1,200 dams and hydroelectric facilities. These ratepayer-funded facilities provide hydropower across the state in addition to other flood control and water supply benefits. Each facility, licensed through the Federal Energy Regulatory Commission and monitored by both federal and State regulators, must maintain a network of stream gages to operate and report on the facility activity. Not all of this information is available publicly and presents a low-cost opportunity to significantly expand gage data availability. Options to make this data publicly available should be further explored to improve the existing stream gage network.

Groundwater Sustainability Agencies

The historic passage of SGMA in 2014 set forth a statewide framework to help protect groundwater resources over the long term. SGMA is composed from a three-bill legislative package, including AB 1739 (Dickinson)[25], SB 1168 (Pavley)[26], and SB 1319 (Pavley)[27], and subsequent statewide regulations. SGMA requires local agencies to form groundwater sustainability agencies (GSAs) for DWR-designated high- and medium-priority groundwater basins. GSAs, or the State in the absence of a GSA or

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25 https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140AB1739

26 https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB1168

27 https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB1319

approved GSA groundwater sustainability plan (GSP), are required to develop and implement GSPs to avoid undesirable results and mitigate overdraft within 20 years.

The GSP General Site Monitoring dataset contains the monitoring sites and associated subsidence, and streamflow measurements collected by GSAs during implementation of their GSP. All data is submitted to DWR through the SGMA Portal's Monitoring Network Module (MNM). Again, an opportunity exists to use these existing stream gage sites to improve the overall stream gage network.

Local Water, Wastewater, and Wholesale Water Agencies

There are approximately 3,000 community water systems in the state. Within the state's 58 counties, there are over 120 individual county service, maintenance, and water districts. Similarly, of the 482 incorporated cities, roughly 60 percent own and operate water utilities. An additional 537 special districts own and operate public water systems[28]. A water system is required to maintain records relative to water quality and supply; however, they may or may not have similar access and responsibilities for stream network gages. These entities are also limited in what they are able to charge their ratepayers by a number of limiting statewide provisions such as Proposition 218[29] and Proposition 26[30]. There are several notable local entities that maintain water systems with stream gaging requirements. For example:

- The Los Angeles Department of Water and Power maintains the Los Angeles Aqueduct from Mono and Inyo counties to a distribution system in Los Angeles.
- Sonoma County maintains a water supply system in the Russian River watershed.
- East Bay Municipal Utility District maintains a water supply system that includes conveyance facilities on the Mokelumne and Sacramento rivers.
- The San Francisco Public Utilities Commission maintains a water supply system along the Tuolumne River.

From large to small, there are hundreds of water agencies that maintain stream gage facilities, with some gage networks available to the public.

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[28] https://privatewaterlaw.com/2013/09/25/the-organization-of-water-utilities-in-california/

[29] https://lao.ca.gov/1996/120196_prop_218/understanding_prop218_1296.html

[30] https://lao.ca.gov/ballot/2010/26_11_2010.aspx

Current Funding Shortfalls

The number of stream gages in use continues to decrease as funding dwindles and gages are decommissioned. These information gaps make it extremely difficult for water management partners at the federal, State, and local levels to make timely, informed decisions. The magnitude and specific issues vary based on the agency and associated revenue streams. The current USGS program has an approximate annual expense budget of $12 million. Of that annual expense budget, 75 percent of the revenue originates from cooperative agencies and entities with reimbursable agreements (Caldwell 2022). The remaining 25 percent of annual revenue originates from federal appropriations. Shortfalls occur from both the reimbursable and federal appropriation sources. Revenue from cooperative agencies is typically tied to specific gages, which are directly impacted if shortfalls occur. Currently, minimal shortfalls have occurred that have impacted fewer than 10 gages over the past couple of years. Shortfalls to USGS revenue are more prevalent from federal appropriations stemming from the potential variations in federal budgeting process.

