Title
Resolving the Water Crisis: There's a Way, But Is There the Will?

Journal
Ground Water, 61(5)

ISSN
0017-467X

Authors
Kram, Mark
Loaiciga, Hugo
Widdowson, Mark
et al.

Publication Date
2023-09-01

DOI
10.1111/gwat.13310

Peer reviewed

Groundwater

Issue Paper/

Resolving the Water Crisis: There's a Way, But Is There the Will?

by Mark Kram[1], Hugo Loaiciga[2], Mark Widdowson[3], Eduardo Mendez[3], Ryan Solgi[2], and Michael Lamar[4]

Abstract

In this issue paper, the authors refine the definition of water sustainability to account for temporal dynamics and spatial variability, identify specific challenges that must be resolved in the very near future to avoid catastrophic outcomes on levels ranging from economic disruption to survival of mankind, discuss related policy changes and potential effectiveness, and describe several technologies available to achieve water security and sustainability. While water quality certainly poses formidable challenges, in this piece we emphasize and address challenges associated with dynamic water supply availability. Our future as a society will depend upon how well and how rapidly we navigate these challenges in the coming years. As such, the main objective is to encourage private and public sector practitioners to consider revising existing programs, and to update current industry business models in a manner that promotes expedited solutions, alignment of beneficial goals, and motivates the biggest consumers of water to adopt modern data collection and decision support technologies.

Introduction

Over the past several years, many have experienced extreme challenges associated with surface water and groundwater shortages. Hardly a day goes by without a mainstream media story about water stresses or related occurrences such as extended drought, fire, or loss of anadromous fish populations. Basin overdraft, stream depletion, land subsidence, and sea water intrusion are becoming more common, and not just in the Western United States (see, e.g., Zektser et al. 2005; Konikow 2013; Bozorg-Haddad et al. 2020). One-sixth of the world's population live in severely constrained agricultural areas (Food and Agriculture Organization of the United Nations 2020) while more than 1.4 billion people currently live in areas of elevated water vulnerability (UNICEF 2021), which can result in community relocations and even armed conflict (Shatanawi 2015). Water shortages, lack of food, and increases in food prices due to water shortages have resulted in political instability and regime change in several Middle Eastern nations. Water shortages have been cited as key factors contributing to the Arab Spring (Shatanawi 2015). In the United States, unsustainable water management practices are commonly resulting in legal actions as public trust resources are pitted against the needs of the food industry, municipalities and even the energy sector. In the center of the arguments are claims to water rights often procured more than a century ago when demand for the precious blue gold was far less. Water trades are being conducted via stock market players who only track demand-related pricing without regard to externalities such as depletion of surface and groundwater supplies or erratic climatic patterns (Rubio-Velázquez et al. 2023). The status quo is resulting in catastrophic water shortages, impulsive rather than proactive activities, and precarious situations in some of the most important food-growing and energy-producing regions and population centers of the world (James 2022;

[1]Corresponding author: Groundswell Technologies, LLC, 7127 Hollister Avenue, #25A-108, Goleta, CA 93117; 805-899-8142; mark.kram@groundswelltech.com

[2]Department of Geography, University of California at Santa Barbara, 3626A Ellison Hall, Santa Barbara, CA

[3]Department of Civil and Environmental Engineering, Virginia Tech, 220-A Patton Hall, Blacksburg, VA, 24061

[4]Abbaroo.com, 6039 Plateu Drive, Felton, CA, 95018

Article impact statement: Our future as a society will depend upon how well and how rapidly we navigate water resource challenges in the coming years.

Received August 2022, accepted March 2023.

doi: 10.1111/gwat.13310

Limón and Blasey 2022; Partlow 2022; Singh 2022). This situation is at least partially solvable using technologies available today. However, is society in general, and are specific industry players willing to make the drastic changes that will be required to assure that water supplies will be sufficient to meet the multitude of demands in perpetuity? Given how humans cannot survive without water, this could very well prove to be the most important decision we make as a species.

The main objective of this paper is to encourage sustainable groundwater and surface water supply management that leverages off technologies that include automation and improvements to data access, processing, visualization, and response capabilities. Successful implementation will result in expedited stakeholder understanding of complex dynamic processes and the ability to address pending challenges with proactive measures. To achieve this, the authors refine the definition of sustainability to account for temporal dynamics and spatial variability. Specific challenges are identified that must be resolved in the very near future to avoid catastrophic outcomes on levels ranging from economic disruption to survival of mankind. Related policy changes and potential effectiveness are also discussed, and several technologies available to achieve water security and sustainability are described. Our future as a society will depend upon how well and how rapidly we navigate these challenges in the coming years.

What Is Sustainability?

