Telemetered Water Monitoring and Reporting (2025)

Telemetry Research Unit, Division of Water Rights, State Water Resources Control Board

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This report is a research document summarizing available information. Any mentions of equipment or services do not represent an endorsement of that equipment or service by the State Water Resources Control Board.

Executive Summary

The Telemetry Research Unit (TRU) of the State Water Resources Control Board (Board) evaluated several sources for information about the current state of telemetered water monitoring at the Board and in California, including 1) convening a Telemetry Technical Group, 2) reviewing submitted Measurement Files, and 3) interviewing equipment manufacturers.

While accurate and timely water data is essential for resource management, many barriers currently exist.

1) Telemetered water monitoring requires technical expertise to select appropriate equipment, install equipment correctly for the site conditions, calibrate and maintain equipment appropriately, and retrieve and manage data.

2) Monitoring can represent a significant cost for small organizations.

3) Telemetered monitoring data can be reviewed promptly, but manually retrieved data may not be reviewed until much later. Organizations may delay some or all data review until reporting windows.

4) Automated data review using software can quicken data approval and decision-making, but few organizations do so.

5) When regulation requirements don’t align with technical recommendations, regulations may create additional costs and monitoring gaps.

6) Many data formats are used by manufacturers and reporters due to lack of acceptance of a single data standard. This situation minimizes the utility of data, causes reporter confusion, and increases staffing costs.

These barriers reduce the timeliness and quality of data available to the Board. The Board may choose to consider the following actions to foster data governance and enhance quality of reported data:

1) Develop educational resources and staff to offer technical information on a) equipment selection, installation, maintenance, b) automated transmission and automated review of data, and c) data management and governance.

2) Offer financial incentives to small organizations for initial procurements to help the organizations afford a) more reliable equipment that has lower operations and maintenance costs and b) telemetered equipment that reduces delays in data review and reporting.

3) Review regulations and remove proscriptive language that requires specific maintenance and calibration actions (e.g., “calibrate every five years”) in favor of language that supports functional goals (e.g. “calibrate following manufacturer’s protocols for the device”).

4) Require reporters perform regular data retrieval and review to ensure data problems are quickly identified and resolved.

5) Promulgate a specific data standard for monitoring data and metadata that aligns with other accepted data standards to reduce reporter confusion and to encourage manufacturers to support standardized data.

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1. Key Findings and Recommendations for Conducting Monitoring and Reporting

1.1 Equipment Selection, Installation, Maintenance, and Calibration

Overall, Telemetry Technical Group Members (Members) used an array of sensor types; frequently measured flow and water height; and preferred sensors that required little maintenance, yielded minimal background noise, and maintained calibration. Sensors that remain in calibration longer reduce equipment maintenance costs, provide more reliable data, and decrease station downtime.

Improperly installed or maintained equipment is costly, not only in the resources spent resolving problems but also with respect to degraded data quality. Recurring or substantial problems can erode trust in the equipment and the data the equipment produces. Users should seek advice from knowledgeable personnel to ensure equipment is appropriate for site conditions and monitoring need, installed correctly, and maintained appropriately.

1.2 Telemetry Improves Data Quality and Reduces Site Visits

Most Members reported reviewing data as part of their maintenance process, where questionable data acts as a trigger to inspect or maintain equipment. Members who lacked telemetered equipment reported the need to visit the site on a regular basis to confirm operation, perform anticipated maintenance, and retrieve data. This static arrangement led to unneeded site visits before maintenance was required and also data loss when maintenance needs or damage occurred undetected. Members with telemetered equipment were able perform data-driven maintenance and repair, with site visits triggered by data anomalies, thereby improving data quality and reducing labor costs.

1.3 Automated Data Review Speeds Data for Decision-Making

Environmental monitoring can produce large datasets with extensive metadata making data management a critical component of project success. Several Members expressed that manual review by staff acted as a bottleneck on their data workflow. Members reported variable timelines for data quality assurance and quality control (QA/QC) depending on organization size, budget, and staffing. Small organizations and organizations with un-telemetered data reported infrequent review, often only annually before reporting data or as needed due to operations and maintenance (O&M) costs. Larger organizations reported some amount of weekly review but often postponed thorough QA/QC until reporting windows (e.g., monthly, quarterly, or annually). These delayed reviews can lead to reduced data quality when data abnormalities are not promptly identified and addressed.

Many software programs support user-defined automated quality validation that can reduce staff workload. Several Members did not use software to automate reviewing and validating data but expressed interest. They also expressed doubt that the data quality would be as high as manually reviewed data. Two Members used automated software tools and were content with the quality of the automatic review for all processes but final approval. More widespread adoption of automated data review processes would enable users to quickly identify data anomalies and address equipment issues.

1.4 Costs

Cost varies greatly depending on monitoring goals, site location, existing infrastructure, selected equipment, and overhead costs. Members reported procurement and installation costs of $1,000 to over $20,000 and annual O&M costs of $100 to over $5,000. Monitoring diversions or other simple waterways are typically less expensive than monitoring streamflow, largely due to increased labor for developing rating curves for streams. Whether performing work internally or contracting their work, Members reported that labor accounted for most of their project costs. Members reported three approaches that reduced their labor costs:

1) Buying more expensive equipment that was more reliable to minimize labor costs for site visits. This approach may also reduce data loss from equipment downtime.

2) Collaborating with an agency close to the monitoring sites for that agency to perform maintenance and repairs in order to reduce staff travel hours. This approach may also improve data quality, by reducing response time when repairs are needed.

3) Using telemetered equipment and reviewing data remotely to reduce site visits for unneeded maintenance.

4) Using automated software tools for initial quality review to save staff time. This approach also flags failing data quickly, reducing delay in recognizing monitoring problems.

2. Key Findings and Recommendations for Supporting Monitoring and Reporting

2.1 SB88 Data Sources and Current Format

Measurement files for Water Measurement and Reporting Regulations (i.e., SB88, California Code of Regulations 23:931-938) are currently submitted to the Board as unstandardized documents, with overall poor data management practices including data lacking explicit headers, mingled data and metadata, repeated data in the document, and embedded images. However, two-thirds of SB88 submissions indicate that the reporters are using equipment from only ten manufacturers. This situation represents a significant opportunity for the Board to work with these manufacturers to develop or adopt a common standard for data that is submitted to the Board. This step may incur an additional burden on reporters but can make reported data usable with minimum staff intervention for timely and targeted resource management decisions.

2.2 Aligning Technical Considerations with Regulations

Equipment manufacturers may suggest calibration intervals or triggers, but these recommendations may not align with legal obligations. For example, current regulations for SB88 require that equipment is re-calibrated every 5 years and certified, regardless of manufacturer recommendations. Calibration events require costly travel and labor to visit a site and perform calibration. Calibration may also lead to data gaps if staff must un-install the equipment and send it to the manufacturer for calibration. As the Board considers regulatory updates, these technical/regulatory mismatches should be considered.

2.3 Data Sensitivity

Most Members indicated a willingness to allow the Board access to their data sources in real-time. Some Members reported concerns about protecting operations and market advantage. Any future regulations requiring reporters to share real-time data (either in reporters' data systems or pushed to Board data systems) should consider reasonable safeguards to protect reporters' business operations while ensuring that data is available to steward public water resources.

2.4 Data Governance

Currently, reporters and manufacturers mostly do not implement or support any of the widely-available and accepted data standards for water monitoring (e.g. WaterML, NWIS). Overall Members displayed limited knowledge or interest in established data standards and mostly did not employ them in their data governance. Likewise, manufacturers that TRU contracted stated they would work with clients to report in a standard that met client needs but did not support particular data standards "out-of-the-box". This reporting environment leads to chaotic data sets that are difficult to integrate, both for reporters who may have many equipment devices and also for Water Board staff receiving monitoring data.

The Board should consider adopting a data standard for all internally-generated monitoring and regulatory data reported to the Board. With the public launch of the Division of Water Rights' new data system, CalWATRS, in 2025, users will be able to submit monitoring data to the Board as files and also as automatic transfers. Both of these submission processes require data that conforms to a submission standard to properly ingest, manage, and govern the data. Adopting a well-documented, comprehensive Board data standard will introduce a new burden on staff who monitor and on water right holders who report data to the Board. The Board will want to consider supporting this new requirement with outreach and engagement to reporters, but also by coordination with equipment manufacturers to develop equipment configurations that automatically generate data in the Board data standard.

2.5 Outreach and Engagement to Support Organizational Change Management

As the Board updates regulations to fully implement the new data system, CalWATRS, and improve SB88 reporting, the Board should consider developing outreach and engagement plans to socialize the new requirements and train on the system. This outreach will be crucial to public acceptance. One Member expressed concerns that as the Board changed regulatory requirements, the updates may create confusion and dissatisfaction among water diverters that have invested resources in complying with previous regulations. Overall, most Members stated increased outreach from the Board would be beneficial and specifically named 1) better communication between the Board and water diverters and 2) clearer explanations of the importance and value of reporting.

3. Research Methods

Several sources of information were used to develop this report and are described below. This report is intended to quickly summarize general knowledge about water data telemetry as part of the Telemetry Pilot Project.

3.1 Technical Group

Staff in the Telemetry Research Unit (TRU) convened a small, diverse Telemetry Technical Group (Technical Group) of interested parties who conduct water monitoring or use telemetered data. Members provided information to staff through a questionnaire and a working meeting on topics of logistics, costs of water measurement, and data reporting. Further details about the Technical Group composition are in Appendix A and a summary of their monitoring and reporting details are in Appendix B.