Funding for operations and maintenance of current stream gages at the State level originate from different program funds with different levels of stability and discretion. Most State-operated stream gages are funded by the Division of Flood Maintenance and the State Water Project, which are both relatively stable funding sources. Maintenance of some gages is funded by annually variable discretionary funds, which are less stable and have competing needs. Additionally, some gages are maintained under cooperative revenue agreements that when not funded are removed from reporting data. The lack of sustained funding for gage operation and maintenance is the primary source of gages going offline. An example of this dynamic is short-term funding for stream gaging to support installation and initial operation of 33 new stream gages and reactivation of five stream gages associated with SGMA funding. While this initial capital funding is critical, it does not sustain gage operation beyond the first couple of years. Without additional stable funding for the operation and maintenance of the current stream gage network, critical gaps will expand, resulting in water managers not being able to obtain the necessary information to effectively manage water resources.

Potential Funding Sources

This section discusses potential funding sources for both one-time capital expenditures as well as ongoing maintenance of a stream gage.

General Obligation Bonds

Capital funding for stream gages (for development and installation) may be obtained from a variety of one-time funding. Statewide General Obligation bond funds have been used to fund individual gages for specific purposes, such as flood water surface elevation, drought monitoring, or in relation to a specific restoration project.

Much like a house mortgage, the cost of the bond is spread out over 30 years and the benefits are anticipated to be met over that period of time. Over the past 20 years, the State has authorized over $30 billion of General Obligation bonds for resources and environmental protection, a small subset of which has been used for stream gage monitoring and development.

Other Types of One-Time Funding

There are numerous additional types of one-time funding that are available periodically. These include federal infrastructure funding to nonprofit investment in specific gages. Over the past several years, State and federal funding for stream gages has declined. Both federal and State government use grants as a way to fund various projects. The grants are typically for a limited amount of funding over a short duration (3–5 years). Typically, one-time funding sources would be a good source for the installation of stream gages but don’t provide for long-term operation and maintenance.

Federal Funding

Gage funding at the federal level is authorized through the federal budget appropriation process each year, and some of the funding is used by specific agencies to fund stream gaging. The USGS gages, for example, receive dedicated stream gaging funds under the Federal Priority Stream Gage Program. In addition, the USGS Water Science Centers in each state receive appropriations for the Groundwater and Streamflow Information Program (GWSIP), commonly known as the Cooperative Matching Fund (CMF) program, and some of that funding is used for stream gages. Congressional appropriations and agreements with 1,400 nonfederal partners funded USGS stream gages with $194.9 million nationwide in Fiscal Year (FY) 2020. The USGS share included $24.7 million for Federal Priority Stream gages (FPS) and $29.4 million for cooperative stream gages through CMF. A dozen other federal agencies provided $38.0 million. Nonfederal partners, mostly affiliated with CMF, provided $102.8 million. In FY 2021, Congress appropriated the same amount of funding as in FY 2020 for FPS and CMF stream gages. In addition, Congress appropriated $24.5 million in FY 2021 for the NGWOS, which is an effort to establish dense water monitoring networks in representative watersheds to model streamflow in analogous watersheds.

At the federal level, the President’s Fiscal Year 2022 budget proposal included a funding increase to USGS to $28.3M for its FPS network. The FPS network includes more than 4,700 sites identified as valuable for streamflow and the related data collection to address long-term federal needs, such as drought and flood forecasting, interstate and international water compacts and decrees, and tracking sentinel trends. This proposed increase would reverse the likely discontinuation of up to 20 FPS stream gages across the nation this year, and up to 58 in future years, related to the rising operational costs of the network. Many FPS sites are supported through a combination of USGS and partner funding. Proposed CMF funding remains essentially unchanged. If a California watershed is selected for NGWOS, additional USGS funds would be used to increase the number of stream gages and types of monitoring in that watershed, potentially freeing up funding from other agencies to monitor in other priority areas.

In addition to USGS stream gages, federal funding through the US Bureau of Reclamation, Army Corps of Engineers, and other entities with jurisdiction and responsibility over water and flood projects are sources of ongoing partner funding.

State Funding

While General Funds are perhaps the best source of ongoing funding, this funding is often variable in nature and highly contested for all types of uses across State government. Within the environment and natural resources budgets, outside of fire suppression and bond repayment costs, a very small amount of funding is available for ongoing resources-related programs such as stream gages. The State could develop a water use fee or tax that would collect money from various groups that rely on stream gage data, such as recreational groups, fishing groups, water districts, and power generators. There are, however, a number of other potential sources of funding available for this purpose which are discussed below.