If the goal is water "sustainability," we must define this and reach a consensus on the definition. The United Nations (UN) established sustainable development goals and a related agenda to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (UN, 2022; https://www.un.org/sustainabledevelopment/development-agenda/). Furthermore, they state that "For sustainable development to be achieved, it is crucial to harmonize three core elements: economic growth, social inclusion, and environmental protection. These elements are interconnected and all are crucial for the well-being of individuals and societies." The authors aim to place a finer point on the water component, as a sustainable water supply is essential for each of the three core elements identified by the UN. More specifically, the authors believe that the term "water sustainability" refers to a condition whereby sufficient water is available at all times in surface and groundwater resources to maintain vibrant ecosystems and economies in perpetuity. Given that temporal dynamics and spatial variabilities are inherent in the challenges associated with seasonal agricultural requirements, anadromous fish migrations and rearing requirements, municipal and industrial needs and uncertainties associated with drought, this simple but targeted definition is meant to be all-encompassing in that water sustainability requires that water supplies are always available when and where needed (see also, Alley and Leake 2004). In contrast, basin overdraft reflects an unsustainable condition whereby anthropogenic forces (e.g., extractions exceeding infiltrations over long periods of time) have negatively impacted natural water cycles to the point that groundwater levels dropped below sustainable levels. This can result in extraction wells going dry, stream depletions that threaten aquatic habitat and fish migrations (Brunke and Gosner 1977; Barlow and Leake 2012), land subsidence (see, e.g., Galloway and Burbey 2011; Borchers et al. 2014), desertification (Chen et al. 2006), and sea water intrusion (see, e.g., Loáiciga and Pingel 2012) that renders coastal groundwater resources unusable without expensive treatment.

Progress To-Date

While some of the recent efforts by GRACE (Famiglietti 2014; Rateb et al. 2020) satellite data processing and imagery have given humans a unique large-scale (i.e., continental or global scales) perspective of the changes in shallow groundwater supply over time and space, most water industry professionals acknowledge that water-stress challenges span local and regional scales. These scales generally govern the jurisdiction over groundwater, which is commonly tied to the groundwater-basin scale. Besides the relevance of spatial scales, water challenges are also time-dependent. For instance, at certain times of the year, snow melt yields runoff that is synchronous with fish migration timing and other surface water habitat cycles (California Department of Fish and Wildlife 2017). However, many agencies issue permits that track annual extractions via self-reporting. For instance, the California Sustainable Groundwater Management Act of 2014 (SGMA) was adopted in response to overdraft in the Central Valley (where groundwater storage declined by about 70 km^3 between 1962 and 2003 [Scanlon et al. 2012]) and the lack of knowledge about the volumes of groundwater withdrawal or long-term impacts in many other basins. As such, SGMA dictates that every year on April first, Groundwater Sustainability Agencies (GSAs) organized for high- and medium-priority groundwater basins shall submit a report to the Department of Water Resources containing the following information about the basin managed in their groundwater sustainability plan:

1. Groundwater elevation data.
2. Annual aggregated data identifying groundwater extraction for the preceding water year.
3. Surface water supply used for or available for use for groundwater recharge or in-lieu use.
4. Total water use.
5. Change in groundwater storage.

SGMA has resulted in agency and consulting activity that includes data collection, modeling, reporting, and review. SGMA, however, does not mandate high-frequency measurement of groundwater withdrawal at each extraction well, which is the key variable for determining basin-wide groundwater extraction impacts for specific temporal aggregations (e.g., seasonal, annual, during drought situations, etc.). Specifically, SGMA reads as follows in this respect: "A groundwater sustainability agency *may require* through its groundwater sustainability plan that the use of every groundwater extraction facility within the management area of the groundwater sustainability agency be measured by a water-measuring device satisfactory to the groundwater sustainability agency." Thus, the GSAs may choose to, but also may choose not to, require the measurement of well extractions. At this time there are no publicly available data of well withdrawals for private wells in medium- and high-priority basins in California. Of special concern is groundwater withdrawal by agricultural wells in California's Central Valley. Agriculture is the major user of groundwater in California (Dieter et al. 2018). Municipal water purveyors in high- and medium-priority basins measure groundwater withdrawal in their wells for reporting on an annual basin to the California Department of Water Resources. Furthermore, GSAs exempt *de minimis* users (i.e., those who use two acre-feet of groundwater annually or less) from any reporting. In some groundwater basins in California the density of *de minimis* water wells exceeds 100 wells per square mile, which may place a small groundwater basin in overdraft due to the occurrence of frequent droughts and erratic recharge (Loáiciga 2015).

The State of Arizona shares in part its water fortunes and water management misfortunes with California. The two states receive water from the Colorado River through a complex interstate and binational water compact (Rubio-Velázquez et al. 2023). Arizona, like California, has attempted to rein in groundwater overdraft that reached 2.5 million acre-feet annually in 1968 with lowering of aquifer levels between 300 and 400 ft in some areas (McGreal and Eden 2021). The Arizona Groundwater Management Act (GMA) was enacted in 1980 to monitor and regulate groundwater use to preserve this source of water supply. The GMA focused on Irrigation Non-expansion Areas (INAs) and Active Management Areas (AMAs) where groundwater overdraft was severe. Development of new irrigated agricultural land is prohibited in the INAs, where anyone withdrawing more than 10 acre-feet of groundwater per year must report groundwater withdrawals annually to the Arizona Department of Water Resources. The AMAs are subjected to the management goal of achieving safe yield withdrawal by 2025. Operationally, this means that there are conservation requirements that limit groundwater use, and any well capable of pumping more than 35 acre-feet per year (or non-exempt wells) must measure and report pumping. In addition, a right or permit must exist for every acre-foot of groundwater withdrawn within AMAs, except for exempt wells. A permit must be obtained to drill a non-exempt well, and residential growth in the AMAs is allowed only if the legal, financial, and physical capability to provide enough good-quality water to supply the development for 100 years is demonstrated. In spite of the GMA's accomplishments, Arizona continues to experience significant problems with respect to groundwater management. For instance, the scientific recognition of the connectivity between groundwater and surface water has not been integrated into Arizona water law; a situation that also persists in California and whose origin dates back to an erroneous understanding of surface water/groundwater interactions (Kinney 1894). Moreover, Arizona continues to experience overdraft throughout the state (Colby et al. 2007), which is due in part to "grandfathered" water rights that existed pre-1980 and to insufficient monitoring of groundwater withdrawals (Ferris and Porter 2021).