3.2 SB88 Data Files

TRU staff reviewed measurement data files submitted by reporters in compliance with SB88. Data content and format were characterized to understand the scope of data currently submitted to the Board and identify ways for the data to be automatically ingested and analyzed. Improving the quality of submitted data will support Board staff in making more responsive and informed water management decisions. Complete details about the SB88 data file review are in Appendix C, as well as in the reports "Clear Lake Watershed Measurement Files Evaluation (2018-2022)", "Large Diverter Measurement Files Evaluation (2018-2022)", and "Reporting Year 2021 Measurement Files Evaluation".

3.3 Equipment Manufacturers

Board staff in the Drought Planning Unit (DPU) evaluated water monitoring device information submitted by reporters for compliance with SB88 and determined that ten manufacturers accounted for two-thirds of submissions. TRU staff contacted these ten manufacturers regarding their telemetry equipment and data processes for water monitoring. Manufacturers shared information regarding their most popular sensors, data loggers, and transmission devices; the devices' default data reporting content, formats, and processes; and application programming interface (API) availability for data transfer. Complete details about the equipment manufacturer assessment are in the report "Evaluation of Water Telemetry Equipment".

4. Monitoring Equipment

4.1 Current State of Technology

Numerous companies in the marketplace supply water monitoring equipment, including measurement devices (Section 4), transmission devices and services (Section 5), and data management services (Section 6). Users can select equipment from various price points, considering their data quality needs, performance requirements, and monitoring goals. Some manufacturers offer equipment support services such as equipment maintenance, calibration, and repair; data transmission management; and data management systems.

Monitoring equipment is available for a large variety of parameters and some equipment has customizable, multi-parameter set-ups on a single device. Common parameters include flow and stage height, while sensors are available for many others including temperature, dissolved oxygen, turbidity, and electrical conductivity. Separate equipment for measurement, transmission, and power supply may be purchased and connected, but integrated equipment choices are also available. Simpler parameters (e.g., temperature) typically do not require routine maintenance and calibration after initial installation and set-up, while more complicated parameters (e.g., water volume or conductivity) require regular maintenance and calibration.

4.2 Equipment Reported in SB88 Submissions

Review of SB88 data files shows that only ten equipment manufacturers represent two-thirds of monitoring equipment used to measure water diversions in compliance with SB88 (Table 1). Of these manufacturers, all except Rosemount offer equipment that can telemeter monitoring data.

Table 1. Ten most commonly used manufacturers in submitted SB88 files. Column one depicts manufacturer name and column two shows the percent of submitted files using equipment by that manufacturer. The remaining percentage of files contained less common manufacturers or unidentifiable manufacturers.

Manufacturer	Percent (%)
McCrometer	32
Seametrics	13
YSI	5
Badger Meter	4

Manufacturer	Percent (%)
Netafim	3
Mace*	2
SonTek	2
Rosemount	2
Sensus	2
Panametrics	2

* Mace was purchased by In Situ in 2017

4.3 Equipment Reported by Technical Group Members

Members reported equipment from a variety of manufacturers, including manufacturers listed in Table 1 and other manufacturers, and covering a variety of different meters and data loggers (Table 2). Members reported varying reasons for the equipment selection, including monitoring needs, equipment capabilities, affordability, and familiarity.

Several members expressed the importance of monitoring and telemetry but stated their organization and/or clients have limited resources to acquire, install, and monitor equipment. Additionally, some lack the available staff or budget to undertake an upgrade to their current monitoring network.

Table 2. Table presenting equipment reported by Technical Group Members. Column one displays the manufacturer, column two shows the equipment model, and column three depicts the equipment type.

Manufacturer	Model	Equipment Type
Campbell Scientific	CR800; CR850; CR1000X	Data logger
Campbell Scientific	CS215	Temperature and humidity sensor
Campbell Scientific	CS451	Pressure and temperature sensor
Campbell Scientific	TB4-L	Precipitation sensor
FTS	DTS-12	Turbidity sensor
In-Situ	Level TROLL	Pressure transducer
In-Situ	VuLink LevelTroll	Pressure and temperature sensor
Kisters (formerly Hyquest Solutions)	HS40/3100	Gas purge compressor & bubbler
Mace*	AgriFlo CXi	Data Logger
Mace*	Mace Series3 XCi	Ultrasonic Flow Meter
Mace*	N3318	Doppler Flow Meter
McCrometer	McMag3000	Electromagnetic Flow Meter
OnSet	HOBO MX2001	Barometer
OnSet	HOBO RX3000	Remote monitoring station

Manufacturer	Model	Equipment Type
Seametrics	PS9800	Pressure transducer
Seametrics	AG 3000	Electromagnetic Flow Meter
Sontek	SonTek SW E1292	Doppler Flow Meter
YSI	WaterLOG 350/355XL	Pressure/bubbler sensor and data logger
YSI	WaterLOG H-3342	Encoder

* Mace was purchased by In Situ in 2017

4.4 Equipment Features and Limitations

4.4.1 Sensors

Sensors are specialized devices that detect the level of the target parameter. In selecting a sensor, factors to consider include compatibility with other equipment, maintenance requirements, calibration requirements, and suitability to monitoring site and measurement goals. Overall, Members used an array of sensor types; frequently measured flow and water height; and preferred sensors that required little maintenance, yielded minimal background noise, and maintained calibration.

Maintenance requirements vary among sensors. Selecting equipment with responsive customer service and quick repairs can improve monitoring and data outcomes. Most Members reported uninstalling damaged devices and sending them to the manufacturer for service. Member #8 shared that the AG 3000 by Seametrics requires little maintenance because it has fewer mechanical components that could fail, and that the integrated meter and data logger made diagnostics easier.

Calibration requirements are important aspects of selecting a sensor and can vary greatly among manufacturers and parameters. Some sensors come pre-calibrated from the manufacturer, others are calibrated only at installation, and others require regular calibration. Member #4 described using pressure transducers from multiple manufacturers including Onset, In-Situ, and Seametrics and reported Seametrics' sensors maintain calibration better. Member #8 reported that Seametrics' AG 3000 does not require periodic calibration according to manufacturer specifications. Sensors that remain in calibration longer reduce equipment maintenance costs and provide more reliable data.

Users requiring highly accurate data in low-flow conditions should consider pressure transducers with a lower pounds per square inch (PSI) rating. Member #4 shared they switched from a 15 PSI to a 5 PSI sensor to achieve accuracy in a low flow stream. The Member also reported that they preferred pressure transducers manufactured by Seametrics because the Member observed the sensor return to a calibrated state better when the sensor was exposed to conditions outside their normal operating range.

4.4.2 Data Loggers

Data loggers record measurements from sensors at programmed time intervals. Some data loggers are manufactured with integrated sensors, while others are stand-alone devices that are connected to sensors. Most Members reported equipment with integrated data loggers, such as Seametrics' AG300, McCrometer's McMag3000, and SonTek's SW E1292 doppler meter. Ten equipment manufacturers were asked about their popular models and only one reported an integrated sensor and data logger device as a popular model (i.e., In-Situ's Vulink device).

Data loggers can typically record readings from multiple sensors simultaneously. Data is usually stored on built-in memory, and telemetry-enabled data loggers can also transmit to remote data systems. The memory capacity of the data logger and the desired sample rate determine the duration of monitoring data that it can record. Factors to consider when choosing a data logger include types of input signals, number of available inputs, planned sample rate, amount of internal memory, and telemetry ability[1]

4.4.3 Equipment Installation and Damage

Sensitive monitoring equipment often needs to be grounded during installation to reduce signal noise and produce reliable data. Members #1, #2, and #8 all shared experiences with improperly grounded or ungrounded equipment producing incorrect data, especially low-level readings when no water flow occurred (i.e., ghost data). Member #1 experienced ghost data recorded by two different flow meters, an electromagnetic flow meter and a doppler meter, when their water pumps were shut off. Member #2 reported multiple malfunctions with a McCrometer McMag3000. Their organization had a representative from McCrometer visit to inspect the equipment and it was discovered the meters were improperly grounded. Member #2 reported that their organization lost data files due to improper grounding.

Several Members reported equipment failures due to animal damage. Member #2 explained that a bird damaged an exposed button from one of their flow meters, rendering the device inoperable. Member #3 stated rodents chewed through some of their exposed communication cables resulting in data gaps. Both Members resorted to installing more protective barriers around their equipment to prevent damage from animals.

Improperly installed equipment is costly, not only in the resources spent resolving the problem but also with respect to unusable or lost data. Equipment failure can also erode trust in the equipment. Users should seek advice from knowledgeable personnel to ensure equipment is installed correctly and appropriate to the site hazards.

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[1] Omega Engineering, Inc. (n.d.). *Data Loggers*. Retrieved December 2023, from https://www.omega.com/en-us/resources/data-loggers

4.4.4 Data Reliability

4.4.4.1 Calibration

Sensor calibration may be conducted on a regular schedule, as needed, or only on initial set-up. Some sensors, such as pH typically require regular calibration for accurate values, while others, such as a staff gage are calibrated only during installation. Equipment manufacturers may suggest calibration intervals or triggers, but these recommendations may not align with data quality plans or with legal obligations. For example, current regulations for SB88 require that equipment is re-calibrated every 5 years and certified, regardless of manufacturer recommendations. Calibration events are costly, since they require staff to travel to the monitoring station, incurring labor and travel costs. They may also lead to data gaps if staff must un-install the equipment and send it to the manufacturer for calibration.