Environmental License Plate Fund (Public Resources Code Section 21190, et seq.).
Aside from dedicated funding to several specific conservancies, Section 21191 (f) states that “The balance of the moneys in the California Environmental License Plate Fund (ELPF) shall be available for expenditure only for the exclusive trust purposes specified in Section 21190, upon appropriation by the Legislature.” Among these purposes, the following are relevant:

- Environmental education, including formal and informal public education programs.
- Protection, enhancement, and restoration of fish and wildlife habitat and related water quality, including review of the potential impact of development activities and land use changes on that habitat.
- Scientific research on the risks to California’s natural resources and communities caused by the impacts of climate change.

Greenhouse Gas Reduction Funds

In adopting Chapter 135 of 2017 (AB 398 E. Garcia), the Legislature extended the State's cap-and-trade program from 2020 to 2030. Cap-and-trade is a key policy to help ensure the State achieves its goal of reducing greenhouse gas emissions to 40 percent below 1990 levels by 2030. The program, in its renewal, allows for funds to be expended to mitigate the impacts of climate change in addition to those funds directed toward reducing greenhouse gas emissions. This key change would allow for these funds to be used to improve the stream gage network. Flashier stream flows, extreme drought, wildfire and ensuing debris flows, and sea-level rise all will require more robust stream monitoring, and funding could be available through the Greenhouse Gas Reduction Funds.

Local Taxing and Bond Measures

The Public Policy Institute outlines the institutional barriers to paying for general water programs, science and data monitoring at the local level in their 2014 *Paying for Water in California report* (Hanek et al 2014). They state:

> Our key conclusions are that: (1) Propositions 218 and 26 have created significant impediments to economically rational and sustainable funding of California's most important water service, management, and regulatory programs; (2) judicial interpretations of the constitutional restrictions generally have compounded these impediments; and (3) reform of the law is needed.

Underrepresented communities can be defined as racial, ethnic, economically disadvantaged, or other groups that historically have had less influence on how society functions or how resources are distributed. Even something as innocuous as stream gages may have been historically distributed in a way that disproportionally benefits some groups over others. The lack of stream gaging in underrepresented communities can result in delayed responses to emergencies, a lack of stream data to manage water resources efficiently, and will have severe impacts on ecosystems. Senate Bill 525 (2012) and Assembly Bill 1550 (2016) established a 25 percent minimum of total climate change investments to provide for improved public health, quality of life, and economic opportunity in California's most burdened communities. As identified in SB 525 and AB 1550, 25 percent of additional funding made available for stream gaging should be invested in underrepresented communities.

The report concludes with recommendations for water agencies, the legislature, the courts, and the voters to consider as a means of correcting (or at least ameliorating) those aspects of the law that are inconsistent with sound and creative water resources administration.

Summary and Recommendations

Plan Summary

SB 19 directs State agencies to develop a plan to deploy a network of stream gages to help identify and address significant gaps in water management and the conservation of freshwater species, identify opportunities for modernization and reactivation of abandoned stream gages, and determine funding needs. Development of this plan required substantial investigation and outreach into historic and current gaging activities within the state, which revealed numerous additional elements that are included as recommendations.

There has been a historical downward trend of gages in operation over the past few decades, primarily attributed to inadequate revenue to operate and maintain gages. Currently, there are 1,021 gages operating and reporting data publicly. Of these, 634 (62 percent) are operated by the USGS, with the remaining gages operated by State or other agencies. There are also a substantial number of gages being operated by third-party entities that are not being reported publicly on statewide databases or lack sufficient data accuracy to be reported as reliable information. This analysis was not able to capture these third-party gages for assessment and inventory, but there are opportunities to incorporate existing third-party stream gage infrastructure and operation into the publicly available stream gage network.

There are also key opportunities to improve both the integrity of data obtained from streamflow gages and the management of data between different agencies and stream gage operators. Analyzing stream gage data from multiple sources highlighted the inconsistent management of data, which leads to less efficient use of this data.