Another example of the statutory reluctance to enforce well metering is the State of Texas, where groundwater law has evolved, driven by the outcomes of court cases and by legislative action (Hardberger 2019). Groundwater conservation districts (GCDs)—in some respects the precursors of California's GSAs—constitute the preferred method for groundwater management in Texas. The Edwards Aquifer Authority (EAA), however, is a special district created by the Texas legislature to comply with a federal mandate to protect groundwater-dependent ecosystems (GDEs) in the Edwards Balcones Fault Zone Aquifer. GCDs may require the installation of well meters and the reporting of groundwater withdrawals. Texas law exempts livestock and domestic wells from permitting requirements, except for those under the EAA's jurisdiction. The EAA does not require metering of livestock and domestic wells. Another difference between the GCDs and the EAA is that the latter imposes a cap on annual groundwater withdrawal within its jurisdiction. The Edwards Aquifer Balcones Fault Zone's basin yield was initially calculated to be 400,000 acre-feet/year (Loáiciga and Schofield 2019); yet it was later increased to 572,000 acre-feet/year (Hardberger 2019).

In Israel, where water stress due to limited access to fresh water resources has been amplified by climate uncertainty and a growing population, institutional and regulatory reforms combined with infrastructure investment are part of a multi-pronged long-term master plan. In 2011, the State of Israel Water Authority adopted their Master Plan for the National Water Sector, which outlines many components aimed at achieving water security by 2050. These components include extensive water metering, strict quotas and enforcement, streamlined water conveyance technologies, desalination, wastewater treatment, and leak detection and prevention technologies throughout the water distribution system (Israel Water Authority 2011). Plans aimed at ecosystem restoration and sustainability have also been adopted.

Are We There Yet?

The type of groundwater use reporting required by SGMA represents a good start and a genuine attempt by the most populous state in the United States to protect groundwater. Yet, the required data collection and reporting are not sufficiently detailed or of adequate frequency if the ultimate goal is to create a sustainable water supply and to ensure that sufficient streamflow and groundwater storage are available at key times of the year. On the one hand, SGMA requires the formation of GSAs in high- and medium-priority groundwater basins to achieve sustainable groundwater management. On the other hand, SGMA does not require that the water use by groundwater-extraction entities within their jurisdiction be measured at a high frequency, thus leaving open the possibility of continuing uncertainty about the status of groundwater storage or changes over time and space. Model simulations are data-starved and hindered by poor three-dimensional characterization of layered aquifers. Detailed cause-and-effect relationships for specific extraction wells and networks of wells continue to be poorly understood, or perhaps impossible to determine given the SGMA data and reporting requirements and the modeling assumptions. More specifically, individual well or aggregated well network impact assessments are not generally considered or even possible. As such, agencies continue to issue groundwater extraction well permits even when basins and riparian zones are documented to be over-drafted. This lenient attitude may be rooted in the ancient misconception that groundwater flow that reaches seas, lakes, and wetlands is wasted water that could otherwise be put to economic use. This perspective remains deeply entrenched in the water industry and does not consider requirements associated with GDEs and the preservation of hydraulic gradients from the land toward the seas to prevent sea water intrusion. This misconception creates institutional resistance by water purveyors to modernize and diversify their water portfolios in favor of water reuse, managed aquifer recharge (MAR) (Dillon et al. 2019), and sea water desalination powered by renewable energy (Loáiciga 2015) while parting from unsustainable and environmentally deleterious groundwater withdrawals.

While there are many well-intended practitioners working to follow the guidance, it is highly probable that SGMA will not result in sustainable groundwater resources or prevent surface water depletions resulting from groundwater extractions in the near term. One analogy would be where every citizen in a watershed shares a single bank account and is able to withdraw funds at-will without having to report withdrawals more than once per year, and that report covers all the transactions over the previous 12 months. This frequency of reporting could result in an account overdraft. The analogy is that just as most banks issue monthly statements and provide up-to-the day status reports on an as-needed basis to allow businesses and individuals to reconcile their account, groundwater monitoring should render similar services and value to groundwater managers. Given all the uncertainty regarding cause-and-effect correlations that might be discovered through a cumulative impact assessment or as a requirement to document impacts for proposed new wells, should we require more prudent and high-frequency data collection and reporting options? It is noteworthy that California's SGMA requires that groundwater sustainability plans be developed for adversely-impacted groundwater basins. However, the GSAs have 20 years to achieve sustainability in the basin from the time they start implementing their groundwater sustainability plans. Many groundwater basins in critical condition and their dependent groundwater ecosystems may be ruined in less than 20 years.