4.4.4.2 Supplemental Data

Other data sources may be needed to support or interpret monitoring data. For projects with data quality goals for completeness, users may run a second monitoring set-up if the first needs repair or concurrent monitoring set-ups if perfect completeness is required. Other projects may require bathymetric surveys or rating curves to calculate water volume based on measured staff height or sensor pressure. Bathymetric surveys are rarely updated due to the perception of slow change rates for reservoir topography. However, rating curves can be disrupted regularly by vegetation growth, flooding, ice, and backwater effects from fauna such as beavers. The frequency of updates varies widely. Some sites require updates with each flow measurement, while others may only require annual revisions. For instance, Member #3 reported updating rating curves monthly due to vegetation growth, resulting in 8-9 updates per year (equipment removed during winter high flows). Bathymetric surveys and rating curves can be integrated with measured data in configured Microsoft Excel workbooks or in more sophisticated software such as Water Information System KISTERS (WISKI) from KISTERS or HydroVu from In-Situ.

4.4.4.3 Data Review

Raw measurement data requires review for accuracy and reasonableness. Equipment may register inaccurate readings due to maintenance issues, such as biological growth on the sensor or improper grounding, or due to damage, such as environmental or animal action (Section 4.4.3). All Members reported that their data must be reviewed to identify and flag or correct errors. A few Members reported using automated data review processes, but all reported using trained staff to manually review and correct data.

Most Members reported reviewing data as part of their maintenance process, where questionable data acts as a trigger to visit the site and inspect or maintain equipment. Member #3 reported periodic sensor drifts causing the sensor to report different values than a staff gage installed at the site. Although their sensor type cannot be calibrated, they correct data from the sensor to match manual spot checks of the staff gage. Members who lacked telemetered equipment reported visiting site on a regular cycle to perform anticipated maintenance and data collection. This static arrangement led to site visits before maintenance was actually needed and also data loss when maintenance needs or damage occurred undetected. However, Members with telemetered equipment were able perform data-driven maintenance and repair, with site visits triggered by data anomalies. Member #3 reported that telemetry has improved their ability to more quickly identify erroneous values or when the station needs maintenance, improving their data quality and maintenance efforts.

Several Members expressed that manual review by staff acted as a bottleneck on their data workflow. Occasionally, data was not reviewed until weeks or months after collection of non-telemetered data or transmission of telemetered data, meaning maintenance and repair needs were delayed leading to reduced data quality or completeness. More wide-spread adoption of automated data review processes would enable users to quickly identify data anomalies and address equipment issues.

5. Transmission Equipment

5.1 Transmission Options

Telemetry enables data collection from remote devices and can deliver data in near real-time, providing water resource managers with the necessary information to make timely, informed decisions. The most common telemetry data transmission methods are cellular, radio, and satellite communications.

5.1.1 Cellular

Cellular networks are comprised of a series of base stations that provide coverage to a particular area. Cellular transmission occurs at 70—850 megahertz (MHz) for the low frequency band and 1700-2100 MHz for the high frequency band. Telemetry by cellular transmission relies on coverage by a cellular network at the monitoring station. The increased use of cellular technology has allowed cellular networks to have expanded coverage. Telemetry by cellular transmission requires monitoring equipment to have a modem, Subscriber Identity Module (SIM) card, and data plan from a cellular provider[2].

5.1.2 Radio

Radio transmission may use Very High Frequency (VHF), Ultra High Frequency (UHF), or spread spectrum radio operating systems to receive and transmit data. VHF and UHF systems transmit hundreds of miles on a narrow frequency and, in the United States, require a license to transmit from the Federal Communications Commission (FCC). Spread spectrum systems use frequency bands between 902 to 928 MHz, do not

[2] OTT HydroMet. (n.d.). *Remote Communication: The Importance of Selecting the Right Telemetry Option*. Ott HydroMet eBook. Retrieved December 2023, from https://cdn.bfldr.com/1XMCM0ZF/at/t5jr5z4k2xfv7728p5shnrw9/HYSUGSwpTelemetry_ebookEN.pdf

require an FCC license, and have a transmission range of approximately 8 kilometers (5 miles)[3].

Long Range (LoRa) transmission is a type of spread spectrum radio telemetry. It operates at 915 MHz in the Unites States and can transmit 2 to 15 kilometers (around 1 to 10 miles) depending on obstructions[4]. It functions by dispersed LoRa-equipped devices communicating to a central node (i.e., star network). The central node then uses cellular, satellite, or radio to communicate with the internet. LoRa has become popular for environmental monitoring due to its energy efficiency and governance through Long Range Wide Area Network (LoRaWAN).

5.1.3 Satellite

Satellite communication occurs through networks of satellites orbiting the Earth, and includes Geostationary Operational Earth Satellites (GOES), Iridium, and Starlink systems. Other satellite systems are anticipated in the future due to the development of reusable rockets.

The GOES system is owned by the United States government and has two primary satellites, GOES East and GOES West (Figure 1), which cover North and South America. The satellites operate at around 22,300 miles above Earth[5]. Users are assigned a channel and a transmission window to transmit data.

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[3] Miles, J., Eduardo. (2009). *Guidelines: Shallow Water Quality Monitoring Continuous Monitoring Station: Selection, Assembly & Construction* (No. 412). Chesapeake Bay National Research Reserve in Virginia. https://www.vims.edu/cbnerr/_docs/monitoring_docs/chpt6.pdf

[4] Adelantado et al. (2017). *Understanding the Limits of LoRaWAN*. IEEE Communications January 2017. https://arxiv.org/pdf/1607.08011

[5] National Oceanic and Atmospheric Administration. (n.d.). *GOES Overview.* U.S. Department of Commerce. Retrieved December 2023, from https://www.noaasis.noaa.gov/GOES/goes_overview.html

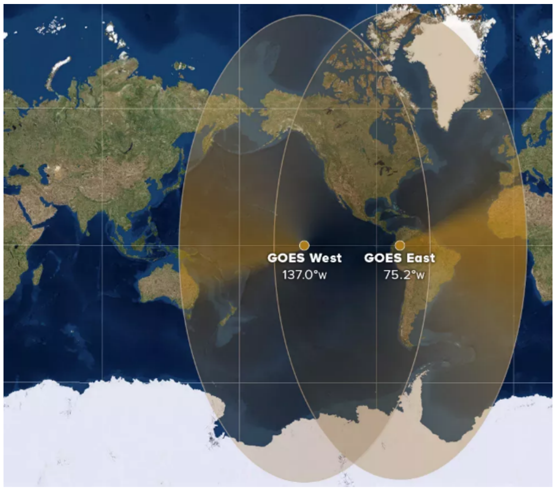

Figure 1. Map showing geographic coverage of the GOES East and West satellites[6].

Iridium satellite system is privately owned by Iridium Communications and has 66 satellites that cover the globe (Figure 2). The satellites operate in Low Earth Orbit (LEO) at approximately 485 miles above the Earth[7]. LEO decreases the latency, or time lag, between the user and satellite due to stronger signals and faster data transfers.

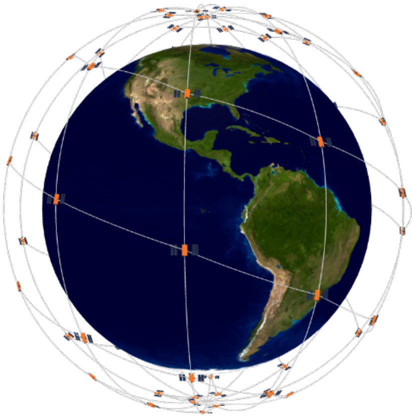

Figure 2. Image showing global coverage of Iridium satellites[8].

[6] National Oceanic and Atmospheric Administration. (2023, January 4). *Earth from Orbit: NOAA's GOES-18 is now GOES West*. U.S. Department of Commerce. https://www.nesdis.noaa.gov/news/earth-orbit-noaas-goes-18-now-goes-west

[7] Iridium Communications Inc. (n.d.). *Iridium Network*. Retrieved December 2023, from https://www.iridium.com/network/

[8] Iridium Communications Inc. (n.d.). *Iridium Network*. Retrieved December 2023, from https://www.iridium.com/network/

Starlink satellite network is owned by SpaceX. Starlink currently has over 4,000 satellites orbiting in LEO with global coverage[9] (Figures 3 and 4). The satellites operate at around 350 miles above Earth, closer than GOES and Iridium satellites, resulting in faster data transfer.

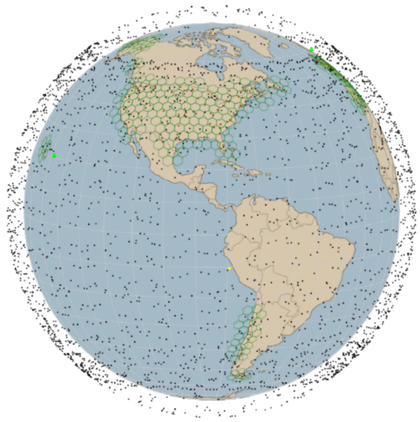

Figure 3. Image showing the Starlink satellite network over Earth. Satellites are displayed by black dots[10].

