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Information Needs for Water Markets: Fair and Effective Water Markets Require Adequate Measurement and Reporting of Diversion and Use

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INFORMATION NEEDS *for Water Markets*

Fair and Effective Water Markets Require Adequate Measurement and Reporting of Diversion and Use

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ABOUT THIS REPORT

This report is part of a larger project to better understand how institutional context affects the potential for water markets to enhance climate resilience for agriculture and ecosystems, what legal and organizational features are likely to facilitate fair and effective water markets in the U.S. Southwest, and where opportunities exist to adapt existing institutions to support more sustainable water management. The report focuses on one legal and organizational feature that is a necessary precursor to fair and effective water markets: the collection and sharing of adequate information about water diversion and use. It synthesizes the discussions and notes from a convening of water experts with additional research and analysis.

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Andrew Erdman, NEW MEXICO INTERSTATE STREAM COMMISSION
Blane Sanchez, ADVOCATE FOR PUEBLO WATER AND NATURAL RESOURCES ASSETS
Brent Vanderburgh, CALIFORNIA STATE WATER RESOURCES CONTROL BOARD
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Molly Bruce, Nell Green Nylen, and Michael Kiparsky organized and facilitated the convening with the help of the following SWF collaborators: Ellen Bruno, Helen Dahlke, Joshua Viers, Larry Forero, Maia Baltzley, Mike Myatt, Nick Santos, Robyn Grimm, Safeeq Khan, Sarah Naumes, and Sarah Null. All convening participants were offered the opportunity to review a draft of this document. We thank Emily Lewis, Ruth Dahlquist-Willard, Ryan Serrano, Tara Moran, and Trevor Nielson for their helpful feedback.

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CONTENTS

1. INTRODUCTION

When appropriately designed and implemented, water markets can enhance climate resilience for people and ecosystems in water-scarce regions. However, adequate information about water diversion and use is a necessary precursor. Based on expert discussions and additional research, this report explores what information on surface water and groundwater diversion and use is currently available in the U.S. Southwest, what diversion and use information is needed to support fair and effective water markets, and how existing information gaps can be addressed.

1.1. BACKGROUND & NEED

Water scarcity is a growing problem for agriculture and ecosystems in the U.S. Southwest, where water supplies are overstretched and increasingly variable.[1] Due to the scale and nature of the challenge, addressing water scarcity requires more than supply-side solutions (such as importing new water supplies and augmenting groundwater recharge). It also requires reducing overall water consumption.[2]

Water markets have the potential to enhance climate resilience for agriculture and ecosystems. As Box 1 explains, water markets encompass the activities and institutions involved in water trading. Because they enable voluntary redistribution of limited water supplies among water users and uses, water markets may help water users cope with abrupt changes in water supply.[3] When appropriately designed and implemented,[4] they can also help water users adapt to long-term restrictions on water diversion and use needed to enable regional transitions to more sustainable water use.[5] Box 1 describes water markets in more detail.

However, water markets are not always viable or appropriate. Successful market implementation depends on area-specific institutional factors, including how applicable laws and governance structures interact with the physical, social, and ecological conditions in the regions affected by trading. Trading changes where, when, and how water is diverted and used, which alters the impacts of withdrawing and using water. If markets are not carefully designed and implemented to ensure they are fair and effective, transactions that benefit market participants can generate unintended and potentially harmful consequences, injuring third parties and impeding broader sustainability goals.[6]

This work is part of a larger project to better understand the potential for and barriers to new or expanded water markets in the Southwest by examining how the institutional contexts in three study areas affect the potential for water markets to enhance climate resilience for agriculture and ecosystems. The study areas, shown in Figure 1 are the San Joaquin Valley in California, Mesilla Valley in New Mexico, and Cache Valley in Utah. We selected these locations based on similarities in agricultural production, groundwater and snowpack dependence, and the importance of sustained water for ecosystems.[7] From this research, we aim to identify broader lessons about what legal and organizational features are likely to facilitate fair and effective water markets across the Southwest and where there might be opportunities to adapt existing institutions to more effectively support such markets.

We focus here on one such feature: adequate measurement and reporting of water diversion and use. In this document, "diversion" refers to any withdrawal of water from a natural water source, whether that source is considered surface water or groundwater (see Box 2). Adequate information about water diversion and use is a necessary precursor for fair and effective water markets because it defines what can be traded, enables tracking of trading transactions and changes in water supply and legal availability, and facilitates assessment of the impacts of trading on others. However, we hypothesize that, in many areas across the Southwest, current water measurement and reporting may be inadequate to meet these basic information needs. Additionally, we hypothesize that there are many opportunities for Southwestern states to improve water measurement and reporting to help meet information needs for fair and effective water markets and meet other societal goals.

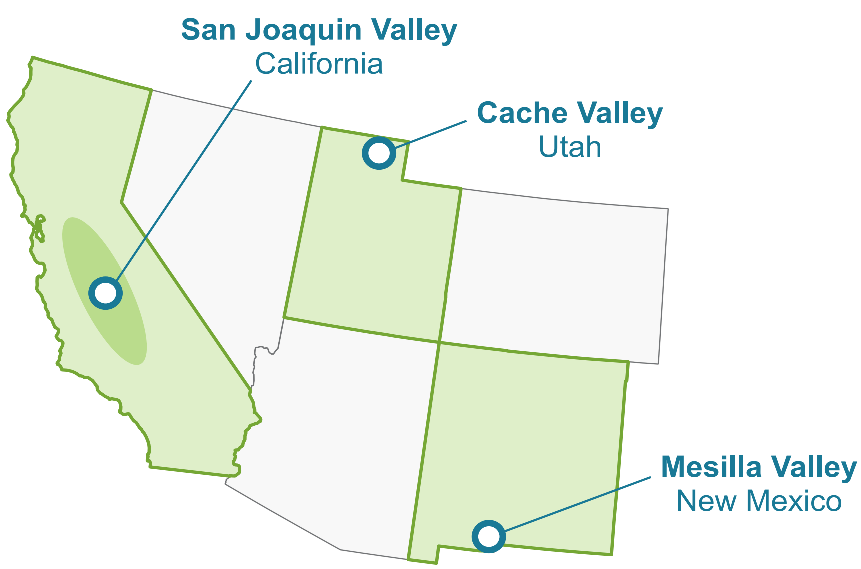

Figure 1. *Locations of the three study areas.*

BOX 1. BACKGROUND CONCEPTS

A ***water market*** broadly encompasses the various activities and institutions involved in ***water trading***, the voluntary transfer or exchange of water rights or other entitlements to use water.[8] Water markets can be informal or formal.[9] They may involve surface water, groundwater, or both.[10] In some cases, water is physically conveyed from the seller to the buyer, while in other cases, the parties transfer a water access entitlement (such as a groundwater extraction allocation) that is fulfilled in the buyer's location.[11]

We intentionally did not define "water market" during or prior to the convening. Instead, we assumed that participants' experiences and expert insights would reflect their unique understandings of what a "water market" can encompass.

Fair and effective markets achieve the goals they are intended to accomplish[12] without causing significant negative side effects (such as reducing surface water availability for those not participating in the market, causing shallow wells used by households and small farmers to go dry, dewatering wetlands and riparian areas, degrading water quality, or concentrating market power).[13] Ensuring that a market is fair and effective requires careful design and implementation to account for the larger social, institutional, and environmental context within which water trading takes place.

Important fairness and equity issues also arise when establishing initial allocations of water rights or other water use entitlements. That context is beyond the scope of this report.

Institutional context includes the rules, norms, and practices that affect decision-making.[14] An array of area-specific factors—such as applicable laws, regulations, and governance structures—interact with the physical, social, and ecological conditions in a region to influence the viability and outcomes of water management decisions and actions.[15]

Resilience is the capacity of social systems, economic systems, and ecosystems to cope with a hazardous event, trend, or disturbance by responding or reorganizing in ways that maintain those systems' essential functions, identity, and structure (including biodiversity, in the case of ecosystems) while also maintaining the capacity for adaptation, learning, and transformation.[16] Taking actions that reduce climate risks for agricultural systems and ecosystems—by reducing climate hazards or those systems' vulnerability and exposure to climate hazards—builds their resilience to future climate hazards and related uncertainty.

Sustainable water use describes patterns and means of water use that are consistent with maintaining a region's ability to meet critical social and ecological needs for water over time.[17] This concept is closely related to resilience.

BOX 2. DEFINING KEY TERMS

Diversion is the withdrawal of water from a natural surface water or groundwater source, such as a stream or aquifer. From the point of diversion,[18] water usually flows or is pumped[19] into a conduit—an ***open channel*** (e.g., a ditch or canal) or a ***closed conduit*** (e.g., a pipe)—that transports the water to its place of use or to a reservoir or other storage location.

Water use describes where, when, how, and how much diverted water is put to specific purposes or lost through evaporation, consumption by crops, leakage, or other processes. ***Consumptive use*** occurs when diverted water is "evaporated, transpired, incorporated into products or crops, consumed by humans or livestock," or otherwise not returned to its source.[20] ***Return flow*** occurs when water re-enters its source after use, becoming available for further use.[21]

Figure 2 illustrates several concepts related to water diversion and use.

Water measurement is a means of quantifying the volume or flow rate of water using some combination of measurement devices and methods. This report focuses specifically on measurements of water diversion and use. A diversion ***measurement device*** enables the direct measurement of some aspect of a diversion (e.g., flow rate, velocity, water level, or volume).[22] A diversion ***measurement method*** provides an indirect means of estimating the volume of water diverted over time.[23] Whether a particular device or method is appropriate in a particular situation depends on factors like the purpose of measurement, applicable requirements, and site-specific conditions that may affect the utility of the device or method.

Reporting is the sharing—whether internal or external, voluntary or mandatory—of records of water diversion and use.