Selected Critical Questions

Before solutions can be derived and implemented, it is critical to ask key questions and have the answers to these questions inform and potentially drive responses and policies.

- What are the maximum sustainable extraction rates for every well in the system that would prevent basin overdraft, sea water intrusion, land subsidence, or stream depletion?
- How much did groundwater storage change (spatial and volumetric) over any timeframe of interest?
- What is the current groundwater level and supply (available storage) relative to critical thresholds and future objectives?
- What are the cumulative impacts of groundwater extractions on storage as well as nearby surface water bodies and sensitive ecosystems?
- How much lost storage due to subsidence, inelastic deformation and disconnected pore space is recoverable and what type of performance testing is required to evaluate this?
- What is the maximum groundwater extraction rate for any well in the network that would still allow for meeting future needs dictated by dynamic population and industrial demand?
- How well are models calibrated over multiple time horizons? Where do predictions best match observations and where do adjustments need to be made?
- Are the MAR efforts meeting sustainability objectives?
- Can these questions be answered in a timely manner given the current data collection and processing and reporting requirements? If not, what additional data, policies, and technology will be required to achieve water sustainability?

What Can We Do Today?

In "The Future is Faster Than You Think" (Diamandis and Kotler 2020), the authors describe how the confluence of accelerating technological advancements will impact society over the next few years. The water industry could serve as a perfect example of this rapid advancement . . . *provided there is a collective will to do so*. For instance, sensors, telemetry, geographical information systems (GIS), Cloud-based data processing and reporting and other developments have become common tools of the water trade. However, for various reasons and with few exceptions, these modern tools are currently used in piecemeal configurations representing project-specific data silos. With appropriate support, these tools represent a pathway forward that could forever change the way we understand and sustainably manage critical water resources.

A useful resource includes the U.S. Geological Survey's National Groundwater Monitoring Network (NGWMN; https://water.usgs.gov/ogw/networks.html). This portal includes water level data from thousands of wells in the United States. This extensive resource can be leveraged to help develop strategies, model simulations, model calibration efforts, and to identify areas where more data can be helpful. This resource could prove to be invaluable for programs such as Duke University's Internet of Water effort (https://internetofwater.org), which aims to modernize water data infrastructure to more effectively and efficiently manage water supplies and enable greater access to critical data.

One extension of this is represented by the Groundwater Basin Storage Tracking (GBST; https://www.groundswelltech.com/WSPGBST.aspx) platform developed by several of the authors (Figure 1). GBST is a Cloud-based automated geospatial processing and visualization platform that enables users to rapidly (e.g., within seconds) estimate changes in available groundwater storage, evaluate geospatial and volumetric trends relative to critical thresholds and established water supply goals. GBST can also assist with model calibration and evaluation of MAR effectiveness. The platform can serve as a basin-wide or even regional data repository for water level and storage change. GBST is already integrated with the entire NGWMN, and additional water level sensors can be added to fill data gaps in critical basin locations. When relying upon groundwater level to derive storage change, practitioners must not forget to consider loss of available storage due to non-elastic deformation caused by excessive groundwater extractions (Alley 2007). Future amendments will include ground-breaking neural-network and machine learning components for future predictive analyses (Solgi et al. 2021).

Some of the authors have also developed what is referred to as the Water Sustainability Platform (https://www.groundswelltech.com/WSPWSP.aspx; Figure 2). This Cloud-based platform merges classical hydraulic theory with game theory and sensors to determine in near real-time the maximum sustainable groundwater extraction rates to prevent basin overdraft, stream depletion, and sea water intrusion. This type of platform requires an understanding of critical water level thresholds and, for preventing stream depletion, minimum sustainable surface water flow rates. This platform requires water level and extraction rate data delivered at a high frequency (e.g., up to the minute) to preemptively respond either through automated alerting or adjustment of extraction rates within a network. The platform can also be used to predict the impacts of proposed extraction wells prior to issuing permits. As with GBST, the Water Sustainability Platform is sensor-neutral and vendor-neutral. Integration only requires mapping vendor-specific data file format and schema to the kernel database. As such, current water level and well meter networks equipped with telemetry can be integrated for automated tracking, reporting and response.

These and other types of automation solutions exist today. There is no shortage of experienced hardware and software vendors who can install monitoring networks within days. The integration of sensors with automated model update and response (what many commonly refer to as "Artificial Intelligence," or "AI") has been impacting human decisions for decades. Applying this type of design toward an even more grand objective that aims to create true water sustainability is not only possible, but it can also be applied now (Figures 1 and 2).

Barriers to Entry

The available solutions have only been implemented on a limited basis. The reasons have to do with several key barriers to entry. Some of these are political, some are related to the economics of disruptive technologies, and others are based on the lack of willingness to change course through regulatory action and an acknowledgment that if we maintain the current water resource allocation and monitoring policies, fundamental societal challenges could rapidly become overwhelming and unmanageable.

First and foremost, policies must acknowledge that natural water cycles operate on a continuous dynamic basis with many interdependent components. As such, reporting water levels and extraction rates on an annual frequency *after the fact* does not allow for rapid understanding or proactive intervention sufficient to maintain sustainability. The frequency of data collection must increase. High-frequency, sensor-based, data collection, and multivariate processing would also allow for higher resolution understanding of cumulative impacts and cause-and-effect correlations between controlling factors and observations. Processing should allow for intuitive understanding of trends and rapid response. The GRACE images are a great example of this type of processing, as they readily convey critical information to a broad swath of industry players and stakeholders with varying levels of hydrogeologic training.