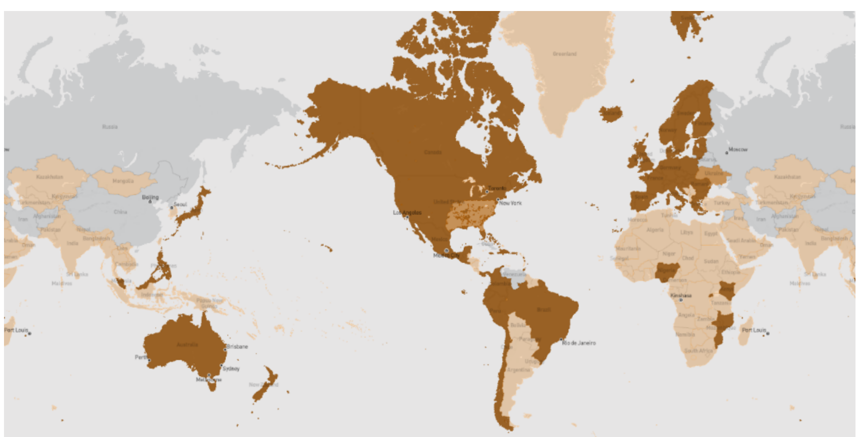

Figure 4. Geographic map showing Starlink access across the globe. The dark brown represents areas where Starlink is available. The lighter browns represent areas where access is waitlisted or planned. The gray areas have no coverage[11].

[9] Starlink. (n.d.). Retrieved December 2023, from https://www.starlink.com/

[10] Satellite Map. (n.d.). Starlink Constellation. Retrieved August 2023, from https://satellitemap.space/

[11] Starlink. (n.d.). Coverage Map. . Retrieved August 2023, from https://www.starlink.com/map

5.2 Selection Consideration

Many factors affect the cost-benefit analysis when choosing a transmission option, including:

1) Monitoring site characteristics
2) Duration of the monitoring effort
3) Initial and ongoing financial resources
4) Data accuracy and completeness requirements
5) Data volume requirements
6) Data transmission delay
7) One-way vs two-way communication

Key advantages and disadvantages for each transmission option are summarized in Table 3. General radio transmission is excluded from this table since it is highly configurable.

Table 3. Table comparing various features of cellular, GOES, Iridium, and Starlink transmission options[12][13].

Attribute	Cellular	GOES	Iridium	Starlink	LoRaWAN
Provider/Owner	Government and Commercial / Commercial	Government	Government and Commercial / Commercial	Commercial	Commercial
Range	Most of U.S.	Nearly global	Global	Global	Global
Reliability[1]	High	High	High	High	High
Robustness[2]	Medium[4] / High	High	High	High	Medium / High
Secure	Medium / High	Yes	Yes	Yes	Yes
Transmission frequency	Flexible	Fixed	Flexible	Flexible	Flexible
Latency[3]	Flexible	1-hour	5 min or >	~25 milliseconds	40 milliseconds or >
Bytes per transmission (max)	Flexible[5]	330 bytes	~300 bytes[6]	-	51-222 bytes
Power consumption	Low / Medium / High	Medium	Low	-	Low
Two-way communication	Full	Planned[7]	Limited	-	Full
Hardware costs	Medium	High	Medium	Medium	Medium
Data costs	Low / Medium	Low	Medium	Medium	Free[8]
Equipment footprint	Medium	Large	Medium	-	Medium
Internet of Things Capability	Yes	No	Yes	Yes	Yes

[12] Cellular, GOES, and Iridium data provided by United States Geological Survey. United States Geological Survey (November 2023). *Telemetry Attributes Comparison [PowerPoint slide]*. Private communication.
[13] Starlink and LoRaWAN data added by Telemetry Research Unit.

Attribute	Cellular	GOES	Iridium	Starlink	LoRaWAN
Live raw data available to external cooperators	Yes / No	No	No	-	Yes / No
Upgradability	Extensible	Limited	Somewhat limited?	-	Extensible

Footnotes:

[1] Reliability- Ability of a system to perform its requested functions under stated conditions; mean time between failures

[2] Robustness- Degree to which a system continues to function in the presence of stressful environmental conditions

[3] Latency- Difference in time between when the value was recorded and when it is transmitted

[4] Cellular signals fade during precipitation events

[5] Mindful of data plan

[6] Immediate addendum transmission if >340 bytes

[7] Limited starting in 2026

[8] Communication between LoRa-equipped devices (including the network central nodes) is free. Cost of transmission from central node to cloud will vary by transmission type.

5.2.1 Availability and Reliability

Availability and reliability of transmission options vary by location. Even in areas with good signal coverage, strong storms or significant overgrowth at a site can impede transmission. Users should conduct an analysis of the field location and their monitoring needs to determine the best transmission option.

5.2.1.1 Cellular

Users will need to verify that coverage is offered at their monitoring location. For very remote or rural areas, there may not be adequate cellular coverage. Poor cellular network coverage or weak cellular signal can cause data loss during transmission. The FCC hosts information about cellular coverage in the United States per provider (Figure 5) and users can also search an interactive map[14].

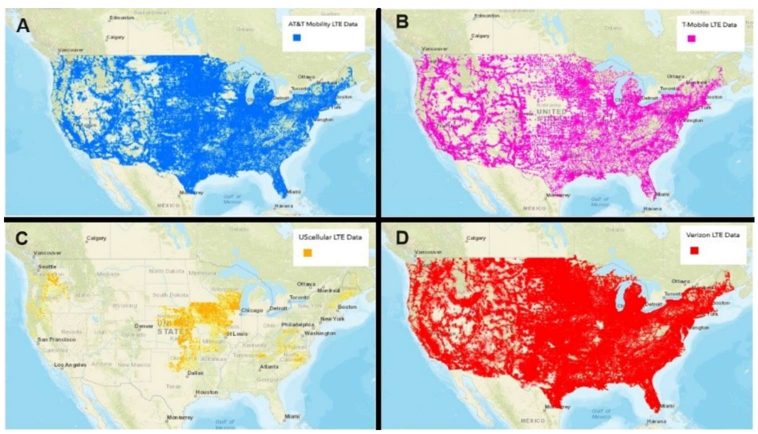

Figure 5. Map displaying estimated 4G LTE mobile coverage in the United States by four largest carriers: A) AT&T; B) T-Mobile; C) US Cellular; and D) Verizon. Map shows expected service at minimum download speed of five megabits per second (5 Mbps) and upload speed of 1 Mbps[15].

Users can use two-way transmission, for example to modify the monitoring interval. However, increased transmission will require a larger data plan and higher costs. Cellular transmission requires periodic hardware and software updates. Older equipment may become obsolete as providers update their cellular network to a new generation of broadband service. Member #3 reported that they retired their older 3G devices due to incompatibility with the advanced 4G and 5G networks.

[14] Federal Communication Commission (n.d.). Retrieved August 2023, from https://www.fcc.gov/BroadbandData/MobileMaps/mobile-map

[15] Federal Communication Commission. Accessed digitally August 2023, from https://fcc.maps.arcgis.com/apps/webappviewer/index.html?id=6c1b2e73d9d749cdb7bc88a0d1bdd25b

5.2.1.2 Radio

Radio communication can be highly reliable and available in nearly all areas. Radio communication can be two-way, thereby reducing trips to monitoring locations. Repeater stations are needed when monitoring sites do not have line-of-sight (LOS) connection to the base station or when the distance to the base station is out of range (Figure 6). Without repeater stations, it can be difficult to maintain a reliable signal via radio due to the degradation of the frequency signal when transmitting over long distances. This additional infrastructure can make radio much more expensive than cellular or satellite, depending on the monitoring situation.

LoRa/LoRaWAN networks have the same considerations as general radio transmission, although for LoRaWAN the central node acts as repeater station that then transmits to a cloud “base station”. LoRa-equipped devices communicate by LoRaWAN protocols can operate solely on battery power for years, avoiding solar panels or other external power supplies at monitoring sites. The central node of the network typically needs external power supplies to support long-range transmission to the cloud. LoRaWAN networks become less efficient as network size increases due to inherent technological characteristics, so networks of several hundred nodes benefit from subsetting into separate networks.

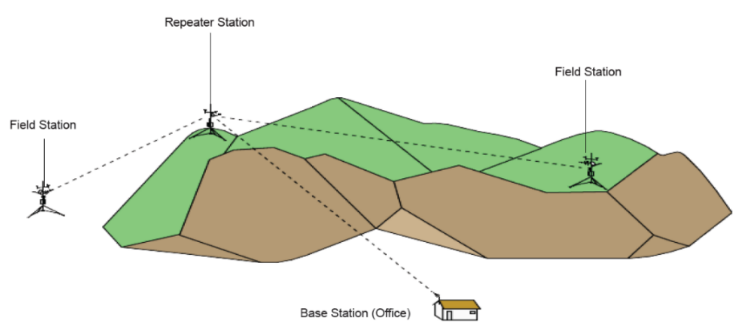

Figure 6. Image shows field stations sending data to a repeater station due to a mountain obstructing each field station's line-of-sight (LOS) to the base station[16].

5.2.1.2 Satellite

Satellite communication is readily available, even in remote locations. GOES coverage is limited to the United States (Figure 1) and is only available to federal, state, and local agencies or government-sponsored cooperators. Iridium and Starlink are privately owned, available to all consumers, and do not limit data transfer, but do scale charges based on data transfer.

Other important features:

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[16] Campbell Scientific, Inc. (2017, March 30). *Stable, Long-Range, Wireless Communication: Using Narrowband, Licensed, UHF/VHF Radios.* Retrieved August 2023, *from https://s.campbellsci.com/documents/cr/product-brochures/b_rf.pdf*

1) GOES limits transmission windows to 10-15 second windows every hour, limiting data transfer.

2) GOES only supports one-way communication, meaning data can be sent to the satellite but operators cannot connect to the station remotely to adjust the programming.

3) Iridium supports two-way communication.