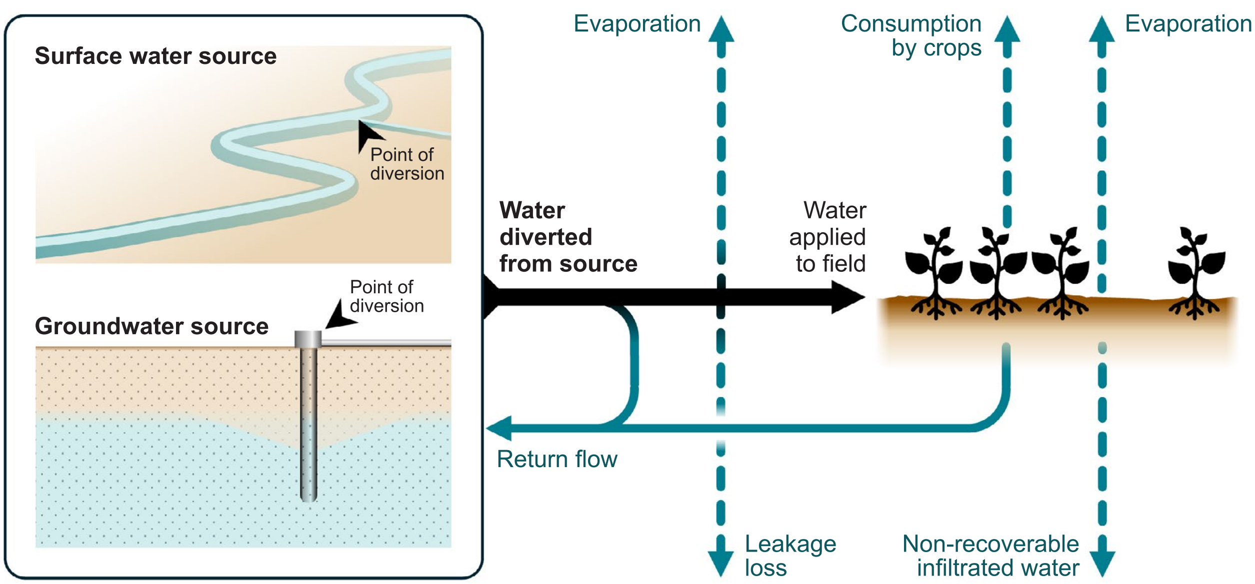

Figure 2. *Overview of the fate of water diverted for agricultural irrigation*[24]

1.2. OVERVIEW OF THE CONVENING AND THIS DOCUMENT

We held a virtual convening on measurement and reporting of water diversion and use with water experts from California, New Mexico, and Utah[25] to explore this foundational prerequisite for fair and effective water markets. The convening sought to address questions about what information about surface water and groundwater diversion and use is currently available in different geographies and sectors; who needs what information about water diversion and use, for what purposes, and in what forms to support fair and effective water markets that enhance climate resilience for agriculture and ecosystems; to what extent currently available information about water diversion and use meets these needs; and how the sources and flows of information could be improved to better meet critical information needs.

The convening used a series of flash presentations, breakout discussions, and full-group discussions organized around three modules that sequentially tackled: (1) the institutional context for measurement and reporting of water diversion and use in the three study areas; (2) technical options for measurement and reporting; and (3) vision-setting for measurement and reporting to support fair and effective water markets that enhance climate resilience for agriculture and ecosystems.

This document synthesizes the convening discussions and notes, as understood and interpreted by the authors, with additional research and analysis.[26]

- Section 1 *provides background on water markets and the role of adequate measurement and reporting of water diversion and use, describes related concepts and definitions, and provides an overview of the convening.*
- Section 2 *describes the broader institutional context for measurement and reporting of water diversion and use in California, New Mexico, and Utah.*
- Section 3 *examines current, and potential, technical options for measuring and reporting water diversion and use.*
- Section 4 *considers what measurement and reporting of water diversion and use are needed to support water markets, in particular. It articulates a vision for fair and effective water markets supported by adequate information about water diversion and use, summarizes key takeaways from the convening, and identifies opportunities to address barriers to achieving the vision.*

We highlight several important background concepts in Box 1 and define key terms related to water diversion, use, measurement, and reporting in Box 2.

2. INSTITUTIONAL CONTEXT

The legal, political, social, and environmental conditions in an area shape water measurement and reporting practices. These factors also determine whether measurement and reporting practices provide an adequate information base for a fair and effective water market.

Institutional context frames measurement and reporting of water diversion and use. Each location has a unique institutional context—shaped by laws and regulations and political, social, and environmental conditions—that influences water measurement and reporting practices and their utility for enabling fair and effective water markets that enhance climate resilience for agriculture and ecosystems.

Convening participants explored the following questions about the institutional contexts for diversion measurement and reporting in California, New Mexico, and Utah:

- *What types of entities currently measure surface water or groundwater diversions?*
- *What are the drivers for diversion measurement and reporting?*
- *What needs are current diversion measurement and reporting intended to serve? How well are those needs being met?*

For simplicity, we focused these questions on diversion measurement and reporting. However, water use measurement and reporting largely share the same institutional context, and Section 3 discusses technical options for both.

Understanding both water diversions and water use—especially the fate of diverted water and how much is consumptively used (see Box 2, Figure 2)—is essential for effective water management, including ensuring fair and effective water markets. In general, the amount of water the holder of a water-use entitlement can legally trade is the volume of water they *would have consumptively used* in the absence of a trade, *not* the total amount of water they *would have been entitled to divert* in the absence of a trade.[27]

2.1. WHICH ENTITIES CURRENTLY MEASURE WATER DIVERSIONS?

In all three states, many different types of entities may measure surface water or groundwater diversions. These include municipal, agricultural, industrial, and environmental water users and a variety of local, state, federal, and tribal government entities that manage or have regulatory authority over water use.

2.2. WHAT DRIVES CURRENT DIVERSION MEASUREMENT AND REPORTING?

Participants identified many potential drivers for measuring and reporting water diversions. We have grouped these drivers into three main categories: (1) mandatory requirements to measure and report, (2) planning and management needs and goals, and (3) hybrid drivers that combine aspects of the first two categories, such as conditions for accessing a desirable funding source or participating in water trading. These categories mirror the broad categories of needs that diversion measurement and reporting are intended to serve: demonstrating compliance with legal or regulatory requirements and aiding water planning, management, and oversight.

2.2.1. Mandatory requirements

Mandatory legal or regulatory requirements—especially requirements associated with acquiring and maintaining a water right—are major drivers for measurement and reporting of water diversion and use. Measurement and reporting can help establish the basis and validity of a water right and demonstrate compliance with applicable requirements by recording the amount and timing of water diversion and use. This information can also be used to defend the right against infringement or claims of non-use, to support a request for a water right change, or to demonstrate that water is available for transfer to another party. Convening participants noted that groundwater diverters are less often subject to measuring and reporting requirements than surface water diverters, but requirements for (and oversight of) groundwater diverters are increasing in many areas. Box 3 provides examples of water right requirements that act as drivers for diversion measurement and reporting in our three study area states.

Both water-specific legislation and more general environmental laws can drive measurement and reporting. For example, California's 2014 *Sustainable Groundwater Management Act* (*SGMA*) is driving more measurement and reporting of groundwater diversions and use in the state.[28] In the surface water context, water quality and ecosystem protections (like instream flow requirements established under the Endangered Species Act, the federal Clean Water Act, or state water quality law[29]) can drive improvements to diversion measurement and reporting. Similarly, water delivery and flow obligations under interstate compacts,[30] international treaties,[31] and tribes' federal reserved water rights or treaty rights[32] can spur diversion measurement and reporting.

2.2.2. Planning and management needs and goals

Planning and management needs and goals are another important category of drivers for diversion measurement and reporting. For example, diversion data are crucial inputs for water balance models that account for water inflows, diversions, return flows, depletions and losses, and other parameters.[33] Such models can inform near-term water management decisions (e.g., how much surface water is currently available for diversion) and longer-term planning and decision-making (e.g., identifying a groundwater basin's sustainable yield and the scale and nature of demand reduction and/or supply augmentation needed to achieve it). Knowing how much water is diverted to irrigate crops and how much of that water is consumptively used can help growers identify opportunities to improve their operational efficiency and support more effective irrigation and nutrient management.[34] This knowledge can also help water distributors, such as canal companies and irrigation districts, with planning. Other planning- and management-related drivers include improving near-term water supply forecasting, reducing vulnerability to flooding and water scarcity, and adapting to climate change. For example, as droughts become more frequent and intense in the U.S. Southwest, regulators need better diversion data to support effective water rights oversight, inform analysis of when curtailments are needed, and track curtailment compliance during times of water shortage.[35]

2.2.3. Hybrid drivers

Hybrid drivers are requirements that arise because of voluntary management choices. For example, diversion measurement and reporting may be necessary to maintain eligibility for a particularly desirable funding source (such as a grant or low-interest loan) or may be a prerequisite for participating in groundwater banking (see example in Box 3).

BOX 3. EXAMPLES OF DRIVERS FOR WATER MEASUREMENT AND REPORTING

Water right requirements are a crucial driver for water measurement and reporting across the Southwest. Utah,[36] New Mexico,[37] and California all require certain water rights holders to measure and report diversion and use under their water rights. While some requirements are longstanding, others continue to evolve, often in response to periods of prolonged drought. For example, to implement legislation passed during a major statewide drought in 2015, California's State Water Resources Control Board established more detailed requirements regarding acceptable devices and methods, accuracy, and monitoring frequency that vary depending on the amount of surface water a party diverts and whether the water is used directly or stored before use.[38] When strict compliance with these requirements is not feasible, a diverter can submit an *alternative compliance plan* (*ACP*).[39] For example, the Sacramento-San Joaquin River Delta's unique hydrology[40] prompted local water agencies to develop a Delta ACP.[41] In lieu of measuring and reporting diversions, the Delta ACP allows each participating agricultural diverter within the "Legal Delta" to report consumptive use data, calculated from OpenET's[42] satellite-based *evapotranspiration* (*ET*) estimates for their place of use, through an online platform.[43]

The need for better data to support water management decisions is another common driver for measuring and reporting water diversion and use. The Utah Legislature created the Colorado River Authority of Utah in 2021 to "protect, conserve, and develop Utah's Colorado River system interests" by working with the other six states that have Colorado River allocations.[44] To help it fulfill this role, the Authority commissioned a "Metering and Gaging Gap Analysis Study" to identify and prioritize gaps in water supply and use data—including diversion gaging—in the Utah portion of the Colorado River system.[45] The study collected and synthesized information about existing and retired water measurement infrastructure, analyzed data gaps, and developed preliminary cost and prioritization criteria to guide strategic expansion of the metering and gaging system to enable better informed water management decisions for the Colorado River,[46] a resource that provides more than 25% of Utah's water supply.[47]

Accounting needs related to recharging groundwater for storage and trading can also drive measurement and reporting. For example, the Kern Water Bank, a semi-private underground water storage project in California, uses infiltration ponds to introduce surface water into the aquifer for later extraction and use (or sale) by member entities.[48] Operating the bank requires tracking both water deposited in the bank, including water delivered under contract from the state and federal water projects and water diverted from the Kern River, and water withdrawn from the bank via recovery wells.[49] The bank applies a 10% "loss factor" to all deposits to account for ET losses from the infiltration ponds and to address local groundwater overdraft.[50] Selling banked water to a non-member entity for use outside Kern County incurs an additional 5% loss factor.[51]

The need to protect or increase environmental flows for ecosystems is another driver for measuring and reporting water diversion and use. For example, Utah allows transfers of water rights to instream flow, including under the 2020 Water Banking Act.[52] A pilot "water bank" in the Price River watershed will enable certain parties to lease water to improve instream flows from shareholders in the Carbon Canal Company who choose to fallow irrigated lands.[53] Leasable water is "limited to the consumptive use of alfalfa (prorated based on the amount of water available in priority) minus conveyance losses," and the Canal Company must "install and maintain measuring and totalizing devices to meter all water used for water banking purposes" and to report those amounts.[54] In California, water right holders can dedicate water to instream flow or carry out temporary or long-term transfers for instream use.[55] These transactions must be supported by adequate information about water diversion and use.[56]

2.3. HOW WELL DO DIVERSION MEASUREMENT AND REPORTING MEET CURRENT NEEDS?

Existing measurement and reporting of water diversion and use serve some purposes relatively well. For example, available data are often sufficient to identify large-scale conditions or trends, like a substantial mismatch between water supply and water demand or between reported water diversions and apparent depletion amounts.