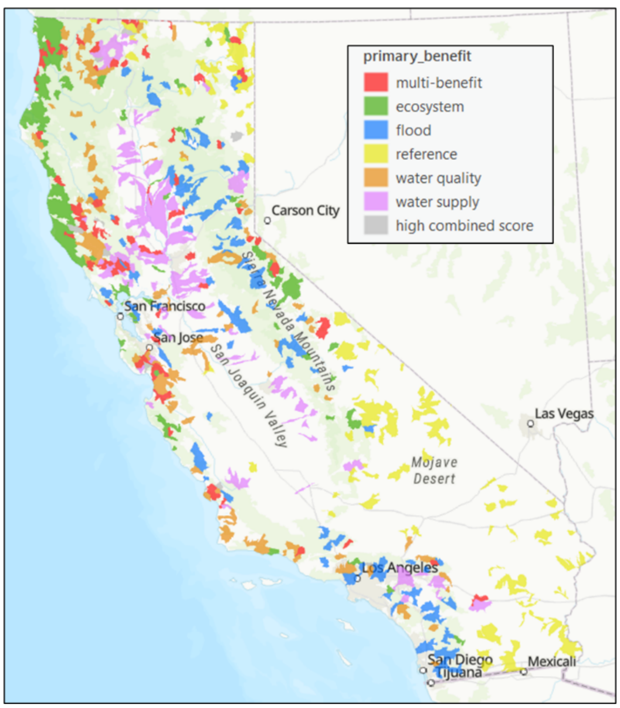
There are approximately 4,500 HUC12-scale watersheds within the state. As a result of the large spatial scale and inconsistencies of existing geospatial data, the plan evaluates and recommends stream gaging deployment at the HUC12 level. Recommendations for specific gage locations are more efficiently made following this initial planning effort. Individual gages were evaluated for potential upgrades or reactivation.

This plan evaluated the current stream gage network in two principal ways, first, by prioritizing watersheds based on water management goals, and second, by looking for opportunities to reactivate historic gages or upgrade existing gages.

Prioritization Summary

Prioritization of watersheds and gages for reactivation or upgrades was a multi-step process analyzing statewide gage gaps, reviewing individual gage characteristics, and combining input datasets into a model to prioritize watersheds and develop recommendations. Each HUC12 watershed was assigned a raw score for each management objective, a gage gap score, and a combined score multiplying each raw score with the gage gap score. The results show that management priorities vary across the state and different regions. High rank in multiple management objective categories is a good indicator of multi-benefit watershed priorities and likely water management conflicts. Only 30 watersheds scored within the top 100 and only 84 in the top 200 for more than one category, for a total of 922 priority watersheds out of 4469 in California.

Figure 29 Map showing watershed prioritization results color-coded by primary benefit.



Gages were evaluated using the same raw watershed score plus gage-specific scores based on location and history, to help select and eliminate candidates. It is important to note that the presence of an active gage in a watershed lowers the combined score of that watershed because that gage is present, but the gage itself may need an upgrade. Sometimes this means that the watershed would have been prioritized if the gage were not present.

Results were divided into tiers to assist with identifying those watersheds in which the State should initially focus its efforts. Tier 1 watersheds are those that scored in the top

100 in at least one management category or scored in the top 200 in at least two management categories. Tier 2 watersheds scored in the top 200 in at least one management category or had a multi-benefit cumulative score that placed them in the overall top 200. Tier 3 watersheds were not specifically assessed but are defined as those that did not score in the top 200 but contain gages recommended for upgrades or reactivation based on the separate gage evaluation. Finally, active gages are recommended for temperature sensors if they are in watersheds that would be in the top 200 if not for the active gage or otherwise serve a known important function such as an active reference or forecasting gage.

Tier 1 includes 516 watersheds and a total of 524 locations recommended for new gage installation, gage reactivation, or gage upgrades (Table 9). Note that it is possible for a watershed to have a recommendation for both a gage upgrade and a new gage or a reactivation. This is because existing upgradeable gages were counted as active in the gage gap analysis, and despite the existence of that gage lowering the overall score, the watershed still ranked high enough to be a priority. There are 30 new gages allocated for CNFRC (5) and FIRO (25) programs, 406 new gages allocated to other high priority watersheds, 80 gages recommended for reactivation, and 8 gages recommended for upgrades in Tier 1.

Tier 2 includes 436 watersheds and a total of 449 locations for new gage installation, gage reactivation, or gage upgrades. There are 382 new gages, 54 reactivations, and 13 upgrades recommended in Tier 2. While not at the highest tier, most of these watersheds represent a priority for a specific management objective.