5.2.2 Costs

There is a wide range in the cost of procuring, maintaining, and operating transmission equipment. Full details are discussed in Section 8.2.

5.3 Equipment Reported by Technical Group Members

Members reported receiving monitoring data by cellular (4 stations), manual download (4 stations), radio (2 stations), and satellite (1 station). Member #6 reported that their data is time-sensitive, so they use radio transmission to transfer data as often as needed (typically less than 1 second) in support of their business operations. For this scenario, radio transmission has higher initial set-up costs for free transmission, but transmitting every second by cellular or satellite would incur high service bills. Member #8 introduced staff to operators of a local water district. The district reported they use Starlink equipment for transmission because some of the district's diversion stations are in a rural area with unreliable or unavailable cellular and radio communication options.

Members reported the following specific transmission equipment:

1) Cellular: MACE FloSeries3 WebComm card, In-Situ VuLink, OnSet, and Wildeye

2) Radio: Schneider Electric SCADAPack 32

3) Satellite: Campbell Scientific TX325

6. Software Services

Environmental monitoring can produce large datasets with extensive metadata, making data management a critical component of project success.

6.1 Transmission Management

Transmitted data must be received by a configured data system. While more sophisticated users may transmit their data directly to an in-house system, many users pay a subscription fee to a provider and access their data through the provider's web portal. These software solutions allow quick access with limited editing functions. Typical functions include:

1) Automatic upload to a system with data back-up

2) Synthesized data from multiple monitoring sites in one interface

3) User-created alarms for parameters that exceed a threshold value

4) Diagnostic information for monitoring equipment

5) Calculation for derived parameters

6) Graphical and tabular display of monitoring data

7) File export of monitoring data

Several software solutions are available and offer similar services, including HydroVu, HydroMet Cloud, and Mace WebComm.

6.2 Data Management

Data management systems offer users more features, control, and automation for their data. Several software options are commercially available, including Aquarius from Aquatic Informatics and Hydstra and WISKI from KISTERS.

Aquarius offers data ingestion, analysis, and access using a centralized database and web-based user dashboard. The data system allows manual and automatic quality control of data including filters to remove erroneous values according to a user's defined criteria. The software can create and implement rating curves. Audit logs are automatically generated to track changes to data. Aquarius is used primarily for water resource management and is widely used by private and public agencies including the United States Geological Survey (USGS).

Hydstra is designed for time-series water data, while WISKI is designed for a wider variety of environmental data. Hydstra includes graphical tools to consolidate multiple monitoring sites, manage and validate monitoring data, integrate metadata (like rating curves), and manage instrument maintenance and usage. Analysis and plotting tools are built into the program. WISKI has an array of features, including graphical tools to review and apply quality control edits to data. WISKI stores data in a raw (original) table and a production table. Raw data cannot be edited; production data can be validated and updated. Both software tools support audit logs. KISTERS products are used in a wide variety of industries including agriculture and irrigation, flood forecasting, groundwater monitoring, surface water, wastewater treatment, and water quality.

6.3 Software Reported by Technical Group Members

Three Members reported transmission management software to receive and view data, namely HydroVu, MACE WebComm, and Wildeye. Two Members reported using data management software, namely Hydstra and WISKI. One of these Members also used a supervisory control and data acquisition (SCADA) system in parallel to control their incoming data and integrate it with their management actions. The remaining three Members received data via manual download and used customized excel spreadsheets or code to curate and manage their data.

7. Contracted Services

Organizations may hire consultants to perform some or all monitoring, data management, and reporting activities. This decision may be caused by 1) lack of technical expertise to conduct and report environmental monitoring, 2) lack of time and labor, or 3) avoiding potential liability from incorrect or missing data. Depending on the business need, one or more consultants may be used to select, procure, and install equipment; perform maintenance, repairs, and upgrades; receive and process transmitted data; or review and report data.

Of the eight Members, three are consultants. One is responsible for procurement, installation, and management of equipment; the second is responsible for data ingestion and curation; and the third performs both. One Member uses consultants only for equipment installation, preferring to procure and maintain equipment in-house. Another Member uses consultants to procure, install, and calibrate equipment. Both of these Members manage and report their own data. The remaining three Members are larger organizations and handle all equipment procurement, maintenance, installation, and data management in-house.

8. Costs

Whether performing work internally or contracting their work, Members reported that labor accounted for most of their project costs.

8.1 Monitoring Costs

8.1.1 Initial Costs

Initial costs of equipment procurement and installation varied among Members (Table 4) depending on their monitoring site, equipment choices, choice to use telemetry, and previous infrastructure or equipment. Notably, some Members reported only materials cost while others reported a combined materials and labor, adding to the variability.

Table 4. Initial costs reported by Technical Group Members, including site preparation and equipment procurement and installation.

Member	Initial Cost (U.S. Dollars)	Interview Notes
2, 3, and 4	1,000 - 4,000	
7	4,000 – 8,000	Installation is site-specific and prices vary by equipment type.
5	8,000 – 12,000	Includes cabinets, pressure transducers, conduit, data loggers, solar power, batteries, and labor.
1 and 8	8,000 – 20,000	Installation is site-specific and prices vary by equipment type.

Member	Initial Cost (U.S. Dollars)	Interview Notes
6	>20,000	Includes new SCADA systems, technical designs, procurement, design engineering, and labor costs.

For comparison, the California Stream Gaging Prioritization Plan 2022 (Gaging Plan) assessed the cost of procuring and installing a streamflow monitoring system that used modern data collection platforms, power supply, and telemetry and reported real-time stage, flow, and water temperature. That report estimated a cost of $28,000-$43,000 per new site, including materials and labor. The Gaging Plan and Member feedback suggest that cost varies greatly depending on site location, existing infrastructure, selected equipment, and overhead costs.

8.1.2 Maintenance and Repair Costs

Members reported lower maintenance and repair costs compared to initial costs (Table 5). Member #6 reported that they budget 10% of initial costs towards annual operation and maintenance (O&M). Initial equipment choice can affect ongoing O&M costs. Member #8 reported that they preferred to purchase Seametrics flow meters because, while the equipment had higher initial costs, the Member reported the equipment required less maintenance and calibration. The Gaging Plan estimated annual O&M costs of $30,000 (including labor costs) for a telemetered station that records stage, streamflow, and water temperature. This number is similar to the report's initial costs and substantially higher than the costs reported by Members, perhaps due to the Gaging Plan including rating curve development in its initial and O&M estimates. Rating curves are essential for instream flow monitoring but irrelevant to some types of diversion, storage, and groundwater monitoring.

Table 5. Annual maintenance and repair costs reported by Technical Group Members.

Member	Annual Maintenance & Repair Cost Range (U.S. Dollars)
2, 3, 5, and 7	100 - 500
1	500 - 1,000
8	500 - 5,000
4 and 6	>5,000

Members reported regular maintenance such as cleaning solar panels to improve efficiency and cleaning submerged sensors due to biofouling. Heavy storms can require site visits to restore equipment and cables dislodged by wind, high water, and debris flow. Most Members reported occurrences of vandalism, with one Member building protective enclosures around equipment. Vandalism was less common for Members with remote sites or where the equipment was inside a secure structure.

8.1.3 Primary Cost Categories

8.1.3.1 Travel and Labor

Whether performing work internally or contracting their work, Members reported that labor accounted for most of their initial and ongoing project costs. The contrast in labor costs becomes evident when comparing Members from large organizations, which use in-house staff and couldn't easily describe their labor costs, with Members from consultants and smaller organizations who act as contractors or hire contractors and know their contracted labor rate. One Member reported that they budgeted approximately $1,000 per worker per day.

Maintenance can incur high labor costs simply due to travel time, with sites that are rural or far from staff workplaces particularly expensive. Member #3 shared that a regularly occurring maintenance task required 2 hours, but travel added 4 hours. They were able to reduce their maintenance costs by partnering with the Shasta Valley Watermaster, who had an office close to their monitoring site and performed the maintenance for them. Collaboration among organizations can be a potential cost-saving mechanism by reducing staff travel and may enable a qualified person to respond more quickly to damaged equipment.

Data review can be a large labor cost. Many software programs support user-defined automated quality validation that can reduce staff workload. Several Members did not use software to automate reviewing and validating data but expressed interest. They also expressed doubt that the data quality would be as high as manually reviewed data. Two Members currently used automated software tools and were content with the quality of the automatic review for all but final approval.

8.1.3.2 Parts

Costs of procuring and replacing parts for monitoring, transmission, and power equipment are included in the initial costs and O&M costs discussed above. Replacement sensors can be the greatest single part cost, with sensors costing $500 to $1,000 and requiring replacement sometimes as frequently as every 6 months (both factors depending on the sensor parameter and sensor type). Members reported reviewing their data to determine if the sensor needed replacement.

Repairs and replacement of other monitoring equipment also contribute to O&M. Member #3 reported spending $500 to $1,000 annually on parts for their monitoring equipment, which include a pressure sensor, temperature sensor, and data logger; cellular transmitter; and cables to solar panel and battery. The Member reported spending $300 on battery replacement at one point. At another time, animals chewed through cables requiring $250 per cable to replace.

8.1.4 Other Costs

Accurate water monitoring data may require other initial or ongoing tasks that vary according to the equipment, legal obligations, required accuracy and completeness for the data, and monitoring goals.

8.1.4.1 Calibration

Calibration may be needed to generate or support valid data. Members reported their calibration costs (if any) as part of their maintenance costs, while the Gaging Plan included calibration costs in the Installation and O&M estimates (Section 8.2.2). Members #2 and #3 reported some equipment can only be calibrated and certified by the manufacturer. This increases O&M costs as hardware must be uninstalled and shipped back for service, which can lead to data gaps.