However, many convening participants expressed that current measurement and reporting do not meet most other information needs identified in Section 2.2, including providing critical context for effective water planning and management. Although current water measurement and reporting may be sufficient to support water management decisions during times of surplus, convening participants suggested the same does not hold for times of water scarcity. In particular, they noted that data quality and accuracy, measurement and reporting frequency, and analysis of collected data are often insufficient to meet the heightened information needs that arise during times of shortage.[57] With water scarcity and rapid and unpredictable swings between drought and deluge becoming more common in many areas of the Southwest, this data sufficiency gap will make it increasingly untenable for decision makers to manage water effectively amidst these extremes.

Most concerning, participants suggested that water measurement and reporting in many areas are inadequate to support sufficient understanding of the spatial and temporal patterns of diversion and use in *either* wet or dry times. Although some participants suggested that flow in larger rivers and the amount and timing of significant diversions are relatively well measured and reported, many indicated that smaller streams, smaller diversions, conditions in particular stream reaches, and groundwater pumping are often poorly measured or not measured at all.

Even when diversions *are* measured, other variables that affect water's physical and legal availability—and, therefore, provide important context for water management—may not be. These include the amount of diverted water that serves its intended purpose, is otherwise consumptively used, or is reintroduced to the source as return flow. These water budget components can be more difficult to measure directly than water diversions.[58] As a result, they are often estimated using proxies (e.g., crop type and acreage, irrigation method, etc.) or conflated with diverted or applied water.

Water diversion and use data are not always transparent or readily useful. Measurement and reporting requirements may be inconsistently applied or followed. Requirements may be imposed through multiple regulatory programs, each with different missions, perceived data needs, and data collection and reporting standards.[59] The data water managers collect for internal decision-making purposes may be proprietary or otherwise externally inaccessible. Fragmented, inaccurate, incompatible, or inaccessible diversion and use data prevent integrated analysis and interpretation and impede transparent, effective decision-making.

The political will to require or invest in measurement and reporting improvements often emerges in response to a discrete event such as a severe drought,[60] and resulting data may not be available until long after the event has abated. Data improvements cobbled together from a reactive, ad hoc approach may not be adequate to support fair and effective water allocation decisions during times of scarcity, coordinated management of surface water and groundwater resources, planning for changes in water availability, or efforts to increase water security in a changing climate.[61]

These shortcomings suggest current measurement and reporting may be insufficient to support fair and effective water markets that increase resilience for agriculture and ecosystems in many parts of California, New Mexico, and Utah and across the Southwest.


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3. TECHNICAL OPTIONS FOR MEASUREMENT AND REPORTING

Diverters select measurement and reporting technologies based on the goals information gathering aims to address, site-specific conditions, regulatory requirements that define acceptable methodologies, and other considerations such as data accessibility and usability. These considerations also shape what technical options will best support fair and effective water markets in a particular area.

Technical realities and practical considerations affect what water diversion and use parameters are actually measured. They also affect the pros and cons of specific water measurement and reporting options for meeting information needs in various physical and institutional contexts.

Convening participants discussed questions about existing and possible technical options for water measurement and reporting and explored those options' potential utility for supporting fair and effective water markets that enhance climate resilience for agriculture and ecosystems:

- *What technical options are currently used to measure water diversions? To measure water use? For reporting? What are their pros and cons?*
- *What could be improved to better meet data needs for water markets? What are the roadblocks to that improvement?*
- *What other technical options might be possible? What are their pros and cons?*
- *Which of these could better inform fair and effective water markets that increase resilience for agriculture and ecosystems?*

This section addresses the first and third sets of questions. We synthesize discussion of the market-specific questions in Section 4.

3.1. CURRENT TECHNICAL OPTIONS

3.1.1. Measuring diversions

A variety of devices and methods are currently used to measure or estimate water diversions. Figure 3 and Table 1 summarize many of these. Whether a device or method is appropriate and feasible in a specific situation depends on a range of factors, including the purposes measurement is intended to serve, applicable requirements (e.g., state regulations that define acceptable devices, methods, and levels of accuracy for water right reporting[62]), and site-specific considerations. Proper installation, calibration, and maintenance are critical for producing reliable data.

In open channels — Devices such as weirs, submerged orifices, flumes, and acoustic velocity meters are used to measure water diverted from a river or stream into a canal or other open channel.[63] To calculate the volume diverted, the first three devices are used in conjunction with a water-level measurement device (such as a pressure transducer or staff gage) and information about the duration of the diversion and the relationship between water level and flow-rate. Acoustic velocity meters are primarily useful for measuring the flow of water with relatively constant acoustic properties in wide channels with low flow variability.[64] Diversion calculations based on acoustic velocity meter data require information about the duration of the diversion and the cross-sectional area of the channel at different water levels.[65]

In closed conduits — A flow meter is commonly used to measure water diverted into a closed conduit, such as a pipe.[66] There are numerous types of flow meters. Mechanical flow meters have moving parts, such as propellers or turbines, that physically interact with the water in the conduit and require frequent checking and calibration.[67] Electromagnetic flow meters use electrodes to measure the voltage induced when a magnetic field is applied to the conduit.[68] Ultrasonic flow meters use an acoustic signal to measure flow, either by reflecting the signal off of floating particles or air bubbles in the water (Doppler flow meter) or by measuring the time it takes a signal to travel from one transducer to another placed further along the conduit (transit time flow meter).[69] To calculate diversion volume, flow-rate measurements are used with information about the duration of the diversion and the cross-sectional area of the conduit. While mechanical flow meters generally cost less to install and require less electricity to operate, electromagnetic and ultrasonic flow meters are usually more robust and more likely to provide accurate measurements over time.[70]

Other methods are sometimes used to estimate diversions:

- ***Proxies for diversions with low flow rates*** include storage tank refill records (records of the number of times an empty storage tank of known volume is filled), pump electricity records (when pump electricity consumption has been calibrated to flow rate), or, if the flow rate is constant, a bucket and stopwatch.[71] The enduring use of rudimentary methods for estimating diversions (like a bucket and stopwatch) highlights that acceptable measurement methods and requirements can vary by jurisdiction, diversion type, and the purpose of measuring water diversion.

- ***When water is diverted to a reservoir for storage***, information about changes in reservoir levels over time and the relationship between reservoir depth and capacity is sometimes used to estimate the volume of water diverted. If some of the water diverted passes back into the water source, there are other water inputs to the reservoir, or water is withdrawn from the reservoir, these inputs and outputs must be factored into diversion estimates.[72]

- ***If water is diverted for agricultural use***, estimates of consumptive use—the amount of water that crops consume or that is otherwise lost, such as through ET—are sometimes used as a proxy for water diversions (see also "Water use," below, and Boxes 2 and 3, above).

- ***Source-water conditions are sometimes used as a proxy*** for diversions. For example, the reduction in streamflow downstream of a point of diversion is sometimes substituted for diversion data. Declines in monitoring-well water levels near a surface or groundwater diversion are sometimes used in similar ways.

Table 1 provides a high-level overview of the relative cost, accuracy, maintenance needs, and data collection possibilities of some technical options for measuring or estimating water diversions. This overview is both generalized and non-exhaustive. Note that listed devices and methods are sometimes used in contexts other than those mentioned here, and costs, specific applications, and maintenance needs can vary widely depending on geography and institutional context. This table illustrates the range and variability of measurement options.

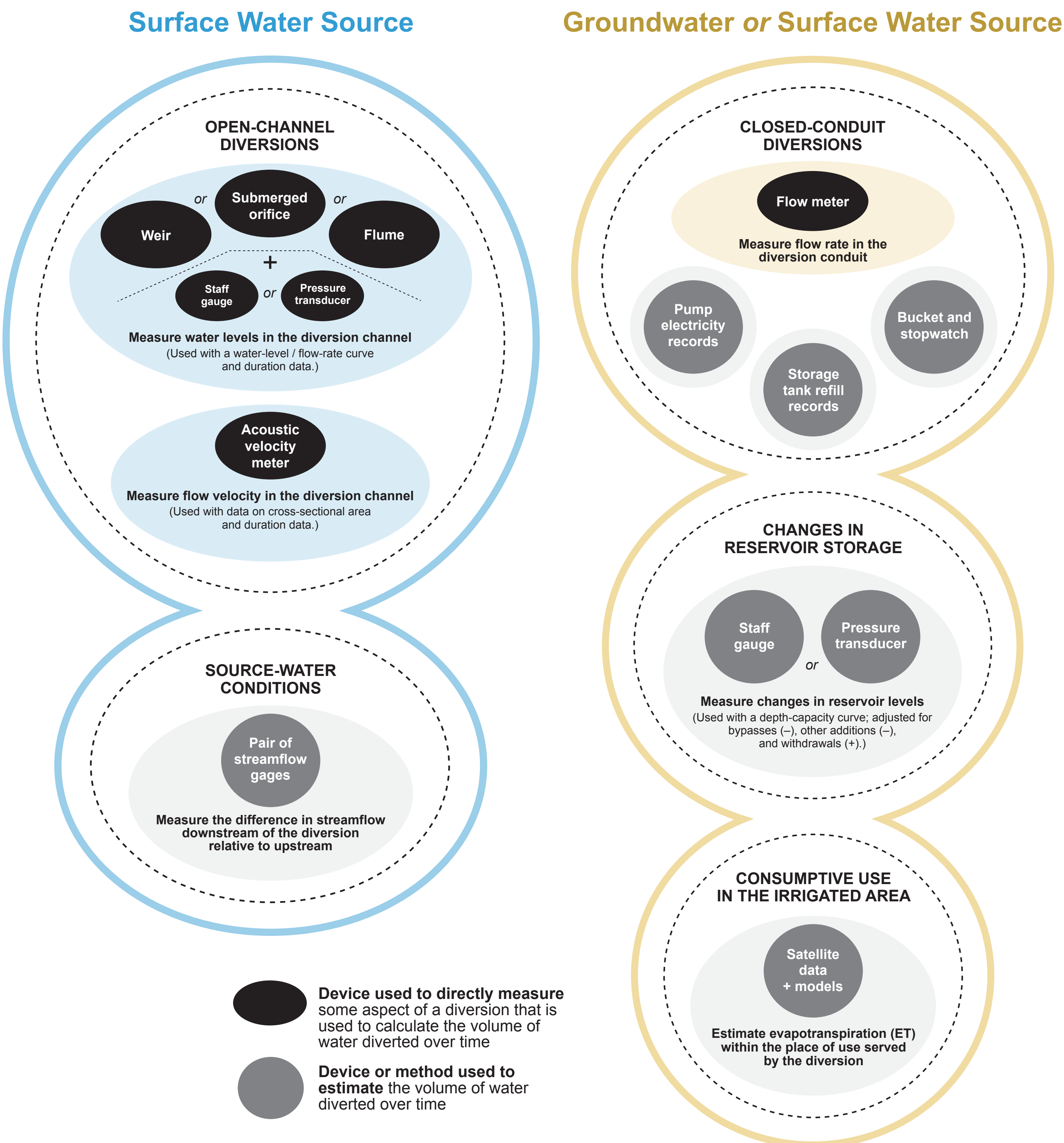

Figure 3. *Some devices and methods used to measure or estimate diversions*[73]