As with most disruptive technologies, we note that the current state of the consulting profession adamantly resists rapid change. More specifically, most water and environmental consulting firms employ a business model based on billable hours. While some innovative firms have integrated sensor technologies, many firms are very protective of their billable hour business model. As such, resistance to automation has prevailed for several decades, as automation reduces labor requirements through increased efficiencies. We currently note that much of the labor is allocated toward data collection, processing, predictive simulations, and report preparation—precisely the key functions that the Cloud and AI are well-equipped to address with far greater efficiency. The Cloud and AI can also automate responses that range from automated alerts to engagement of machines.

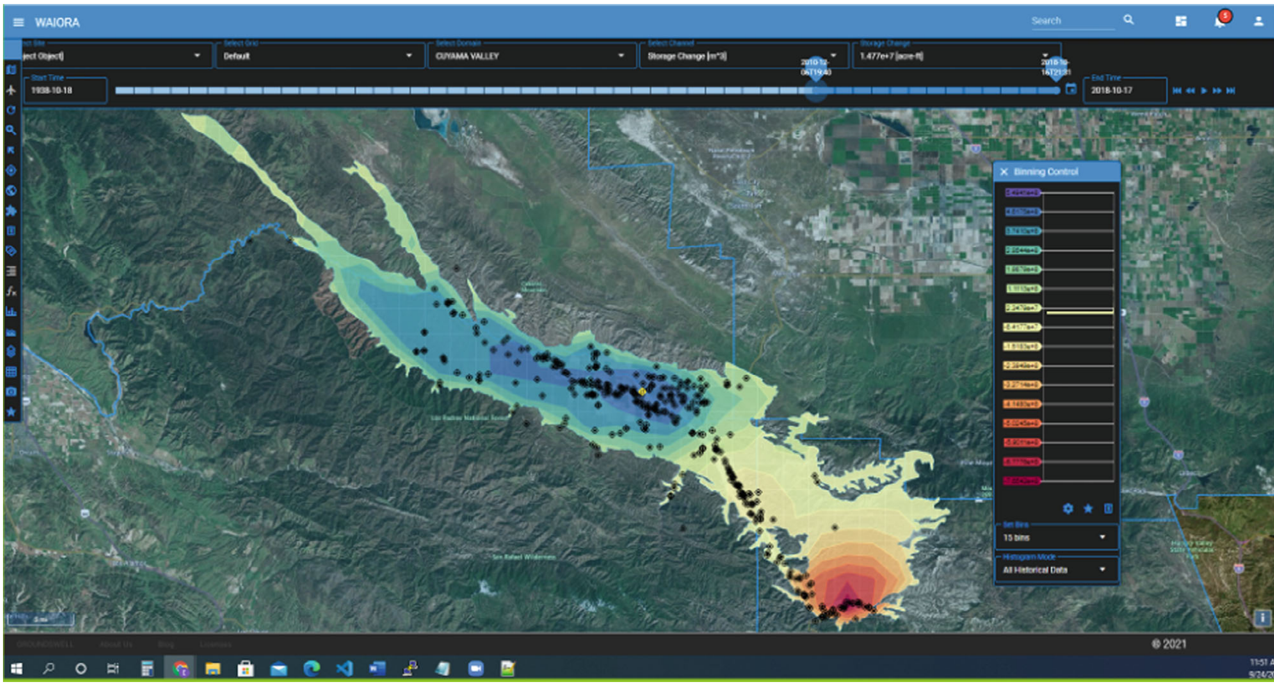

Figure 1. Screenshot of Groundwater Basin Storage Tracking (GBST) Output. Using only U.S. Geological Survey (USGS) water level sensor data, this image shows the distribution of, and estimated cumulative change in aquifer storage between December 6, 2012, and October 16, 2018. This analysis takes only seconds to generate.

This observation is not intended to be an indictment of the consulting industry. On the contrary, by bringing attention to this systemic challenge, our goal is to stimulate open dialog and identify approaches that reward expediency and long-term low-maintenance resolution of pressing water supply issues. As a society, we must come up with a way to break through this resistance by encouraging firms (and agencies) to adopt more efficient and effective solutions. We continue to use the 20th century approaches to address a 21st century set of challenges. Based on the current situation in critical food-producing regions that rely on groundwater resources, we appear to be at a tipping point. The status quo is therefore insufficient, as response times for traditional labor-intensive approaches preclude us from successful intervention prior to catastrophic impacts. The question becomes one of how best to align stakeholder objectives in an efficient and effective manner that results in water sustainability as defined above.