8.1.4.2 Supporting Data

Other data sources may be needed to support or interpret monitoring data, such as bathymetric surveys or rating curves to quantify water volumes. For programs with data quality goals for completeness, users may run a second monitoring set-up for confirmation or back-up. Generally, Members did not include the costs of supporting data when they reported their initial or O&M costs. Initial and O&M estimates in the Gaging Plan do include development of rating curves since that document focuses on gaging stream flows.

8.2 Transmission Costs

Transmission costs vary by transmission type. Transmitting data via cellular, Iridium, or Starlink requires a data plan, whose cost typically varies according to the amount of data being transmitted and can range from $30-$120 per month for either cellular or commercial satellite. Similarly priced plans typically offer larger data allowances with cellular, but cellular coverage is more limited (Section 5). Transmission by GOES satellites is free to use by authorized users but GOES transmission is limited in both data amount and timing. Radio and LoRaWAN transmissions can be free, but if another transmission type is used to deliver data from a repeater station or central node to a cloud, that transmission will incur charges based on its type.

8.3 Software Costs

Software costs are difficult to generalize. Quotes are provided by the provider based on the complexity of the monitoring data, such as number of stations and parameters, frequency of transmission, and software features like automatic quality assurance or metadata integration. Members did not report any information on software costs. These costs will vary substantially based on the monitoring scope and specific software that a user selects.

9. Data

Monitoring data submitted for SB88 reporting and provided by Members rarely adhered to a commonly accepted data standard such as WaterML or NWIS. Data varied widely in parameter names, unit names, and organization and elements of metadata were often missing. Most data sets were not compliant with essential elements of FAIR Principles (Findability, Accessibility, Interoperability, and Reuse of digital assets) (Section 9.3). The Board should consider adopting a data standard for all internally-generated monitoring data and data reported to the Board.

9.1 Data Submitted for SB 88

TRU staff reviewed files of water diversion and storage data submitted by reporters for compliance withSB88. Staff characterized the variety of data content and format of submitted files and the potential for the files to be automatically summarized for more timely and targeted resource management.

9.1.1 Small Watershed

TRU staff reviewed SB88 files in the Clear Lake watershed (HUC 1802011603). The full assessment is in the report, "Evaluation of Water Measurement Files for Clear Lake Watershed".

Between 2018 and 2022, reporters in the Clear Lake watershed submitted 23 data files, which represented reporting compliance of less than 23%. The Division's evaluation of these files found that reporters submitted different types of water data, namely volume, level, flow rate, and evaporation, using a variety of data formats.

While all the files were in tabular, digital form, these variations in data types and format limit data usability, as the data requires considerable manual staff processing before any automated analysis. These barriers limit the Division's ability to accurately assess water availability in a timely manner. A major finding was that data format sometimes changed even when the device didn't change, highlighting that devices can produce a wide range of data formats and the Water Board may need to establish a reporting format in order to receive standardized data. Additionally, low reporting compliance provides an incomplete picture of water use, further hindering effective water management.

9.1.2 Large Diverter

TRU staff reviewed SB88 files submitted by a large diverter. The full assessment is in the report, "Large Diverter Measurement Files Evaluation (2018-2022)".

Between 2018 and 2022, the large diverter submitted a total of 523 files for 86 different water rights across 12 different watershed basins in California. The Division's evaluation of these files found that the large diverter submitted different types of water data using three unique parameters (flow, storage, and an unspecified parameter called "mean") and two unique units (cubic-feet per second and acre-feet). Parameter names and unit names were mostly consistent across files. However, 13% of files were missing a parameter name or unit name and 2% were missing both.

Although all data were collected and submitted by a single entity, there was considerable variation among the monitoring equipment. Equipment from 18 different manufacturers was reported, with some watersheds containing equipment from several different manufacturers. Some water rights reported the same measurement device from year to year but also reported different details about the device each year, suggesting reporter confusion or error.

While all the files were in tabular, digital form, variations in data content and format limit data usability, as the data require manual staff processing before any automated analysis. These barriers limit the Division's ability to accurately assess water availability in a timely manner, highlighting that the Water Board may need to establish a standard reporting format and improve the water rights reporting system necessary to enhance data quality and improve the reporting experience.

9.1.3 All 2021 Submissions

TRU staff reviewed all SB88 files submitted for the year 2021. The full assessment is in the report, "Reporting Year 2021 Water Measurement Files Evaluation".

In 2021, 5,426 files representing 2,688 individual water rights were submitted to Water Board for compliance with SB88. This total included updated files for the same monitoring dates and files for part of the year (e.g., due to changing measuring devices).

The files came from water rights in 57 of California's 58 counties and from 102 out of 140 Hydrologic Unit Code 8 watersheds. A majority of the files, about 29%, came from just three counties: Sonoma, Napa, and Mendocino. These counties remained the highest reporting, even when corrected for the number of water rights in each county. On the other hand, the fewest files were received from San Francisco, Del Norte, and Imperial counties, making up just 0.1% of submissions. The three watersheds with the most reports were the Russian River, San Pablo Bay, and Sacramento-Stone Corral, all in Northern California. Together, they made up another 29% of all reports. At the same time, 32 watersheds with water rights subject to SB88 did not have any submissions.

Across the state, only 23 percent of water rights holders submitted reports. Water rights with larger approved diversion amounts generally submitted their reports more often than the state average. For example, water rights with >10,000 acre-feet diversions and >1,000 acre-feet reported at 31 percent and 27 percent, respectively. In contrast, reporters with smaller diversion submitted files less often. There are two potential reasons for this disparity. First, large water rights are usually held by large organizations with more staff, technical skills, and funding to measure and monitor their water diversions. Second, these large organizations may be more concerned about being audited for reporting compliance and therefore put more resources into reporting.

Although all files were submitted in digital form, inconsistencies in content and formatting reduce their usefulness. The data often required manual processing by staff before any automated analysis can be accomplished. These challenges make it difficult to make the most accurate and timely decisions. This shows the need for the Water Boards to establish a standardized reporting system.

9.2 Data from Technical Group Members

9.2.1 Access

Six Members reported web-based dashboards (e.g., Wildeye, HydroVu, Hydstra), application-based dashboards (e.g., FloCom+), or government-supported platforms (e.g., HADS) to access data. The remaining Members store data internally, either within networked hard drives or within a secure system (e.g., SCADA). Member #2 reported they manually download data from field equipment and upload and edit on local machines. Member #4 reported extracting data from various field devices using PicoVale, HydroVu, and OnSet software and then uploading the data to WISKI. In WISKI, they validate and update data and then export it as comma-separated values (csv) or Microsoft Excel files.

All Members reported they could download data as csv or txt file formats. Member #4 also reported xls and xlsx file format. Member #6 reported that files were saved in their system as dat, ini, and txt file formats. Member #3's files contained an htm file that linked to requested data on the web dashboard in a table format that could be downloaded.

Many Members indicated a willingness to allow Board access to their data sources. Member #6 reported that their data has high business sensitivity, and they tightly control access to protect their operations and business advantage. Any future regulations around requiring reporters to share real-time data (either in reporters' data systems or pushed to Board data systems) should consider reasonable safeguards to protect reporters' business operations while ensuring that data is available to steward public water resources.

9.2.2 Versions

All Members reported backing up their raw data and editing a secondary dataset. For example, Member #2 reported that their workflow included: 1) making a manual copy of raw measurement data, 2) manually validating and visualizing the secondary dataset, and 3) approving the validated dataset, leading to two versions of the data. For Members using Wildeye and HydroVu, those systems can perform some automatic data validation that generates a secondary dataset. All Members reported manually reviewing auto-curated data, with some editing the secondary dataset and others creating a tertiary dataset. Other subsequent datasets may be generated as artifacts of re-formatting the data for client reports or online publication. For example, Member #7 removes non-essential data and restructures data to submit it to the Board.

9.2.3 Content and Format

Members were asked to provide examples of their monitoring data. Five Members submitted 21 examples representing various monitoring sites and stages of data review. Data files often included 1) date and time, 2) water flow rates, 3) water quantities, and 4) various water quality indicators such as total suspended matter or conductivity.

Additionally, files often contained metadata, such as equipment model/serial numbers, locations, and battery statistics, in the file with the monitoring data.

Some Member data files were initial monitoring data, with only measured parameters. Other files had manual additions of calculated parameters as additional columns in the data. It can be impossible to determine which data is measured and which is calculated from simply reviewing files. Reporters would need to supply this information in the metadata.

Data files from Members exhibited various formats. Some interesting features are listed below:

1) Four Members's files listed date and time in one column, while one Members' files omitted time but split month and year into separate columns.

2) One Member's files omitted units.

3) Three Members listed metadata (site, equipment, and parameter information) at the top of the spreadsheet, above columnar monitoring data. One Members' files listed metadata as a tab in a spreadsheet workbook, with monitoring data on a second tab

4) Parameters and units, when present, were named in various ways (e.g., Acre-Feet, af, acft).

Three Members reported standardized formats. Members #4 and #6 reported their data adheres to the United States Geological Survey (USGS) standards, but could not clarify if they meant NWIS or another USGS standard. Member #4 reported they follow an "EPA protocol" for temperature data but could not name the format. Only one Member could name a specific data standard for their data; Member #5 reported the standard hydrometeorological exchange format (SHEF) for their data. Overall Members displayed limited knowledge or interest in established data standards and mostly did not employ them in their data governance.