Table 1. *Comparison of some devices and methods used to measure or estimate water diversions.*[74] *Figure 3 provides additional context.*

OPTION	DIVERSION TYPE	ACCURACY Low > 15% error Med. 5–15% error High < 5% error	DATA COLLECTION	SETUP COSTS	MAINTENANCE NEEDS
Weir / flume + staff gauge	Open channel	Low–High	In-person	Weir construction requires forms and concrete. Precast structures require delivery equipment. Weir and flume costs can vary significantly (often several thousand dollars). Staff gauges typically cost $300–$500.	Relatively easy to maintain, although water level readings and diversion duration must be recorded manually and periodic streamflow measurements may be necessary to improve data quality. Gauge may need periodic cleaning to remove biological growth to maintain readability. The weir approach channel may need to be cleared of sediment and other debris periodically.
Weir / flume + pressure transducer requirements	Open channel	Low–High	Downloaded, Telemetered	Weir construction requires forms and concrete. Precast structures require delivery equipment. Weir and flume costs can vary significantly (often several thousand dollars). Pressure transducers typically cost $300–$1,000. A data logger adds ~$500, while telemetry adds ~$1,500.	After establishing a rating curve, the pressure transducer and rating curve must be calibrated periodically to account for erosion and accretion, although incorporation of a weir and flume or use of a concrete-lined channel will minimize the need for re-calibration and frequent site visits to verify streamflow. The pressure transducer needs to be checked and maintained occasionally to ensure proper function. Weir approach channel may need to be periodically cleared of sediment and other debris.
Acoustic velocity meter	Open channel	Low–High	Downloaded, Telemetered	Acoustic velocity meter costs can vary significantly (e.g., $1,200 to $6,000). A data logger adds ~$500, while telemetry adds ~$1,500.	Acoustic velocity meters require a power source and must be calibrated to the local environment. Annual examination is often sufficient.
Bucket and stopwatch	Closed conduit	Low	In-person	Very low setup costs.	Replace as needed.
Pump electricity records	Closed conduit	Low–Med.	Downloaded, Telemetered	Relatively low setup costs, although technical expertise may be needed for initial calibration. A data logger adds ~$500, while telemetry adds ~$1,500.	Electricity consumption must be periodically calibrated to flow, particularly if water levels or pumping conditions have changed over time.
Mechanical flow meter	Closed conduit	Low–High	In-person, Downloaded, Telemetered	$800 to $3,500, (avg. $2,000) telemetry adds ~$1,500.	Propeller must be checked regularly to ensure nothing is tangled in the head. The meter must be checked periodically for leaks and function and calibrated frequently. Regular maintenance of moving parts and cables required. Reoccurring maintenance prolongs the life and accuracy of these meters
Magnetic & acoustic flow meters	Closed conduit	High	In-person, Downloaded, Telemetered	Typically cost ~$1,500 each. A data logger adds ~$500, while telemetry adds ~$1,500.	Require a power source. Magnetic flow meters may not function properly if placed near magnetic objects.
Staff gauge	To reservoir	Low–Med.	In-person, Downloaded, Telemetered	Costs can vary significantly (e.g., ~$300–$1,500). Surveying a reservoir to develop a rating curve can cost from ~$100 to ~$10,000. A data logger adds ~$500, while telemetry adds ~$1,500–$2,000.	Requires periodic calibration and reservoir survey to maintain an accurate rating curve.

3.1.2. Measuring water use

Water use information complements information on diversion timing, location, and amount to provide a more complete picture of the diversion's net effect on source water availability and quality. This includes information about the amount, timing, and location of water application; the irrigation technology and how much of that water is consumptively used (i.e., beneficially used or lost through evaporation, transpiration, or other means); and the amount, timing, and location of any return flows that re-enter the water source.

Crop ET accounts for much of the water diverted for agricultural irrigation that is consumptively used. However, crop ET does not account for other losses, such as water lost during conveyance or to seepage (see Box 2). There are numerous methods for deriving crop ET, including methods based on direct measurements, field-based estimates, remote sensing methods, or crop coefficient calculations.[75] Many of these methods rely on sophisticated equipment or calculations.[76]

Both diversion data and ET data are valuable and, when used together, provide a more complete and accurate understanding of the water budget, including water use and movement through the environment.

3.1.3. Data collection and reporting

Diversion measurement data are sometimes collected and reported manually. However, partially or fully automatic data collection and reporting are becoming increasingly common and support more accurate, transparent, and timely decision making.[77] Manual methods can require significant, ongoing time investments to take onsite measurements, record those measurements, and report the resulting data, either in paper form or electronically. When data are reported on paper, the receiving entity (e.g., state water rights regulator) must spend additional time entering and validating data. By contrast, automatic methods require more sophisticated data collection and reporting systems that involve more substantial up-front investment, but usually require less ongoing onsite attention and time investment. Partially or fully automated data collection and reporting also reduce the risk of inadvertent reporting errors and intentional misrepresentations of water diversion and use. Theoretically, telemetered data loggers can enable both internal data collection and external reporting in near real time. However, most diversion measurement data are still only reported on a periodic basis—often monthly or annually—regardless of the temporal resolution of data collection.[78]

Reported data are sometimes incorporated into a public, open-access data system.[79] In other cases, some or all aspects of reported data remain largely inaccessible due to privacy concerns[80] or the limitations of existing data systems. Online databases, sometimes populated by data gleaned from mailed paper reports, are commonly used to capture reported data.

Generally, less technologically sophisticated measurement and reporting methods offer less accuracy and precision at lower upfront cost, while more sophisticated methods improve accuracy and precision at higher upfront cost, but can potentially reduce long term costs. Cost is a reflection of human capital, technological capital, ongoing operation and maintenance needs, and measurement frequency.

Some states require diverters to use certain devices or methods for measuring and reporting their diversion and use (see Box 3). Requirements may vary depending on factors such as the characteristics of the water source, the quantity of water diverted, or the purpose of use.

3.2. OTHER POTENTIAL TECHNICAL OPTIONS

There are other potential technical options for measuring and reporting water diversion and use, including some that exist but are not commonly used and others that are theoretically possible but have not yet been put into practice. Many participants suggested that more technologically advanced measurement and reporting options could provide a more detailed and thorough picture of water diversion and use, generally at a greater cost than current commonly used options.

Participants mentioned the following possible technical options for measurement or reporting:

- Making fully telemetered measurement systems standard;
- More comprehensive mass-balance accounting that adequately accounts for various aspects of consumptive use, return flows, and groundwater–surface water interactions;
- Time-stamped photos of measurement devices (e.g., staff gauges) in operation, combined with information on channel geometry and geomorphology; and
- Computer-vision, non-contact flow gauging of streams and open-diversion channels that employs cost-effective stereo camera systems based on old cell phones.[81]

In addition to identifying an array of potential technical options for measurement and reporting, participants discussed ways to improve data accessibility, interoperability, and quality. For instance, a data aggregator or other centralized system—supported by open data requirements and data governance rules—could help bridge data-collection silos and provide broader, more equitable access to useful and usable diversion and use data. Standardizing measurement and reporting with clear data format and metadata requirements could improve equity, interoperability, and quality.

Participants emphasized the need for guidance on the appropriate use of different measurement methods and data types, including which are complementary and which can substitute for one another. Use cases could demonstrate helpful examples.

Future measurement and reporting technologies and strategies could build in explicit mechanisms for feedback and adjustment. Such mechanisms might include frequent performance evaluation, independent verification and auditing, and reporting systems that incorporate consistent methods for flagging data *quality assurance and quality control* (*QA/QC*) concerns.

Finally, some participants noted that if states used open-source water data platforms, they could share codebases and potentially improve data infrastructure without significant new financial investments in information technology.

4. MEETING INFORMATION NEEDS FOR FAIR AND EFFECTIVE WATER MARKETS

Adequate measurement and reporting are necessary components of a vision for fair and effective water markets. We outline that vision, summarize the current status of diversion and use information in the U.S. Southwest, and identify opportunities for researchers, diverters, and policymakers to advance the information foundation needed to support fair and effective water markets.

To explore information needs for water markets, in particular, we engaged convening participants in collaborative vision setting for water measurement and reporting capable of supporting water markets that enhance climate resilience for both agriculture and ecosystems. The group explored the overarching questions:

- *Which entities need information about water diversion and use to enable fair and effective water markets? What information do they need? For what purposes? In what form?*
- *How well does currently available information meet these needs? How does it not?*
- *How can information sources and flows be improved to enable water markets that enhance climate resilience for agriculture and ecosystems?*

Together with our own research, the convening discussions clarified a vision for fair and effective water markets supported by adequate information about water diversion and use:

1. ***Water markets have clear goals***[82] that advance climate resilience for agriculture and ecosystems while avoiding unintended consequences.
2. ***The risks and benefits of water trading are adequately understood***, including the potential impacts on third parties and ecosystems of changing the location, timing, or purpose of diversion and use.[83] Ideally, these risks and benefits are well understood.

3. ***Measurement and reporting of water diversion and use are adequate—given basin conditions, vulnerabilities, and uncertainties—to inform trading rules, characterize how much water can be traded, and enable effective tracking of trades and their impacts.***[84] Because timely and accurate data best meet these needs, measurement and reporting would ideally be fully telemetered, capture not only the timing and volume of diversions but also the amount consumptively used, and feed into a centralized data system that provides high-quality, real-time data in proper context, including accounting by water right, point of diversion, and place of use.

4. ***Trading rules reflect local conditions, vulnerabilities, and uncertainties*** such that they prevent trading from causing significant negative externalities.[85] Ideally, rules minimize harm to third parties and the environment, build climate resilience for agriculture and ecosystems, and serve other local needs and goals.

5. ***Potential parties to trades understand the rules and how those rules apply to their water rights or use entitlements***, including how much water is physically and legally available for diversion, use, and transfer.[86]

6. ***Information about trading prices is transparent and publicly available***, providing all potential parties to a trade with the same access to pricing knowledge.[87]

7. ***Frequent evaluations assess whether markets are functioning as intended.***

8. ***Contingencies are in place to address serious unintended consequences that may arise from trading.*** For example, there are robust contingency plans for remedying negative impacts to water quality or access for historically marginalized and underserved communities and small farmers that rely on shallow wells.[88]

9. ***Adjustments to trading rules, market administration, and oversight are made as needed.***[89]

In the remainder of this section, we summarize key takeaways from the convening and highlight opportunities to advance this vision for fair and effective water markets.

4.1. KEY TAKEAWAYS FROM THE CONVENING

The convening provided insights into the current information landscape for measurement and reporting of water diversion and use in the U.S. Southwest—and how well it meets information needs for fair and effective water markets. Key takeaways include the following:

Water rights administration, particularly during times of drought, is a key driver for measurement and reporting of water diversion and use.