The recommendations also include 22 additional reactivations, 18 additional upgrades (Tier 3), and temperature sensors for 364 active-high quality and 139 active-limited use gages (not including gages already recommended for upgrades in Tier 1 and 2). Upgrades in this context refer to adding telemetry or incorporating flow measurement equipment and operation and maintenance tasks necessary to establish high quality flow data, plus additional site-specific needs including adding sensors. There are other types of upgrades, such as replacing obsolete equipment or rebuilding gage site features, that are not captured in this statewide analysis. In some cases, a new gage may be warranted instead of a reactivation or an upgrade.

Table 8 Recommended high priority watersheds for gage reactivation, upgrades, and installation

Tier #	Tier Category	Number of HUC12 Watersheds	Number of Reactivation Gages	Number of Upgrade Gages	Number of Watersheds with New Gages
1	Very High	516	80	8	436
2	High	436	54	13	382
3	Ranked Gages	*NA*	22	18	*NA*
4	Not Ranked	3517	787	181	3651
	Total Count	4469	943	220	4469

This effort is intended to provide high-level guidance that generally captures the different management priorities but does not supersede local experience and more specific knowledge. Specific locations were not analyzed for access, suitability, roads, permitting conditions, or other impediments. The exact location of future FIRO and Flood-MAR projects is not entirely known, and they may benefit more from precipitation or snow-depth monitoring than stream gaging, but they deserve serious gaging support as they fundamentally change the water management operations in the state. In addition, a single watershed may score highly in multiple datasets, but the priority locations may be in different parts of the watershed; for example, salmon rearing habitat may be well upstream of a SGMA basin. There are other places where upgrading or modernizing a gage or reactivating an unranked historical stream gage provides local value to the stream gage network, but the analysis did not capture that need. We encourage future water management planners to review the input dataset on their own merit and to conduct more localized analysis to help inform actual gage locations.

Finally, the raw prioritization scores (e.g., without the gage gap score) provide insight into how well the existing gaging network covers the state's management objectives. In total, 81% of active high-quality gages and 69% of active limited-use gages are in high priority watersheds, are critical for forecasting, and/or are reference gages.

Underrepresented Communities

The SB19 team does not have the resources for an in-depth analysis of underrepresented communities and their stream gage priorities; however, we recognize that our analysis could be implicitly biased and wish to check and adjust our results as appropriate.

DWR supports analysis of underrepresented, also called disadvantaged communities (DAC), via a DAC mapping tool[31] and downloadable data[32]. The data source is the US Census (American Community Survey) with attribute table additions by DWR, which designates places with a median household income less than 60 percent ($56,981 in 2018) or 80 percent ($42,737 in 2018) of the California median as DAC or severe DAC, respectively. No other factors are included in this layer.

We analyzed the overlap between DAC census place boundaries (e.g., the smallest geographic boundary, instead of large areas) with our HUC12 watersheds and prioritization. The communities are generally downstream in the watershed areas and therefore should benefit from any upstream gages. The results show that watersheds containing DACs are slightly more likely to be included than not (**Table 9**).

Table 9 The number of priority watersheds and all watersheds containing and not containing underrepresented communities, showing that priority watersheds comprise a higher percentage of DACs (30%) compared to all watersheds (24%)

Community Present in HUC12	Priority HUC12	All HUC12
Severely Disadvantaged	142	621
Disadvantaged	138	463
Community with No Data	0	1
Community not a DAC	159	612
No Census Communities	483	2,772
Total DAC	280	1,084
Total HUC12	922	4,469
Percent DAC	30%	24%

Recommendations

The recommendations in this section prioritize actions that will provide the best potential to enhance the stream gage network in a timely and cost-efficient manner. The plan to improve the state's stream gage network is presented as four core recommendations. The recommendations will allow for near-term solutions and long-term planning. The recommendations are independent and do not rely on one recommendation being completed before another recommendation can be implemented.

[31] https://gis.water.ca.gov/app/dacs/
[32] https://data.cnra.ca.gov/dataset/dacs-census

Integrate Third-party Gages

There are many gages that are operated by third parties that are not reported publicly. Third parties include utility companies, private landowners, community groups, non-government organizations, Tribes, and local agencies. There are many potential reasons that currently limit the non-public distribution of stream gage data including privacy or confidentiality concerns, inconsistent data or lack of operations and maintenance, inability to telemeter data, or simply the need for data formatting.