9.2.4 Quality Assurance Processing and Clean-Up

All Members asserted that manual review using professional judgement and institutional knowledge was a core component of their QA/QC review for monitoring data, including visualization in graphs. Reviewers visually identified outliers, such as spikes in usage or data gaps, and flagged and/or adjusted the values using historical data, operational records, or professional judgement. Most members reported multiple tiers of data review, where one staff member reviewed and cleaned data before a supervisor or client also reviewed.

In cases where Members use dashboards or online services (e.g., HydroVu, WISKI, OnSet, Hydstra, Wildeye, HADS), automated QA/QC of data is followed by final staff review and approval. For example, Member #7 reported that their equipment automatically flags data gaps and includes a message with a suspected cause. Then their staff review the flag and message before approving the dataset.

Frequency of data review depended on organization size, budget, and staffing. Small organizations and organizations with un-telemetered data reported infrequent review, often only annually before reporting data or as needed due to O&M. Larger organizations reported some amount of weekly review but often postponed thorough QA/QC until reporting windows (e.g., monthly, quarterly, or annually).

9.3 Data Standard and Data Submission at the Water Board

The Board should consider adopting a data standard for all monitoring data and metadata that applies to both internally-generated monitoring data and data reported to the Board. This data standard would need to include essential data and metadata elements to support staff operations and decision-making and to support reporting elements required by regulations. The data standard should also be compatible with other widely-used data standards such as WaterML and NWIS and incorporate FAIR Principles (Findability, Accessibility, Interoperability, and Reuse of digital assets). Consolidating data to a single standard in the future will greatly improve data usability, simplify reporter compliance and reduce reporter confusion, and reduce staff time for synthesizing data sets.

In addition to their standard-compliant monitoring data, reporters should submit “raw” data files representing their real monitoring data and “supporting” files that document their QA processes and calculation methods. The Board should evaluate whether implementing a data standard is reasonable for these raw and supporting files. One Member also reported an interest in a Water Board standard for how to report data when no water was diverted in a reporting period.

With the public launch of the Division of Water Rights’ new data system, CalWATRS, in 2025, users will be able to submit monitoring data to the Board as files and also as automatic transfers through application program interfaces (APIs). Both of these submission processes require data that conforms to a known data standard in order to properly ingest, manage, and govern the data.

Adopting a Board data standard will introduce a new burden on staff who monitor and water right holders who report data to the Board. The Board will want to consider supporting this new requirement with outreach and engagement to reporters, but also by coordination with equipment manufacturers to develop equipment configurations that automatically generate data in the Board data standard.

10. Implications for Water Boards Operations

10.1 UPWARD

In July 2021, the Water Board received funding to modernize the data systems in the Division of Water Rights. The funding established the Updating Water Rights Data

(UPWARD) Project. UPWARD will develop a modern geospatial data management system (CalWATRS) to replace older reporting systems. Members provided valuable feedback on their instrument devices, transmission types, and data processes. As discussed in Sections 4, 5, and 9, a variety of manufacturers, transmission methods, and data processes are used. Information in this report should inform UPWARD staff as the project builds and updates CalWATRS to ingest data from diverse equipment and equipment currently used by reporters.

UPWARD staff should evaluate the information in this report and companion reports to inform CalWATRS development. About half the Members download data manually from their measuring device, while the remaining Members transmit their data to management system. Anecdotal evidence suggests a large proportion of water rights reporters manually collect their data. CalWATRS will need to support both batch file uploads of manual data and automated (e.g., API) connections to telemetered data. To simplify the reporting experience, UPWARD staff should consider building automated connections to equipment from common manufacturers.

CalWATRS should also make better use of existing data sources such as the California Data Exchange Center (CDEC), National Oceanic and Atmospheric Administration (NOAA), United States Geological Survey (USGS), and others. Using these reliable sources of data will assist the Board in making the best-informed management decisions. By providing simpler and quicker access to these data through CalWATRS, it will also reduce overhead costs and staff time to synthesize these data with reported data, leading to more timely decision-making in response to current conditions or pressing issues.

UPWARD staff will need to develop data governance procedures for telemetered data. As discussed in Section 9, the Board should adopt or develop a data standard for all water monitoring data to enhance data quality and usability and enable CalWATRS development. Data governance will need to also consider system checks for ingested data. Telemetered data has QA/QC topics that are typical for monitoring data, and additional concerns about contextualizing and flagging real-time data that has not been reviewed by the collecting organization. Members overwhelmingly expressed a need for manual review and approval of data before publication as “final data”. As CalWATRS is developed, un-reviewed data should be flagged as “provisional” until approved or validated. CalWATRS will need to support both un-reviewed data for quick management response and reviewed data for modeling and wider program action.

Some Members reported updating rating curves and retroactively correcting monitoring data; others reported applying a retroactive calibration correction. CalWATRS should record these metadata and provide them with the monitoring data. Provisional data may need to reflect when metadata was last updated.

10.2 Internal Water Monitoring

Staff at the Board currently conduct water monitoring to support program goals such as instream flow requirements when monitoring data from other sources do not meet data needs. Expansion of telemetered water monitoring in-house provides several advantages since it provides control over monitoring site locations, measured parameters, measurement frequency, and timely data availability. These targeted data streams enhance the Boards' ability to fulfill its mandated tasks, such as:

1) Make timely and informed management actions, such as curtailments.

2) Evaluate effectiveness of management actions.

3) Support fiduciary diligence, by allowing oversight when the Board has agreements reporters who commit to reduced water consumption.

4) Protect water rights by identifying illegal diversions.

10.3 External Water Monitoring

Members expressed a need for increased Board engagement to improve SB88 compliance. They pointed out that one possible reason for low compliance is ineffective outreach efforts in disseminating essential information to the right individuals. Members also highlighted the challenges of navigating and using the current reporting systems (e.g., eWRIMS, Survey Portal). Implementation of SB88 has increased the reporting burden on water right holders and the legacy reporting systems are a barrier to data reporting. CalWATRS should be designed to provide clarity and simplified processes for water reporters.

The creation of CalWATRS has vast potential to simplify water reporting for the public through a user-friendly interface for file uploads and telemetered data connections. However, this change will initially place a new burden on reporters to understand and comply with the new regulations and reporting structure. Board staff must carefully manage this organization change to support public adoption (Section 10.1).

Appendices

Appendix A. Technical Group Process

A.1 Formation

In April 2023, the California State Water Resources Control Board (Board) convened a small, diverse Telemetry Technical Group (Technical Group) of interested parties who conduct telemetered water monitoring or use telemetered data. The Technical Group was formed to help the Board (1) better understand current data standards and data transfer processes; (2) explore best practices that can streamline and enhance telemetered reporting; and (3) develop relationships with interested parties. Participation in the group provides a unique opportunity for interested parties to directly communicate with Board staff on water telemetry issues and provide feedback to support and enhance the Board’s future reporting processes.

Community members who conduct water telemetry or use telemetry data were screened for invitation by evaluating SB88 reporters (i.e., Water Code 23:931-938), Delta Measurement Experimentation Consortium members, California Water Data Consortium participants, and Water Boards staff. Twenty-one individuals were invited to join the Technical Group based on business sector diversity, watershed diversity, water diversion volume, and data goals. Invitees included organizations from the private sector, Native American tribes, water irrigation districts, and local and state government. Invitees were affiliated with a variety of watersheds including the Delta, Kings River, Russian River, Sacramento, San Juan, Santa Ana River, Truckee River, Upper Calaveras, and Yuba River.

A.2 Events

The Technical Group was a voluntary, limited-term activity in 2023-2024. Members attended three meetings and supplied telemetry knowledge through a questionnaire. In this report, Technical Group Members are referenced as Member #1, 2, 3, etc., which does not represent the order listed in Table A.1.

A.2.1 Launch Meeting

The launch meeting for the Technical Group was held virtually via Zoom on April 19, 2023. Of the 21 invited individuals, 17 participated in the meeting (Table A.1). During this meeting, TRU staff members introduced themselves, explained project objectives, discussed the timeline and goals for the Technical Group, discussed the questionnaire to be completed by Members, and defined the roles and responsibilities of Members. The meeting concluded with a session for invitees to provide feedback, comments, and questions.

A.2.2 Questionnaire

A questionnaire was developed by TRU staff for the Technical Group, and covered a wide variety of telemetry topics, including technical and logistical practices for conducting water telemetry; costs, maintenance, and calibration of equipment; and data transmission, formatting, processing, and reporting. Staff provided notice at the launch meeting that the questionnaire would take around 1 hour to complete depending on the complexity of the monitoring station being described, the details provided, and knowledge of the person filling out the form. The questionnaire was emailed to Members as a Google Form with an email attachment of a questionnaire preview. Of the 17 people that participated in the launch meeting, TRU received 11 questionnaire responses from 8 Members (Table A.1).

A.2.3 Follow-Up Meetings

Upon receiving completed questionnaires, TRU staff reviewed the answers provided by Members and identified areas that required additional clarification. From June through July 2023, TRU staff scheduled virtual meetings via Microsoft Teams with each Member that submitted a questionnaire response. During the meetings, staff asked follow-up questions and participants discussed lessons learned, best practices, and challenges of telemetry.

At these meetings, staff requested Members provide at least one data set of their real-world water telemetry data. The files were assessed for automatic upload to a data system that supports graphical display of data. This assessment informed development of data pipelines to receive and ingest water telemetry data, improve water rights reporting, and aid design of watershed-scale research project(s).