Many entities need information about diversion and use in areas with water trading, including parties (and potential parties) to trades, consultants, state water right regulators, entities with authority over water distribution and trading like watermasters, water users who are not participating in trading, and those whose interests may be affected by water trading, such as communities and small farmers that rely on shallow wells, environmental advocates, and ecosystem managers. For example, potential parties to water trades need to understand their individual use and tradable allocation; watermasters need to track trades to understand the implications for managing water within their service area; and water rights regulators need information that helps them analyze whether a water right change request in support of a water transfer meets the conditions required for approval, such as not injuring other legal water users or causing unreasonable impacts to fish and wildlife.

There is no one-size-fits-all prescription for measurement and reporting needed to support fair and effective water markets. Rather, area-specific hydrology, ecology, laws, and social and economic conditions determine minimum measurement and reporting needs.

In the U.S. Southwest, current water measurement and reporting are often insufficient to meet the basic needs they are intended to serve, much less to support fair and effective water markets. Where water measurement and reporting are poor, markets carry a heightened risk of causing unintended consequences to communities and ecosystems. There is a clear need for more timely, accurate, and accessible data on water rights, water diversions, water use, and changing surface and groundwater conditions—data that clarifies what can be traded, who can trade, and the impacts of trading on particular communities and ecosystems.

Expanded use of telemetry will enable more real-time and near-real-time measurement and reporting. However, implementing telemetry may not be technically or financially feasible for small water users. Additionally, effective data systems and governance practices are needed to ensure that telemetered data is useful and usable.

Data reporting and management systems improvements are needed to more effectively meet data needs for water markets and other aspects of water management. Systems that promote standardization, transparency, and an ability to audit data can build trust in the reliability of those data and any related market transactions. Standardization also allows for system consolidation and interoperability, which can in turn reduce cost barriers associated with reporting technology.

There is currently institutional momentum in several Southwestern states to improve the timeliness, accuracy, and accessibility of water data by introducing more robust measurement and reporting requirements and improving the data systems state agencies use to organize, analyze, and provide public access to reported data. For example, in the face of growing challenges like increasing precipitation extremes, some states are working to modernize their water rights data systems and data governance practices to enable more timely, effective, and transparent water decision-making at all levels.

Measurement and reporting technologies and data systems can be expensive to develop, implement, and maintain. In addition to up-front costs, there are ongoing costs associated with maintaining infrastructure, training people to use the technologies, and achieving sufficient broadband connectivity to comply with advanced measurement and reporting expectations.

Some water users may perceive efforts to increase the accuracy of water measurement and reporting as increasing their personal risk. They may fear that more accurate data will enable increased government scrutiny of their diversion, use, and reporting practices, heightening the threat of enforcement actions to address any violations. Some may intentionally overstate the amount of water they divert because they incorrectly assume that conservation-based reductions in water use automatically risk forfeiture of the unutilized portion of their water right.

Funding gaps exacerbate other barriers to fair and equitable water markets. More complete, transparent, and systematized data collection and reporting require more time, money, and staff than states currently allocate. While data improvements are sorely needed, meeting more stringent measurement and reporting requirements can be especially challenging and create disproportionate burdens for smaller, less well-resourced, less technologically savvy water users.

4.2. OPPORTUNITIES TO ADVANCE FAIR AND EFFECTIVE WATER MARKETS

The takeaways summarized above shed light on current barriers to meeting information needs for fair and effective water markets, but also on actionable solutions for overcoming those barriers. **Table 2** outlines three categories of barriers and potential solutions for overcoming those barriers. It also highlights the types of entities that may be well suited to implement each solution, such as researchers, water diverters (or associations of diverters), government agencies (including state water rights regulators or other federal, state, or local agencies that oversee aspects of water allocation and management), and state legislatures.

Table 2. *Potential solutions for addressing barriers to meeting information needs for water markets, highlighting potential implementers.*

BARRIER	POTENTIAL SOLUTIONS	RESEARCHERS	DIVERTERS	GOVERNMENT AGENCIES	STATE LEGISLATURES
INADEQUATE UNDERSTANDING OF WATER DIVERSION AND USE	**Establish or improve requirements for measuring and reporting diversion and use.** This would help fill existing information gaps, support more effective water rights administration, and enable timely and accurate evaluation of potential water transfers.			●	●
	Develop and maintain a publicly accessible data system for reporting diversion and use information to reduce fragmentation, inaccuracy, incompatibility, and inaccessibility concerns.			●	●
	Provide clear guidance and more extensive educational outreach to help diverters understand measurement and reporting requirements and technical options.	●	●	●	
	Expand use of telemetry to enable near-real-time measurement and reporting.	●	●	●	●
	Develop a more complete picture of consumptive water use.	●	●	●	●
	Better integrate groundwater and surface water data to support more holistic analysis of the impacts of water diversions, consumptive use, and water trading.	●	●	●	●
REPORTING AND DATA MANAGEMENT DEFICIENCIES	**Establish clear data standards** for collecting and reporting data.			●	●
	Provide guidance to help diverters understand applicable measurement and reporting requirements and improve the quality of the data they gather and report.	●	●	●	
	Incorporate adequate QA/QC measures into reporting and data management systems.	●	●	●	●
	Examine similarities and differences in different parties' data needs and how well available data are meeting those needs.	●		●	
FUNDING AND AFFORDABILITY CHALLENGES	**Identify stable, long-term funding sources** for collecting, maintaining, and analyzing water rights data—including diversion and use data.	●	●	●	●
	Identify critical broadband gaps that would need to be addressed to support fully telemetered measurement and reporting systems.	●	●	●	●
	Subsidize the buildout of telemetered measurement and reporting mechanisms for under-resourced diverters, such as via cost-sharing programs.			●	●
	Develop and share open-source reporting and data management platforms.	●		●	


CR310 Datalogger

5. CONCLUSION

Water markets have the potential to enhance climate resilience for agriculture and ecosystems, helping water users in the U.S. Southwest adapt to both abrupt short-term variations in water supply and long-term restrictions on water diversion and use needed to enable regional transitions to more sustainable water use. However, this promise can only be realized if markets are truly fair and effective—able to achieve the goals they are intended to accomplish without causing significant negative side effects. Adequate information about water diversion and use is a necessary precursor for fair and effective water markets because it defines what can be traded, enables tracking of trading transactions and changes in water supply and legal availability, and facilitates assessing the impacts of trading on others.

We held a convening to explore this foundational prerequisite for fair and effective water markets. The convening sought to identify the institutional context and technical options for measuring and reporting water diversion and use in the Southwestern United States, with a focus on California, New Mexico, and Utah. It explored overarching questions about what information regarding surface water and groundwater diversion and use is currently available; who needs what information about diversion and use, for what purposes, and in what forms to support fair and effective water markets that enhance climate resilience for agriculture and ecosystems; the extent to which currently available information meets those needs; and how data sources and flows could be improved to better meet critical information needs for water markets. This document synthesizes the convening discussions and notes along with additional research and analysis.

The convening surfaced many relevant insights regarding the current information landscape, the barriers it presents to meeting information needs for fair and effective water markets, and opportunities for overcoming those barriers. Key takeaways include the importance of water rights administration as a central driver for water measurement and reporting; significant variation, both within and across states, in who measures water diversion and use, why they measure, how they measure, and what information is needed to support fair and effective markets; and the need for more timely, accurate, and accessible data on water rights, water diversions, water use, and changing surface and groundwater conditions in many parts of the Southwest. However, there are also clear opportunities to improve water measurement and reporting in the U.S. Southwest. Researchers, diverters, and policymakers at government agencies and in state legislatures can all take concrete steps to improve understanding of water diversion and use, increase the accuracy and utility of reported data, and address long-term funding and affordability challenges.

Creating the information conditions to support fair and effective water markets that enhance climate resilience for both agriculture and ecosystems is feasible in the U.S. Southwest, but will require adequate political will and financial resources.




ENDNOTES

All URLs last visited September 26, 2024. Some may be paywall- or subscription-restricted.

1 See, e.g., E. Elias, A. Rango, R. Smith, C. Maxwell, C. Steele, and K. Havstad, "Climate change, agriculture and water resources in the Southwestern United States," 158(1) ***Journal of Contemporary Water Research & Education*** 46–61 (2016), available at URL: https://doi.org/10.1111/j.1936-704X.2016.03218.x; M. Dettinger, B. Udall, and A. Georgakakos, "Western water and climate change," 25 ***Ecological Applications*** 2069–2093 (2015), available at URL: https://doi.org/10.1890/15-0938.1; "Groundwater Declines in the U.S. Southwest," ***NASA Earth Observatory***, URL: https://earthobservatory.nasa.gov/images/152970/groundwater-declines-in-the-us-southwest; J. Lund, J. Medellin-Azuara, and A. Escriva-Bou, ***The Magnitude of California's Water Challenges*** (2024), available at URL: https://cawaterlibrary.net/document/the-magnitude-of-californias-water-challenges/.

2 See, e.g., S.P. Langarudi, C.M. Maxwell, and A.G. Fernald, "Integrated policy solutions for water scarcity in agricultural communities of the American Southwest," 9 ***Systems*** 26 (2021), available at URL: https://doi.org/10.3390/systems9020026.

3 See, e.g., K. Schwabe, M. Nemati, C. Landry, and G. Zimmerman, "Water markets in the Western United States: Trends and opportunities," 12 ***Water*** 233 (2020), available at URL: https://doi.org/10.3390/w12010233; J. Arellano-Gonzalez, A. AghaKouchak, M.C. Levy, Y. Qin, J. Burney, S.J. Davis, and F.C. Moore, "The adaptive benefits of agricultural water markets in California," 16 ***Environmental Research Letters*** 044036 (2021), available at URL: https://doi.org/10.1088/1748-9326/abde5b.

4 See, e.g., D. Garrick, S. Balasubramanya, M. Beresford, A. Wutich, G.G Gilson, I. Jorgensen, N. Brozović, M. Cox, X. Dai, S. Erfurth, R. Rimšaitė, J. Svensson, J. Talbot Jones, H. Unnikrishnan, C. Wight, S. Villamayor-Tomas and K. Vazquez Mendoza, "A Systems Perspective on Water Markets: Barriers, Bright Spots, and Building Blocks for the next Generation," 18(3) ***Environmental Research Letters*** 031001 (2023), available at URL: https://doi.org/10.1088/1748-9326/acb227; S. Heard, M. Fienup, and E.J. Remson, "The first SGMA groundwater market is trading: The importance of good design and the risks of getting it wrong," 75 ***California Agriculture*** 50–56 (2021), available at URL: https://doi.org/10.3733/ca.2021a0010; N. Green Nylen, M. Kiparsky, K. Archer, K. Schnier, and H. Doremus, ***Trading Sustainably: Critical Considerations for Local Groundwater Markets Under the Sustainable Groundwater Management Act*** (2017), available at URL: https://www.law.berkeley.edu/trading-sustainably; S.A. Wheeler, A. Loch, L. Crase, M. Young, and R.Q. Grafton, "Developing a Water Market Readiness Assessment Framework," 552 ***Journal of Hydrology*** 807–20 (2017), available at URL: https://doi.org/10.1016/j.jhydrol.2017.07.010; N. Brozović and R. Young, "Design and Implementation of Markets for Groundwater Pumping Rights" 283–303, in ***Water Markets for the 21st Century: What Have We Learned?*** (eds. K.W. Easter and Q. Huang, 2014), available at URL: https://doi.org/10.1007/978-94-017-9081-9_15.