Perhaps the key to this profound challenge lies in the hands of policy makers and regulators tasked to implement these policies. More specifically, there is an overwhelming acknowledgment that there is a need for more data, yet many groundwater extractors resist any suggestion that meters be installed on their wells, or that nearby monitoring wells be installed and equipped with water level sensors to calibrate simulations and evaluate dynamic impacts relative to dynamic extractions and stream flows. This is understandable, as there is fear that allocations could be reduced. Most extractors will not voluntarily meter their wells or integrate telemetry for automated real-time upload to a dynamic "living" iterative model designed to answer specific questions. Policy makers must be willing to make the difficult decisions regarding extraction well metering and water level monitoring. If they are unwilling to enforce this for current extractors, at a minimum, this could be required for all future extraction well permit applicants. If we are unable to base decisions upon good quality and timely information, we will not resolve the many challenges we face as a society due to water shortages any time soon. A thorough review of water rights must also be performed, and changes adopted to allow for more flexibility or even adjustment based on what the natural systems can tolerate combined with anticipated needs based on prevailing and predicted climatic patterns and population increases. The creation of GCDs in Texas, GSAs in California, and AMAs in Arizona demonstrate that legislation has been effective in curtailing water rights that threatened groundwater sustainability. Experience to-date also reveals that monitoring of groundwater use must be enforced to achieve groundwater sustainability. This will not be an easy undertaking, but it is essential.

Moving Forward

Dr. Luna Leopold is a widely acknowledged pioneer of sustainable water resources management (USGS 2015). He served as the first Chief Hydrologist for the USGS. Many decades ago he stated that "Water is the most critical resource issue of our lifetime and our children's lifetime. The health of our waters is the principal measure of how we live on the land." His words have never been more relevant.

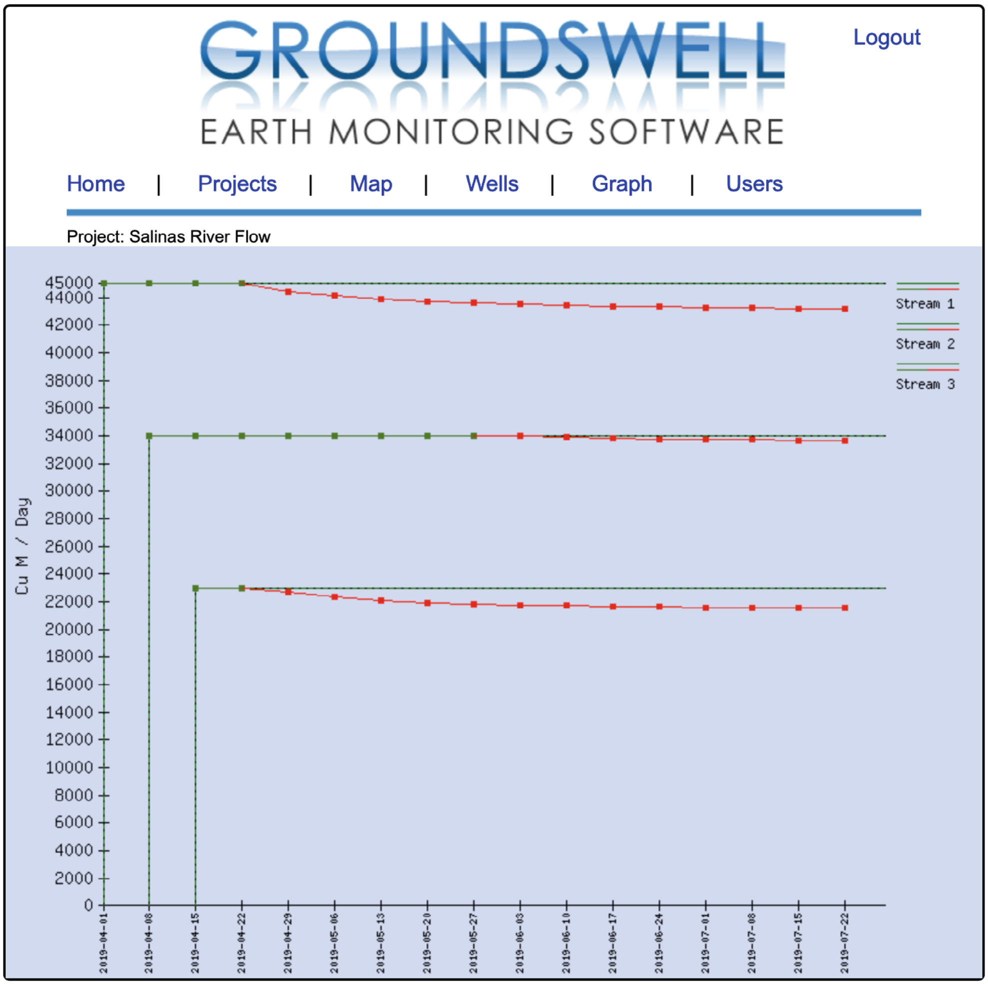

Figure 2. Screenshot of Water Sustainability Platform to Prevent Stream Depletion. The Optimized Well-Stream Interaction System (OWSIMS) module tells practitioners when specific wells will become unsustainable (e.g., result in stream flows below established ecological thresholds) given the current extraction rates (in cubic meter/day). In this case, three wells in the hyporheic zone will result in stream depletions at various future times given the amount of dynamic up-reach flow, proximity to the stream, extraction rates, hydrogeologic factors and cross-sectional areas of the stream adjacent to each of the wells.