A.2.4 Close-Out Meeting

At the Close-Out Meeting in May 2024, the major findings of this report, including information from Members' questionnaire answers and follow-up meetings, was shared with participants. This report was also shared, and participants were given a one-month comment period.

Table A.1. Table of Technical Group participants. Column one shows organization affiliation, column two shows attendance at the Launch Meeting, column three shows submission of a Questionnaire response, and column four shows participation in a Follow-Up meeting. Order in Table A.1 does not reflect numbering in Table B.1.

Organization Name	Attended Launch Meeting	Submitted Questionnaire Response	Attended Follow-Up Meeting
Banta Carbona Irrigation District	Yes	No	No
Bureau of Reclamation	Yes	Yes	Yes
California Nevada River Forecast Center	Yes	Yes	Yes
Department of Water Resources	Yes	No	No
Division of Water Rights	Yes	Yes	Yes
Irvine Ranch Water District	Yes	No	No
MBK Engineering	Yes	Yes	Yes
McBain Associates (contractor for Hoopa Tribe)	Yes	Yes	Yes
Mendocino County Russian River Flood Control & Water Conservation Improvement District	Yes	Yes	Yes
Pacific Gas and Electric Company	Yes	Yes	Yes
The Nature Conservancy	Yes	No	No
Wagner & Bonsignore Consulting Civil Engineers	Yes	Yes	Yes
Wildeye	Yes	No	No
Yuba Water Agency	Yes	No	No

Appendix B. Technical Group Member Profiles, Monitoring Scenarios, and Reporting Processes

Table B.1. Table of Technical Group Members' profiles.

	Interviewee profile	Procurement and installation	Monitoring and calibration	Data management	Reporting	Challenges that Water Rights Holder Uses Contractor For
Member #1	The interviewee is a consultant for a business. The work involves monitoring diversions to off-stream storage, reservoir surface elevation, and withdrawal for beneficial use as required by the water permit.	The contractor is responsible for procuring and installing the monitoring equipment.	Consultant conducts monitoring and calibration. Regular calibration for stage height is not performed; it's done as needed by comparing sensor readings with direct measurements of reservoir level relative to a benchmark. The velocity meter is calibrated annually, using a portable meter for side-by-side comparison.	Stage height data is automatically recorded at intervals of 10-30 minutes, and volume is calculated using stage data referenced to an elevation-capacity curve for the reservoir. No data processing or cleanup affects the original data. For the velocity meter, consultant manually check data and may delete or overwrite it if necessary.	Reservoir level data is plotted on a hydrograph to visually check for obvious data errors. Consultant checks flow meter data with operational records to confirm when the meter should and should not have recorded flow. Consultant prepares a report for the Division of Water Rights for annual reporting purposes.	The consultant's role involves overseeing the monitoring of water rights in the winery project. The contractor handles procurement and installation, calibration is conducted as needed, data management includes automatic recording, and reporting involves visual checks and comparisons with operational records for accuracy.
Member #2	The interviewee is a manager at a water supplier organization. The organization oversees monitoring stations and manages the water diversion operations for contract delivery.	The organization procures the equipment, but contractors install and maintain equipment.	The organization initially calibrated its equipment upon purchase but lacks a comprehensive calibration plan. There is uncertainty about the need for periodic re-calibration, and the logistics of this process may involve uninstalling meters. The practicality and necessity of such calibration efforts are questioned due to the margin of error and the cost-benefit analysis.	Data related to water diversion is collected and managed by contractees. They use water use worksheets and additional meters to attribute monthly quantities to the appropriate user/water right. Data is downloaded from devices to a laptop using a program provided by McCrometer and is converted into Excel format. Limited control over data format is mentioned, and data undergoes a quality control check in Excel. Flags or additional content may be added during processing.	The organization reviews and reports the data. Staff reformat data in Excel, perform quality control checks to identify outliers, and issue water use reporting worksheets to each District customer. These worksheets capture values of water diverted under the district's water rights license for compilation into an annual report.	The organization faces challenges related to data management, calibration practices, and the practicality of improving monitoring accuracy.

	Interviewee profile	Procurement and installation	Monitoring and calibration	Data management	Reporting	Challenges that Water Rights Holder Uses Contractor For
Member #3	The interviewee is a state government employee and conducts monitoring in one northern county.	The organization is responsible for procuring and installing equipment.	There has been one equipment replacement in the past 15 months, and it was sent to the manufacturer for repair. Staff can perform calibration and maintenance tasks.Calibration involves installing an onsite staff gage at the monitoring station and adjusting the sensor to match the water level observed on the staff gage.	Staff conduct all the data management activities including: Data on total pressure and water temperature is recorded every 15 minutes and stored in a datalogger to calculate water depth. Manual post-processing of data is done to correct anomalies. Anomalies are identified, and correction factors are applied to problematic data. Data is imported into Excel for this purpose.	Staff conduct all the reporting activities including: Data from the primary station equipment is automatically transmitted to a website for staff to view. Periodic post-processing may be required, but no data processing occurs before posting on the website.	In summary, the interviewee's role involves monitoring equipment procurement, installation, and maintenance, data collection and correction, and the reporting of data to the Hydrovu website. The station primarily collects stage/water level data. It seems contractors do not play a role for this organization
Member #4	The interviewee is a consultant for one local agency and one federal agency.	Both agencies own the equipment. The contractor installs the equipment.	Consultant is responsible for monitoring and calibration of the equipment. Annual calibration includes cleaning sensors and performing diagnosis.	Consultant is responsible for transmitting data, collecting data and storing in an appropriate format.	The consultant reviews the data and prepares reports for their client.	Most of the tasks are completed by contractors.
Member #5	The interviewee is a federal government employee and uses telemetered data for analysis.	The organization is responsible for procuring and installing the monitoring equipment.	The organization conducts maintenance tasks, typically 1 to 2 times per year, to ensure the proper functioning of equipment and systems.	The organization is responsible for all aspects of data management, including receiving, processing, and storing meteorological data.	The organization is also responsible for reporting activities, which involve reviewing and reporting on the analyzed meteorological data.	The interviewee's role primarily involves analyzing meteorological data, while the organization takes care of procurement, installation, maintenance, data management, and reporting related to the meteorological data. It seems contractors do not play a role for this organization.
Member #6	The interviewees are consultants. They are responsible for monitoring monthly diversions to storage for water right reporting.	The organization is responsible for procuring and installing the monitoring equipment.	All maintenance activities, including inspection, system purge, and calibration, are conducted monthly by staff.	Staff calculate the volume of water diverted using surface elevation data and its relationship with the surface area of the storage.	All data review tasks, such as deleting, overwriting, and flagging data, are conducted by staff.	The engineers from the company oversee the monitoring of monthly diversions for water right reporting in the Shasta watershed. The organization handles procurement and installation, while staff is responsible for monthly maintenance and data review. It seems contractors do not play a role for this organization.

	Interviewee profile	Procurement and installation	Monitoring and calibration	Data management	Reporting	Challenges that Water Rights Holder Uses Contractor For
Member #7	The interviewee is a federal government employee. They monitor water diversions for contractees.	The organization is responsible for procuring and installing the monitoring equipment.	Monthly maintenance tasks, including inspection, system purging, and calibration, are carried out by organization staff.	Data collection includes water flow and other quality parameters, and staff are responsible for receiving and processing the collected data.	Staff oversee all data review activities, which encompass deleting, overwriting, and flagging data as needed.	The interviewee's role primarily involves data collection and monitoring activities, while maintenance, data management, and data review are handled by staff. It seems contractors do not play a role for this organization
Member #8	The interviewees are consultants for various California projects.	The contractor is responsible for procuring and installing the monitoring equipment.	Maintenance involves measuring pressure transducers and temperature sensors. Some maintenance tasks are carried out by contractors. The consultant goes out monthly to redo rating curves.	Consultant does the following items: Data is transmitted to the internet. Data is downloaded and configured, with supplemental data from backup sensors if needed (e.g., due to beaver dams affecting rating curves). To get data into WISKI, a CSV file matching their upload format is created. Raw stage data is uploaded to WISKI every few months, with data analysis and corrections done at the end of the water year.	The consultant reviews the data and prepares reports for their client.	Most of the tasks are completed by contractors.

Appendix C. SB88 File Review

The Division of Water Rights receives approximately 5,000 files each year of water monitoring data from reporters to comply with their SB88 reporting requirements. Since SB88 regulations currently do not specify a data standard for these files, files contain a wide variety of structured, unstructured, tabular, and image data with variable content and formats. These files require considerable staff time to clean and organize before they are useful for modeling, accounting, or decision making.

TRU staff reviewed three subsets of SB88 files to understand the data standards currently in use by reporters. Files from a small watershed, a large diverter, and a monitoring year (i.e., 2021) were selected to represent the diversity of files and assess any common elements consistent to a reporter group. This information is valuable to inform the UPWARD project and future SB88 regulation updates.

TRU staff followed a standardized process for each data set to manually assess each file and log required information in a summary file. Data files were analyzed for file extension type, header (i.e., column) labels, parameter names, unit names, and commonalities between files. A copy of each file was amended to delete whitespace and metadata and bring the data headers into the first row of the file. The summary files and amended copies were analyzed to generate statistical information and visualizations using Excel, Python, R, and PowerBI. This work was reported in “Clear Lake Watershed Measurement Files Evaluation (2018-2022)”, “Large Diverter Measurement Files Evaluation (2018-2022)”, and “Water Year 2021 Water Measurement Files Evaluation”. The results are summarized in Section 9 of this report.