5 See, e.g., E.M. Bruno and K. Jessoe, "Designing water markets for climate change adaptation," 14 ***Nature Climate Change*** 331–339 (2024), available at URL: https://doi.org/10.1038/s41558-024-01964-w; L. McEwen, "Farmers in Tulare County set to test groundwater market they hope could help keep them in business and replenish the aquifer," ***SJV Water*** (February 2, 2024), URL: https://sjvwater.org/farmers-in-tulare-county-set-to-test-groundwater-market-they-hope-could-help-keep-them-in-business-and-replenish-the-aquifer/.

6 See, e.g., Green Nylen et al. 2017, supra note 4; C.N. Morrisett, R.W. Van Kirk, L.O. Bernier, A.L. Holt, C.B. Perel, and S. Null, "The irrigation efficiency trap: rational farm-scale decisions can lead to poor hydrologic outcomes at the basin scale," 11 ***Frontiers in Environmental Science*** 1188139 (2023), available at URL: https://doi.org/10.3389/fenvs.2023.1188139; N. Green Nylen and M. Kiparsky, "Trust in water markets must be earned," ***The Source*** (January 28, 2019),

available at URL: https://thesourcemagazine.org/trust-in-water-markets-must-be-earned/; J.H. Skurray and D.J. Pannell, "Potential Approaches to the Management of Third-Party Impacts from Groundwater Transfers," 20 ***Hydrogeology Journal*** 879–91 (2012), available at URL: https://doi.org/10.1007/s10040-012-0868-9.

7 See, e.g., sources cited supra notes 1–3; A. Escriva-Bou, H. McCann, E. Blanco, B. Gray, E. Hanak, J. Lund, B. Magnuson-Skeels, and A. Tweet, *Accounting for California's Water: Technical Appendix* at 3–15 (2016), available at URL: https://www.ppic.org/wp-content/uploads/content/pubs/other/716EHR_appendix.pdf.

8 See, e.g., J.A. Swaney, "Trading water: market extension, social improvement, or what?" 22 *Journal of Economic Issues* 33-47 (1988), available at URL: https://doi.org/10.1080/00213624.1988.11504732.

9 See, e.g., examples cited in Green Nylen et al. 2017, supra note 4, at 8, 46–47.

10 See id.

11 See generally id., see also, e.g., G. Meran, M. Siehlow, and C. von Hirschhausen, *The Economics of Water* at 185–189 (2021), available at URL: https://doi.org/10.1007/978-3-030-48485-9_5.

12 ***The most basic goal of a water market is to enable voluntary redistribution of water. However, markets can be explicitly designed to further other goals, including sustainable water use.*** See, e.g., Green Nylen et al. 2017, supra note 4 at 23, 32–33.

13 See Heard, Fienup, and Remson, supra note 4; see also generally Green Nylen et al. 2017, supra note 4. ***Some indications a market is fair and effective include: market participants have adequate information about the water resource, their entitlements to use it, market rules, and the impacts of trading; market rules succeed in minimizing negative externalities; and market power is minimal so that those who want to participate in the market, consistent with applicable market rules, are able to do so fully.*** See, e.g., generally A. Ayres, E. Hanak, B. Gray, G. Sencan, E. Bruno, A. Escriba-Bou, and G. Gartrell, *Improving California's Water Market: How water trading and banking can support groundwater management* (2021), available at URL: https://www.ppic.org/publication/improving-californias-water-market/.

14 M. Kiparsky, D.L. Sedlak, B.H. Thompson Jr, and B. Truffer, "The innovation deficit in urban water: the need for an integrated perspective on institutions, organizations, and technology," 30 *Environmental Engineering Science* 395-408 (2013), available at URL: https://doi.org/10.1089/ees.2012.0427.

15 See, e.g., Green Nylen et al. 2017, supra note 4; Green Nylen and Kiparsky 2019, supra note 6.

16 ***We adapted this definition from the*** Intergovernmental Panel on Climate Change (IPCC), "Summary for Policymakers," at 7, note 12, in *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (2023), available at URL: https://doi.org/10.1017/9781009325844.001.

17 ***This definition draws on concepts discussed in*** Peter Gleick, "Water in Crisis: Paths to Sustainable Water Use," 8 *Ecological Applications* 571–579 (1998), available at URL: https://doi.org/10.1890/1051-0761(1998)008[0571:WICPTS]2.0.CO;2; "Water and sustainable development," *United Nations*, URL: https://www.un.org/waterforlifedecade/water_and_sustainable_development.shtml.

18 ***The point of diversion is the location (e.g., diversion dam, headgate, well, etc.) where water is withdrawn from the natural source.*** See, e.g., Cal. Code of Regs. tit. 23, § 931(k); N.M. Admin. Code 19.26.2.7(X); "Glossary," *Utah Division of Water Rights*, URL: https://waterrights.utah.gov/water-rights/glossary.

19 ***Surface water diversions can operate under gravity or use a pump, while diverting groundwater generally requires a pump. A key exception is artesian wells, which flow on their own.*** See, e.g., "Artesian Water and Artesian Wells," *U.S. Geological Survey*, URL: https://www.usgs.gov/special-topics/water-science-school/science/artesian-water-and-artesian-wells.

20 Water Resources Mission Area, "Water-Use Terminology," ***U.S. Geological Survey*** (February 27, 2019), URL: https://www.usgs.gov/mission-areas/water-resources/science/water-use-terminology (website, last visited April 22, 2024). ***Non-consumptive use occurs when water is designated for use within the water source itself (e.g., instream use of a stream by fish and wildlife) or when diverted water rapidly returns to its source with minimal losses (e.g., during some hydroelectric power generation). Note that some hydropower uses involve temporary impoundments that may increase the amount of water lost to evaporation and affect the timing, temperature, or other characteristics of downstream flow.*** See, e.g., T. H. Bakken, Å. Killingtveit, K. Engeland, K. Alfredsen, and A. Harby, "Water consumption from hydropower plants – review of published estimates and an assessment of the concept," 17 *Hydrology and Earth System Sciences* 3983–4000 (2013), available at URL: https://doi.org/10.5194/hess-17-3983-2013.

21 See, e.g., Water Resources Mission Area, supra note 20. ***Note that, although we use "return flows" generically to describe water re-entering the source (whether groundwater or surface water) after use, others may reserve the term for surface water only.*** See, e.g., California Department of Water Resources, *Draft Handbook for Water Budget Development* at 8 (2020) [hereinafter **Draft Handbook**], available at URL: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Data-and-Tools/Files/Water-Budget-Handbook.pdf. ***Some examples of return flows are: water that is diverted from a stream channel for a short distance to bypass a dam or other in-channel obstruction, the portion of water diverted from a stream for irrigation use that flows back to the stream as surface runoff or infiltrates to groundwater and flows back into the stream as baseflow, the portion of groundwater extracted for irrigation use that percolates back down to the water table, or discharges of treated wastewater.*** See, e.g., R. Healy, T.C. Winter, J.W. LaBaugh, and O.L. Franke, *Water Budgets: Foundations for Effective Water-Resources and Environmental Management* at 57 (2007), U.S. Geological Survey Circular 1308, available at URL: https://water.usgs.gov/watercensus/AdHocComm/Background/WaterBudgets-FoundationsforEffectiveWater-ResourcesandEnvironmentalManagement.pdf; K. Moyers, R. Sabie, E. Waring, J. Preciado, C.C. Naughton, T. Harmon, M. Safeeq, A. Torres-Rua, A. Fernald, and J.H. Viers, "A Decade of Data-Driven Water Budgets: Synthesis and Bibliometric Review," 59(11) *Water Resources Research* e2022WR034310, available at URL: https://doi.org/10.1029/2022WR034310; A. Escriva-Bou, H. McCann, E. Hanak, J. Lund, and B. Gray, *Accounting for California's Water* at 8 (2016), available at URL: https://www.ppic.org/wp-content/uploads/content/pubs/report/R_716EHR.pdf; Draft Handbook, supra this note, at 121.

22 See, e.g., California State Water Resources Control Board, *Measurement and Reporting Manual* at 5 (2023), available at URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/diversion_use/docs/2023/measurement-reporting-manual-2023-12.pdf; see also sources cited infra note 73.

23 ***For example, when water is diverted to a storage facility (such as in a reservoir), diversions are sometimes estimated based on measurements of the amount of water collected in and withdrawn or released from the storage facility, instead of measured at the point of diversion or within the diversion channel or conduit.*** See California State Water Resources Control Board, Fact Sheet: Reservoir Diversions to Storage (2019), available at URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/measurement_regulation/docs/water_measurement/res.pdf.

24 ***This figure was informed by Figure 2 in*** B.D. Richter et al., "Opportunities for saving and reallocating agricultural water to alleviate water scarcity," 19 *Water Policy* 886–907 (2017), available at URL: https://doi.org/10.2166/wp.2017.143. ***Differences in arrow length do not reflect the relative scale of the water budget components, which will vary depending on the conditions of a particular instance of diversion and use. "Consumption by crops" includes transpiration, evaporation, and incorporation of water into harvested components such as leaves, fruits, or seeds.***

25 ***This group included 13 members of the Secure Water Future research group and 25 participants from our study areas, including 6 people from New Mexico, 9 from Utah, and 10 from California.***

26 ***We did not vet all factual assertions made by participants for accuracy.***

27 See, e.g., Escriva-Bou et al. supra note 7, at 23, 48, 59, 70, 91, 113 (summarizing transfer requirements in California, Colorado, Idaho, Kansas, New Mexico, Oregon, and other states); see Green Nylen et al. 2017, supra note 4, at 30, 48 (regarding California); California Department of Water Resources and U.S. Bureau of Reclamation, California-Great Basin Region, ***DRAFT Technical Information for Preparing Water Transfer Proposals*** (***Water Transfer White Paper***), at 2–8, 11 (2019), available at URL: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/State-Water-Project/Management/Water-Transfers/Files/Draft_2019WTWhitePaper-012324.pdf; California State Water Resources Control Board, ***A Guide To Water Transfers*** (***Draft***) 3-7 to 3-9 (1999), available at URL: http://www.waterboards.ca.gov/waterrights/water_issues/programs/water_transfers/docs/watertransferguide.pdf; see also generally California Department of Water Resources, ***DRAFT - Water Transfer Approval: Assuring Responsible Transfers*** (2012), available at URL: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/State-Water-Project/Management/Water-Transfers/Files/Draft-2012-Responsible-Water-Transfers-010620.pdf; Cal. Water Code § 1706.