We have described a few, but important water resource management challenges we face at this critical time. The status quo is not sustainable and is not working, as we are depleting water resources in areas with profound economic and ecological value. This touches almost every facet of society. Food, energy, biodiversity, security, health and safety, and even the survival of the human species itself all depend upon secure and sustainable water supplies. According to the United Nations (https://www.un.org/sustainabledevelopment/water-and-sanitation/), worldwide one in three people do not have access to unpolluted drinking water. We are convinced that while recent technical and policy advances are impressive, they are not yet able to resolve these challenges and will most likely never be sufficient to achieve the stated programmatic goals regarding water sustainability.

We have described a few of the solutions that allow us to answer select critical questions and establish a change in the societal trajectory toward a sustainable water supply that is sufficiently robust to enable rapid adaptation to dynamic conditions as they arise. These solutions involve the automated collection and processing of significantly more data, implementation of superior models, integration of live sensor data with real-time modeling (and calibration) and decision support tools aimed at answering very specific questions about maximum sustainable extraction rates and impacts on groundwater storage that have the potential to vastly improve the current water supply situation. Several of these tools exist today. Each situation will require site-specific decisions regarding measurement frequency, spatial density, and hardware maintenance. These will be dictated by project-specific objectives. For instance, seasonal considerations for anadromous fish migrations may require relatively higher frequency monitoring of stream gauges, extraction rates, and water levels in hyporheic zones for critical tributaries in the mid to late Spring.

Annual support for the expansion of the USGS NGWMN (and similar international programs) and integration with other public and private well and sensor networks can lead to continuous overall improvement with respect to analytical capabilities, accuracy, and model calibration. Given that Cloud capacity for data storage, organization, and processing continues to improve, "data inundation" could someday become a thing of the past. However, without the formidable will (and the courage to make difficult decisions) supported by strong policies aimed at implementing appropriate automation solutions in the near term, we will only partially resolve these challenges and may not achieve water sustainability before economic and environmental chaos ensues. Our future as a society will depend upon how well we navigate these challenges in the coming years.

Authors' Note

The authors do not have any conflicts of interest or financial disclosures to report.

References

Alley, W.M. 2007. Another water budget myth: The significance of recoverable ground water in storage. *Groundwater* 45, no. 3: 251.

Alley, W.M., and S.A. Leake. 2004. The journey from safe yield to sustainability. *Groundwater* 42, no. 1: 12–16.

Barlow, P.M., and S.A. Leake. 2012. Streamflow depletion by wells – Understanding and managing the effects of groundwater pumping on streamflow. United States Geological Survey Circular 1376.

Borchers, J.W., V. Kretsinger-Grabert, M. Carpenter, B. Dalgish, and B. Cannon. 2014. *Land Subsidence from Groundwater Use in California*. Sacramento, CA: Water Education Foundation.

Bozorg-Haddad, O., B. Zolghadr-Asli, P. Sarzaeim, A. Aboutalebi, X. Chu, and H.A. Loáiciga. 2020. Evaluation of water shortage crisis in the Middle East and possible remedies. *Journal of Water Supply: Research and Technology-AQUA* 69, no. 1: 85–98. https://doi.org/10.2166/aqua.2019.049

Brunke, M., and T. Gosner. 1977. The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biology* 37: 1–33.

California Department of Fish and Wildlife. 2017. *Habitat and Instream Flow Evaluation for Steelhead in the Ventura River*. Sacramento, CA: Ventura County.

Chen, Y.-N., N. Zilliacusb, W.-H. Lia, H.-F. Zhang, and Y.-P. Chen. 2006. Groundwater level affects plant species diversity along the lower reaches of the Tarim river, Western China. *Journal of Arid Environments* 66, no. 1: 231–246.

Colby, B.G., K.L. Jacobs, and D.R. Smith. 2007. Lessons for semiarid regions facing growth and competition for water. In *Arizona Water Policy*, ed. B.G. Colby, and K.L. Jacobs. Washington, DC: Resources for the Future Press.

Diamandis, P.H., and S. Kotler. 2020. *The Future Is Faster than you Think*, 365. New York: Simon and Schuster Publishers.

Dieter, C.A., Maupin, M. A., Caldwell, R.R., Harris, M.A., Ivahnenko, T.I., Lovelace, J.K, Barber, N.L., and K.S. Linsey. 2018. Estimated use of water use in the United States in 2015. United States Geological Survey Circular 1441.

Dillon, P., P. Stuyfzand, T. Grischek, M. Lluria, R.D.G. Pyne, R.C. Jain, J. Bear, J. Schwarz, W. Wang, E. Fernandez, C. Stefan, M. Pettenati, J. van der Gun, C. Sprenger, G. Massmann, B.R. Scanlon, J. Xanke, P. Jokela, Y. Zheng, R. Rossetto, M. Shamrukh, P. Pavelic, E. Murray, A. Ross, J.P. Bonilla Valverde, A. Palma Nava, N. Ansems, K. Posavec, K. Ha, R. Martin, and M. Sapiano. 2019. Sixty years of global progress in managed aquifer recharge. *Hydrogeology Journal* 27: 1–30. https://doi.org/10.1007/s10040-018-1841-z

Famiglietti, J.S. 2014. The global groundwater crisis: Groundwater depletion the world over poses a far greater threat to global water security than is currently acknowledged. *Nature Climate Change* 4: 945–948.

Ferris, K., and S. Porter. 2021. The myth of safe yield: pursuing the goal of safe yield isn't saving our groundwater. Kyl Center for Water Policy, Arizona State University, Phoenix, Arizona.