Integration of third-party gages into the public gaging system is a low-cost opportunity to significantly expand publicly available gage data. For example, in the highest tier watersheds, there are over 20 third-party gages operating. An effort is needed to identify third-party gages, create minimum data standards for publicly available gage data, and develop mechanisms to integrate the third-party gage data into the public gaging system, which could involve mandates, funding incentives, or other approaches. The effort should include outreach to other private entities that operate stream gages to solicit input on how to incorporate their stream gage data into the public systems and understand any impediments. An approximate timeline is on the order of three years to develop a plan to integrate third-party gages.

Improve and Expand the State's Gaging System

Reactivate Historical Gaging Sites

There is unique value in reactivating historical gaging sites. Combined with prioritization of watershed management objectives. Table A-2 in Appendix A identifies the top locations to install stream gages near historical gaging sites. The table identifies multi-benefit gages that support more than one water management need (e.g., water supply, water quality) or are located in high-priority watersheds (Tier 1 and Tier 2). Gages on this list should be prioritized for reactivation if a qualified gage operator (most likely DWR, USGS, or local water managers) and funding source can be identified to support their installation and long-term operation, with consideration for why the gage was initially de-activated (e.g., funding, site access, etc.). Additional potential sites in lower priority watersheds have also been identified and can be found on the SB 19 Stream Gage website.

156 of the 1196 inactive gages are recommended for reinstallation, at an approximate cost of $5,148,000 and approximate timeline of five years. The approximate annual operations and maintenance cost to sustain this recommendation is $4,680,000.

Upgrade Existing Gages

Similar to gage reactivation, there is value in investing in existing gages to enhance current gage data and telemetry. Table A-3 in Appendix A identifies the top existing gage sites to upgrade to collect additional streamflow data with the installation of additional sensors (e.g., temperature, dissolved oxygen), equipped for telemetry (recording and transmitting of data without in-person effort), or at which a flow rating curve to convert stage to flow could be added. The table identifies multi-benefit gages that support more than one water management need or are in high-priority watersheds.

Coordination with the existing gage operators and funding sources should be identified to implement upgrades at these sites, with consideration for why the upgrades are not currently active at the location (e.g., funding, site access, etc.). An approximate timeline is 2–5 years depending on the number of sites and related site conditions, available resources, and gage operator. Of the 359 active-limited use gages, 39 are recommended for upgrade at an approximate cost totaling $1,287,000. The approximate annual operations and maintenance baseline cost to sustain this recommendation is $1,170,000.

Adding temperature sensors is also recommended because over 77% of active gages lack temperature sensors and SB 19 lists temperature as a priority consideration. Approximately 77% of active gages are serving a critical function or are in watersheds that would be high priority if the gage was not present; of those, 74% lack a temperature sensor. It is recommended that all gages in high priority areas have temperature sensors, in addition to the gages recommended for more comprehensive upgrades listed above. There are 364 active-high quality and 139 active-limited use gages that are recommended for temperature sensors at an approximate total cost of approximately $5,030,000 with a 5-year timeline. Operations and maintenance for these gages is already covered and is not expected to add additional cost.

Install new stream gages.

Table A-4 in Appendix A identifies the top locations (Tier 1) to install new stream gages. The table identifies watersheds that have high priority water management needs, including multi-benefit locations. New stream gaging locations are identified and prioritized by their water management categories (i.e., water supply, flood, water quality, and ecosystem) separately so that parties with a specific interest (e.g., flood) can identify which watersheds are prioritized for that water management category.

Tier 1 watersheds in Table A-4 should be prioritized for installation if a qualified gage operator (most likely DWR, USGS, or local water managers) and funding source can be identified to support their installation and long-term operation. Because of the variability and scale of potential deployment, timeline parameters are provided for reference in future planning efforts. Depending on the site location and gaging needs, deployment can take as little as 3–4 months and as long as a few years to install. 436 out of 4469 watersheds are recommended for new gage installation at an approximate capital cost of $15,696,000. The approximate annual operations and maintenance cost to sustain this recommendation is $13,080,000.