28 See e.g., "Meter and Telemetry Requirements and Rebate," ***McMullin Area Groundwater Sustainability Agency***, URL: https://www.mcmullinarea.org/rebate/; "Sustainable Groundwater Management Act Reporting and Fees," ***California State Water Resources Control Board***, URL: https://www.waterboards.ca.gov/water_issues/programs/sgma/reporting_and_fees.html.

29 See, e.g., California State Water Resources Control Board, Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary (December 12, 2018), available at URL: https://www.waterboards.ca.gov/plans_policies/docs/2018wqcp.pdf; "Bay-Delta Watershed," ***California State Water Resources Control Board***, URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/.

30 See generally Interstate Council on Water Policy, A Primer: Interstate Water Resource Management Agreements and Organizations (December 2020), available at URL: https://icwp.org/wp-content/uploads/2020/12/Primer_ICWP-Interstate-Water-Agreements_FINAL_12_18_2020.pdf.

31 See id. at 5; see also, e.g., International Boundary and Water Commission, United States and Mexico, Fact Sheet: Minute 319 Environmental Flow (2014), available at URL: https://www.ibwc.gov/wp-content/uploads/2023/04/Min319_Fact_Sheet.pdf.

32 See, e.g., Rio de Chama Acequia Association and Rio Arriba County, in collaboration with La Calandria Associates, Inc., Regional Water Plan Rio Chama Watershed, Chapter 3: Legal Issues (2006), available at URL: https://www.ose.nm.gov/Planning/RWP/14_RioChama/2006/3-Legal-Issues.pdf.

33 ***Water balance models can be very helpful. However, it is important to acknowledge the inherent uncertainty associated with the various methods used to quantify stores and fluxes of water in space and across time.*** See Moyers et al., supra note 21.

34 See, e.g., C.D. Pérez-Blanco, A. Hrast-Essenfelder, and C. Perry, C., "Irrigation technology and water conservation: A review of the theory and evidence," 14 ***Review of Environmental Economics and Policy*** 216–239 (2020), available at URL: https://doi.org/10.1093/reep/reaa004.

35 See, e.g., N. Green Nylen, D. Owen, J. Harder, M. Kiparsky, and M. Hanemann, ***Managing Water Scarcity: A Framework for Fair and Effective Water Right Curtailment in California*** (2023), available at URL: https://www.law.berkeley.edu/curtailments/.

36 See Utah Code Ann. §§ 73-5-4, 73-5-8; Utah Admin. Code r.309-105-15, r.655-15-11, r.655-17-1 to r.655-17-5.

37 See N.M. Stat. Ann. §§ 72-2-1, 72-2-8, 72-2-9, 72-2-9.1, 72-2-9.2, 72-5-20, 72-5-26; N.M. Code Regs. §§ 19.25.13.10, 19.25.13.20; New Mexico Office of the State Engineer, Statewide Groundwater Measurement Standards and Specifications (April 2, 2018), available at URL: https://www.ose.nm.gov/RulesRegs/Measurement/StatewideGWstndspecs_2018_signed.pdf; see also, e.g., Office of the State Engineer, Order No. 168: In the Matter of the Requirements for Metering Groundwater Withdrawals in the Lower Rio Grande Watermaster District, New Mexico (December 3, 2004), available at URL: https://api.realfile.rtsclients.com/PublicFiles/5f809ddfc9864dad89f9d03375144a14/9a82904d-ba90-434b-92ea-6e1d44bdf404/ose%20order%20168.PDF; Office of the State Engineer, Order No. 184: In the Matter of the Requirements for Metering Surface Water Diversions in the Mimbres Water Master District, New Mexico (June 12, 2013), available at URL: https://api.realfile.rtsclients.com/PublicFiles/5f809ddfc9864dad89f9d03375144a14/c221c303-4de0-4fbe-9252-4f1a53f03952/OSE%20Order%20184.pdf.

38 See Cal. Water Code §§ 1840–1841.5 (Senate Bill 88, 2015); Cal. Code Regs. tit. 23, §§ 931–938; "Water Measurement and Reporting Regulation," *California State Water Resources Control Board*, URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/diversion_use/water_measurement.html.

39 See Cal. Code Regs. tit. 23, § 935; "Alternative Compliance Plans," *California State Water Resources Control Board*, URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/measurement_regulation/acp_list.html. ***For example, the Delta Alternative Compliance Plan allows agricultural diverters within the Sacramento-San Joaquin River's "Legal Delta" to submit satellite-based evapotranspiration (ET) estimates of consumptive use in lieu of diversion data.*** See "About Delta ACP," *Delta ACP*, URL: https://deltaacp.com/about.

40 ***Within the Delta region, most crops are grown below sea level on islands formed by a network of levees and irrigated with turbid water that is siphoned from the surrounding tidally influence channels, while water seeps in as well as out through the levees, resulting in a complex hydrologic environment where the traditional means of measuring diversions (flow meters) would not meet the state's accuracy requirements and would be expensive to maintain.*** See W. Carrara and G. Amidi-Abraham, "In a statewide first, California is using satellite-based ET data for water use reporting in the Delta," *OpenET* (June 27, 2023), URL: https://openetdata.org/in-a-statewide-first-california-is-using-satellite-based-et-data-for-water-use-reporting-in-the-delta/.

41 About Delta ACP, supra note 39; see also CDWA and SDWA Delta Alternative Compliance Plan (Delta ACP) (December 21, 2021), available at URL: https://www.waterboards.ca.gov/water_issues/programs/delta_watermaster/docs/deltaacpfinal.pdf.

42 **For more about OpenET, see** Forrest S. Melton et al., "OpenET: Filling a Critical Data Gap in Water Management for the Western United States," 58(6) *JAWRA* 971–994 (2022), available at URL: https://doi.org/10.1111/1752-1688.12956; John M. Volk et al., "Assessing the accuracy of OpenET satellite-based evapotranspiration data to support water resource and land management applications," 2(2) *Nature Water* 193–205 (2024), available at URL: https://doi.org/10.1038/s44221-023-00181-7.

43 See About Delta ACP, supra note 39.

44 "Mission & Vision," *The Colorado River Authority of Utah*, URL: https://cra.utah.gov/mission-vision/.

45 Bowen Collins & Associates and Jones & DeMille Engineering for The Colorado River Authority of Utah, *Metering and Gaging Gap Analysis Volume 1 Report* (June 2023) [hereinafter **Gap Analysis**], available at URL: https://cra.utah.gov/2023/09/20/metering-and-gaging-gap-analysis/.

46 See id. at ES-1 to ES-2.

47 See "Management Plan & Annual Workplan," *The Colorado River Authority of Utah*, URL: https://cra.utah.gov/management-plan/.

48 See, e.g., M. Kiparsky, K. Miller, P. Goulden, A. Milman, and D. Owen, "Groundwater Recharge for a Regional Water Bank: Kern Water Bank, Kern County, California," 5 ***Case Studies in the Environment*** 1223400 (2021), available at URL: https://doi.org/10.1525/cse.2021.1223400.

49 Id. at 4–6.

50 Id. at 6.

51 Id. at 6.

52 See Utah Code Ann. §§ 73-3-3, 73-3-30 (amended by House Bill 33 (2022)); see also Utah Code Ann. §§ 73-31-104(2)(d), 73-31-203(2)(b), 73-31-501 (added by Senate Bill 26 (2020)); A. Wildeman, S.J. Page, and T. Pepper, "Strategies to Secure Water for Great Salt Lake: Public Support and Survey Results," 237 ***The Water Report*** 8–21 (2023), available at URL: https://www.thewaterreport.com/wp-content/uploads/TWR-237.pdf; B. Lane and D. Rosenberg, Expanding Instream Flows to Protect Ecosystems in Overallocated River Basins (2019), Utah State University, available at URL: https://digitalcommons.usu.edu/water_rep/678/. ***For more on water trading in Utah, see the resources available at*** "Water Marketing Strategies & the Utah Water Banking Act," ***Utah Division of Water Resources***, URL: https://water.utah.gov/water-marketing/.

53 See "Price River Water Bank Pilot Project," ***Utah Division of Water Resources***, URL: https://water.utah.gov/water-marketing/price-river-water-bank-pilot-project/.

54 Utah Division of Water Rights, Order of the State Engineer for Fixed Time Change Application Number 91-3 (f48448), December 15, 2022, available at URL: https://www.waterrights.utah.gov/docImport/0649/06495713.pdf.

55 See Green Nylen et al. 2023, supra note 35, at 56–57, 59, 66–70, 74–76, 79 (Table 14); Cal. Code Regs. tit. 23, § 875.6, 875.8, 879, 917; Cal. Water Code § 1707; Small Watershed Instream Flow Transfers (SWIFT) Working Group, ***A Practitioner's Guide to Instream Flow Transactions in California*** (2016) [hereinafter **SWIFT Guide**], available at URL: http://www.calinstreamguide.org/. ***For a list of petitions for instream flow dedication, see*** "Instream Flow Dedication," ***California State Water Resources Control Board***, URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/applications/instream_flow_dedication/.

56 See SWIFT Guide, supra note 55, at 17–19, 30–32.

57 See, e.g., Nick Cahill, "California to Uncloak Water Rights as It Moved Records Online: State Also Aims to Make Water Use Data Readily Available to Public," ***Water Education Foundation*** (January 25, 2024), URL: https://www.watereducation.org/western-water/california-uncloak-water-rights-it-moves-records-online; "State Water Board: Reviewing the State Water Board's actions during the 2014–15 drought years," ***Maven's Notebook*** (February 24, 2021), URL: https://mavensnotebook.com/2021/02/24/state-water-board-reviewing-the-state-water-boards-actions-during-the-2014-15-drought-years/.

58 See, e.g., Escriva-Bou et al., supra note 21, at 11, 15–17.

59 ***Such as can result when water quality and water quantity regulation are siloed.***

60 ***For example, the California Legislature passed new measurement and reporting requirements during major statewide droughts in 2009 and 2015.*** See N. Green Nylen, M. Kiparsky, D. Owen, H. Doremus, and M. Hanemann, ***Addressing Institutional Vulnerabilities in California's Drought Water Allocation, Part 1: Water Rights Administration and Oversight During Major Statewide Droughts, 1976–2016***, at 27, 33–34 (2018), available at URL: https://www.law.berkeley.edu/drought-water-allocation/.

61 See, e.g., id.; Green Nylen et al. 2023, supra note 35 at 105–107; N. Green Nylen, M. Kiparsky, D. Owen, H. Doremus, and M. Hanemann, ***Addressing Institutional Vulnerabilities in California's Drought Water Allocation, Part 2: Improving Water Rights Administration and Oversight for Future Droughts***, at 25–29 (2018), available at URL: https://www.law.berkeley.edu/drought-water-allocation/; Joshua H. Viers, "Hydropower Relicensing and Climate Change," 47(4) ***JAWRA***

655–661 (2011), available at URL: https://doi.org/10.1111/j.1752-1688.2011.00531.x; California State Water Resources Control Board, ***Staff Report: Recommendations for an Effective Water Rights Response to Climate Change*** at 19–27 (2021), available at URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/climate_change/.