Food and Agriculture Organization of the United Nations. 2020. The state of food and agriculture 2020. In *Overcoming Water Challenges in Agriculture*. Rome. https://doi.org/10.4060/cb1447en

Galloway, D.L., and T.J. Burbey. 2011. Review: Regional land subsidence accompanying groundwater extraction. *Hydrogeology Journal* 19, no. 8: 1459–1486.

Hardberger, A. 2019. Texas groundwater law and the Edwards aquifer. In *The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource*, ed. J.M. Sharp, R.T. Green, and G.M. Schindel. Boulder, CO: Memoir 215, The Geological Society of America.

Israel Water Authority. 2011. Long-Term Master Plan for the National Water Sector, Policy Document, Version 3. https://www.gov.il/BlobFolder/policy/masterplan-main/he/masterplan_Water_Sector_Master_Plan.pdf. Accessed April 7, 2023.

James, I. 2022. A 'full-on crisis' for groundwater: Experts say the supply for future generations is at risk as new wells outpace regulations, *Los Angeles Times*, December 22, 2022.

Kinney, C.S. 1894. *A Treatise on the Law of Irrigation*. Washington, DC: W.H. Lowdermilk.

Konikow, L.F. 2013. Groundwater depletion in the United States (1900-2008). United States Geological Survey, Scientific Investigations Report 2013–5079, Reston, Virginia.

Limón E., and L. Blasey. 2022. Today' headlines: A fifth of California water agencies expect drought shortages, *Los Angeles Times*, December 1, 2022.

Loáiciga, H.A., and M. Schofield. 2019. Climate variability and change and Edwards aquifer water fluxes. In *The Edwards Aquifer: The Past, Present, & Future of a Vital Water Resource*, ed. J.M. Sharp, R.T. Green, and G.M. Schindel. Boulder, CO: Memoir 205, The Geological Society of America.

Loáiciga, H.A. 2015. *Geotechnical/Hydrologic Evaluation of Three Proposed Groundwater Wells in the Coastal Sub-Basin (Storage Unit 3) of the Montecito Groundwater Basin, Santa Barbara County, California*. Contract Report CC-15-30 for the California Coastal Commission, November 1, 2015, 77 p.

Loáiciga, H.A., T. Pingel, and E. Garcia. 2012. Seawater intrusion by sea-level rise: Scenarios for the 21st century. *Groundwater* 50, no. 1: 37–47.

McGreal, B., and S. Eden. 2021. *Arizona Groundwater Management – Past, Present, and Future*. Tucson: Arroyo, Water Resources Research Center, University of Arizona.

Partlow, J. 2022. Officials fear 'complete doomsday scenario' for drought-stricken Colorado River, *Washington Post*, December 1, 2022.

Rateb, A., B.R. Scanlon, D.R. Pool, A. Sun, Z. Zhang, J. Chen, B. Clark, C.F. Faunt, C.J. Haugh, M. Hill, C. Hobza, V.L. McGuire, M. Reitz, H. Müller-Schmied, E.H. Stanudjaja, S. Swenson, D. Wiese, Y. Xia, and W. Ze. 2020. Comparison of groundwater storage changes from GRACE satellites with monitoring and modeling of major U.S. aquifers. *Water Resources Research* 56, no. 12. https://doi.org/10.1029/2020WR027556

Rubio-Velázquez, J., H.A. Loaiciga, and D. Lopez-Carr. 2023. Human-induced resource scarcity in the Colorado River basin and its implications for water supply and the environment in the Mexicali Valley transboundary aquifer. *Annals of the American Association of Geographers*: 1–18. https://doi.org/10.1080/24694452.2022.2162477

Scanlon, B.R., C.C. Faunt, L. Longuevergne, R.C. Reedy, W.M. Alley, V.L. McGuire, and P.B. McMahon. 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences* 109, no. 24: 9320–9325.

Shatanawi, M. 2015. The Arab spring and water security. In *Proceedings of the 11th Kovac Colloquium of Hydrological Sciences and Water Security: Past Present and Future*, June 24th, Paris, France, IAHS Publication 366.

Singh, M. 2022. California's largest reservoirs at critically low levels – Signaling a dry summer ahead, *The Guardian*, 24 June, 2022.

Solgi, R., H.A. Loaiciga, and M. Kram. 2021. Long short-term memory neural network (LSTM-NN) for aquifer level time series forecasting using in-situ piezometric observations. *Journal of Hydrology* 601: 126800. https://doi.org/10.1016/j.jhydrol.2021.126800

UNICEF. 2021. Reimagining WASH: Water Security for All, 2021. https://www.unicef.org/media/95241/file/water-security-for-all.pdf.

United Nations. 2022. Sustainable Development Goals, 2022, https://www.un.org/sustainabledevelopment/development-agenda/.

United States Geological Survey. 2015. Office of Communications and Publishing, October 7, 2015, https://www.usgs.gov/news/featured-story/lessons-learned-legend-luna-leopolds-view-river.

Zektser, I.S., H.A. Loáiciga, and J. Wolf. 2005. Environmental impacts of groundwater overdraft: Selected case studies in the southwestern United States. *Journal of Environmental Geology* 47, no. 3: 396–404.