Deployment of Tier 2 gages, or even select gages within Tier 2, is expected to add value to the stream gage network. Though, as a primary focus of time and resources, the watersheds identified in Tier 1 are recommended. Similarly, there are watersheds outside of this prioritized list where gage deployment has value, and these watersheds can always be included in future gaging opportunities when conditions warrant.

A summary of recommended costs is provided in Table 10.

Table 10 Summary of Recommendations and Associated Costs

	Reactivation Gages	Upgrade Gages	Watershed with New Gages	Total
Recommended Count	156	39	436	631
Capital Unit Cost	$33,000	$33,000	$36,000	
Subtotal Capital Cost	$5,148,000	$1,287,000	$15,696,000	$22,131,000
Annual O&M Unit Cost	$30,000	$30,000	$30,000	
Annual O&M Cost	$4,680,000	$1,170,000	$13,080,000	$18,930,000

Note: Unit costs used are the average of Class 3 for reactivation and new gages, and gage upgrade Package B. Costs provided are estimated in early 2022 and do not account for escalation.

Improve Gage Data Quality and Management.
This plan recommends the implementation of a water data management system based on current known issues, anticipated data use needs, and evolving recommendations from data experts. We recommend that the State consider stream gage data management to be a public service, and to place a high emphasis on meeting the FAIR (findable, accessible, interoperable, and reusable) criteria for all stream gage data by all data producers. This plan also recommends that the State facilitate this effort by developing data standards and QA/QC flags; implementing persistent identifiers; providing a central repository free-of-charge for all water data producers; requiring the sharing of most publicly funded data; providing advanced data filtering, searching, and access tools; linking to external databases that host stream gage data; and providing analysis and data visualization tools that can been used by the general public.

Recommendations also include continuous funding for data management, visualization, and data access in service of the public. We recommend continued outreach and inventory for stream gage data produced by independent entities, and to facilitate bringing those data up to current standards and then sharing this data. We recommend adding real-time telemetry equipment to gages that may support flood management forecasting.

An approximate timeline to develop this program is approximately two years, with ongoing facilitation and activity. An approximate cost to fulfill this recommendation for the development and implementation of the improvements is an appropriation of $600,000 annually for three years. To continue the maintenance of the data tools, an annual appropriation of $275,000 would be needed.

Prioritize Funding
Funding and associated resources are needed to implement the recommendations outlined in this report. Reliable and sufficient funding are key elements of the state's stream gage deficit. In general, there are two costs associated with a stream gage: (1) initial capital cost for installation of the stream gage; and (2) annual cost for operation and maintenance of a stream gage.

- **At the state level.** Long-term funding sources are needed to support the installation of new gages, re-activation of historic gage sites, and upgrade of existing gages using the prioritized lists provided in Recommendation 2.
- **At the local or private level.** Additionally, funding should be provided to incentivize local agencies to install and operate new gages or upgrade existing gages to meet established standards and share their data publicly. For example, a grant program could be established where local agencies could apply for funding to install and operate stream gages for a limited number of years (e.g., five years), whereafter the local agencies agree to operate the gage for an additional time (e.g., 15 years).

Potential funding sources at the State level are the Environmental License Plate Fund, Greenhouse Gas Reduction Funds, Wildlife Conservation Funds, the establishment of water use fees, and the General Fund. Without additional stable funding, critical gaps in the stream gage network will continue to expand, further limiting water managers' ability to effectively manage the state's limited water resources.

Streamline Regulatory Permitting.
Over the last ten years, the environmental regulatory costs associated with the installation of stream gages has by far surpassed the actual cost of installing the gage. Such costs can prevent operators from installing gages. In November 2020, CNRA released the Cutting Green Tape — Regulatory Efficiencies for a Resilient Environment

initiative. The initiative is an effort to increase the pace and scale of environmental restoration (California Landscape Stewardship Network November 2020). California has laws that protect our environment from the effects of development and resource extractions. Unfortunately, projects that are beneficial to the environment can be slowed by the same processes and procedures that are designed to protect them. Stream gaging is a vital tool in protecting the environment and should be included in the Cutting Green Tape effort. This could include allowing for exemptions for gages with a footprint of less than ten square feet and the development of a standard permitting process to install and maintain stream gages.

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