62 See, e.g., California State Water Resources Control Board 2023, supra note 22.

63 See Idaho Department of Water Resources, Minimum Acceptable Standards and Requirements for Open Channel and Closed Conduit Measuring Devices at 1 (2023), available at URL: https://idwr.idaho.gov/wp-content/uploads/sites/2/water-measurement/MinAcceptStandards-MeasDevices-2023Update.pdf; U.S. Bureau of Reclamation, ***Water Measurement Manual: A Guide to Effective Water Measurement Practices for Better Water Management*** at 4-8 to 4-9 (2001), available at URL: https://www.usbr.gov/tsc/techreferences/mands/wmm/WMM_3rd_2001.pdf; California State Water Resources Control Board, Measuring Flow in Open Channels (2015), available at URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/measurement_regulation/docs/water_measurement/channel.pdf.

64 See U.S. Bureau of Reclamation, supra note 63, at 11-7 to 11-10.

65 See id.

66 See, e.g., New Mexico Office of the State Engineer, supra note 37, at 1–2 (requiring entities who must measure their groundwater diversions to use a totalizing flow meter that meets certain criteria); California State Water Resources Control Board, Measuring Flow in Pipes and Closed Conduits (2016), available at URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/measurement_regulation/docs/water_measurement/conduit.pdf (***stating that "[t]he Division recommends direct measurements in pipes or closed conduits using flowmeters due to their high degree of accuracy"***); Idaho Department of Water Resources, supra note 63, at 2.

67 See, e.g., U.S. Bureau of Reclamation, supra note 63, at 4-5, 10-1.

68 See id. at 10-1, 14-10 to 14-11.

69 See id. at 10-2, 11-1 to 11-7.

70 See id. at 4-10 to 4-11, 11-7 to 11-10.

71 California State Water Resources Control Board, Measuring Low Flow Rates (2016), available at URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/measurement_regulation/docs/water_measurement/low_flow_rates.pdf.

72 See, e.g., California State Water Resources Control Board 2019, supra note 23.

73 See U.S. Bureau of Reclamation, supra note 63; "Water Measurement and Reporting Regulation: How to Measure Diversions," ***California State Water Resources Control Board***, URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/diversion_use/water_measurement.html#how-to-measure; J. Medellín-Azuara et al., ***A Comparative Study for Estimating Crop Evapotranspiration in the Sacramento-San Joaquin Delta*** (2018), available at URL: https://watershed.ucdavis.edu/delta-et; University of California Agriculture and Natural Resources, Low-Cost Methods of Measuring Diverted Water (2013), available at URL: https://anrcatalog.ucanr.edu/pdf/8490.pdf; Idaho Department of Water Resources, supra note 63; "Water Measurement," ***Idaho Department of Water Resources***, URL: https://idwr.idaho.gov/water-data/water-measurement/; University of California Cooperative Extension, Water Measurement Using a Rectangular or 90º V-Notch Weir (2012), available at URL: https://ceshasta.ucanr.edu/files/141039.pdf; State of Oregon Water Resources Department, ***Legislative Report: Water Use Measurement and Reporting*** (2022), available at URL: https://www.oregon.gov/owrd/WRDReports/OWRD_2022_LegislativeReport_WaterUse_Measurement_Reporting.pdf; California State Water Resources Control Board, Division of Water Rights, ***SB88 and Emergency Regulation for Measuring and Reporting Water Diversions: Average Cost of Measurement*** (2016) [hereinafter **Average Cost of Measurement**], available at URL: https://www.waterboards.ca.gov/waterrights/water_issues/programs/measurement_regulation/docs/measure_cost_tables.pdf.

74 See University of California Cooperative Extension, supra note 73; U.S. Bureau of Reclamation, supra note 63, at 4-5, at 4-10, 4-11, 11-7 to 11-10; State of Oregon Water Resources Department, supra note 73, at 20–21; **Average Cost of Measurement**, supra note 73. California State Water Resources Control Board 2016, supra note 71; U.S. Geological Survey, Techniques of Water-Resource Investigations of the United States Geological Survey: Acoustic velocity meter systems (1985), available at URL: https://pubs.usgs.gov/twri/twri3-a17/pdf/twri_3-A17_a.pdf; "Current Meters: Classes of current meters," U.S. Bureau of Reclamation, URL: https://www.usbr.gov/tsc/techreferences/mands/wmm/chap10_02.html (website, last visited July 16, 2024).

75 See, e.g., Medellín-Azuara et al., supra note 73.

76 See id.

77 See, e.g., Escriva-Bou et al., supra note 7, at 15.

78 See Escriva-Bou et al., supra note 7, at 13.

79 See Escriva-Bou et al., supra note 7, at 15.

80 See, e.g., "Public Access to Public Water System Well Location Information on GAMA GIS," ***California State Water Resources Control Board***, URL: https://www.waterboards.ca.gov/gama/well_location_information.html; "Well Completion Reports," ***California Department of Water Resources***, URL: https://water.ca.gov/Programs/Groundwater-Management/Wells/Well-Completion-Reports; M. Kiparsky, K. Miller, R. Roos-Collins, E. Roos-Collins, and D. Rademacher, ***Piloting a Water Rights Information System for California*** at 18 (2021), available at URL: https://www.law.berkeley.edu/research/clee/research/wheeler/water-data/wris/.

81 See N. Reece Hutley, R. Beecroft, D. Wagenaar, J. Soutar, B. Edwards, N. Deering, A. Grinham, and S. Albert, "Adaptively monitoring streamflow using a stereo computer vision system," 27 ***Hydrology and Earth System Sciences*** 2051–2073 (2023), available at URL: https://doi.org/10.5194/hess-27-2051-2023; J. Viers and N. Santos, "Hydrolapse Videography: A Coupled Hydroinformatic Stack for Improved Visual Assessment of River Dynamics," ***11th International Conference on Hydroinformatics*** (2014), New York City, USA, available at URL: https://academicworks.cuny.edu/cgi/viewcontent.cgi?article=1050&context=cc_conf_hic.

82 See Green Nylen et al. 2017, supra note 4, at 23.

83 See Green Nylen et al. 2017, supra note 4, at 8–9, 28–32; Garrick et al., supra note 4; Wheeler et al., supra note 4, at 811–812; Bruno and Jessoe, supra note 5, at 333–336; Skurray and Pannell, supra note 6; Brozović and Young, supra note 4, at 286–287.

84 See Green Nylen et al. 2017, supra note 4, at 11, 34–39; Heard, Fienup, and Remson, supra note 4, at 54–55; Wheeler et al., supra note 4, at 811–812.

85 See Green Nylen et al. 2017, supra note 4, at ix–x, 32–33; Heard, Fienup, and Remson, supra note 4, at 54; Wheeler et al., supra note 4, at 812; Skurray and Pannell, supra note 6.

86 See Green Nylen et al. 2017, supra note 4, at 11, 34; Wheeler et al., supra note 4, at 811.

87 See Green Nylen et al. 2017, supra note 4, at 34; Heard, Fienup, and Remson, supra note 4, at 53; Bruno and Jessoe, supra note 5.

88 See Self-Help Enterprises, Leadership Counsel for Justice and Accountability, and the Community Water Center, ***Framework for a Drinking Water Well Impact Mitigation Program*** (2022), available at URL: https://www.selfhelpenterprises.org/wp-content/uploads/2022/07/Well-Mitigation-English.pdf; N. Atume and D. Voss-Gonzalez, ***SGMA and Underrepresented Farmers Impact of Groundwater Sustainability Plans on Underrepresented Farmers*** (2022), available at URL: https://cleanwater.org/publications/sgma-and-underrepresented-farmers-impact-groundwater-sustainability-plans; Green Nylen et al. 2017, supra note 4, at 31.

89 See Green Nylen et al. 2017, supra note 4, at 37–39; Heard, Fienup, and Remson, supra note 4, at 55; Wheeler et al., supra note 4, at 812.

PHOTO CAPTIONS

Cover: Groundwater pumping from production wells fills agricultural waterways to irrigate fields in Yolo County, California, August 5, 2024, 2024_08_05_XM_0119_Groundwater_Conaway_Ranch_DRONE.JPG, by Xavier Mascareñas / California Department of Water Resources.

Page 4: A telemetered diversion gate measures flow and controls diversions to a groundwater recharge basin in Fresno County, California, May 13, 2024, 2024_05_13_XM_1046_Groundwater_Recharge.JPG, by Xavier Mascareñas / California Department of Water Resources.

Page 11: *Top:* Diversion gates on Burney Creek in Shasta County, California, July 23, 2024, 2024_07_23_SN_0008_Water_Master_DRONE.jpg, by Sara Nevis / California Department of Water Resources. ***Bottom left:*** Acequia Madre (Mother Ditch) Santa Fe, New Mexico, June 23, 2022, Acequia Madre (Santa Fe) June 2022.jpg, by Netherzone, used under CC BY-SA 4.0. ***Bottom right:*** The Red Bluff Pumping Plant and Fish Screen on the Sacramento River at Red Bluff, California, January 16, 2014, 2014_02_16_PH_0235_Red_Bluff.jpg, by Paul Hames / California Department of Water Resources.

Page 18: Groundwater is pumped to irrigate rice fields in Yuba County, California. Photo taken May 27, 2009, 2009_05_27_DBK_0228_ground_water.jpg, by Dale Kolke / California Department of Water Resources.

Page 26: *Top:* Water flows through a Parshall Flume diversion at Burney Creek in Shasta County, California, July 23, 2024, 2024_07_23_SN_0239_Water_Master.jpg. *Bottom:* A watermaster looks up the flowrate for a diversion using a Parshall Flume table at Burney Creek in Shasta County, California, July 23, 2024, 2024_07_23_SN_0233_Water_Master.jpg. Both photos by Sara Nevis / California Department of Water Resources.

Page 32: Telemetry for groundwater monitoring wells in Colusa County, California, July 25, 2024, 2024_07_25_XM_1105_Groundwater_Telemetry.JPG, by Xavier Mascareñas / California Department of Water Resources.

Page 35: *Top:* The San Luis Reservoir in Merced County, California, August 10, 2021, 2021_08_10_AI_0152_San_Luis_Level.jpg, by California Department of Water Resources. ***Middle-right:*** Water being diverted into a groundwater recharge basin in Fresno County, California, May 13, 2024, 2024_05_13_XM_0001_Groundwater_Recharge.JPG, by Xavier Mascareñas / California Department of Water Resources. ***Middle-left:*** Groundwater wells that are pumping water to flood fields and supply water for waterfowl at Gray Lodge Wildlife Area in Gridley, California, February 24th, 2015, KMG_Gray_Lodge_gw_19340.jpg, by California Department of Water Resources. ***Bottom:*** Canal in Richfield, a city in Sevier County, Utah, August 6, 2007, 1118902929_e58f54a76b_o.jpg, by Ken Lund, used under CC BY-SA 2.0.

Page 44: An egret flies over irrigated rice fields in Colusa County, California, August 23, 2024, 2024_08_23_XM_0529_DRA_Groundwater_Well_Run.JPG, by Xavier Mascareñas / California Department of Water Resources.

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