Water Resources Management in Agriculture and Ecosystems to Improve Climate Extreme Resilience in Mexico and the United States: A Research Agenda for Collaborative Action

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Executive Summary

Climate-related extremes characterized by higher temperatures and whiplash precipitation have been noted globally, compromising the reliability of water resources to serve agriculture, ecosystems, and population. Increased frequency and intensity of such hydrologic extremes has impacted both water infrastructure and access to usable water in California and many regions in Mexico alike. California, the major producer of agricultural commodities in the United States and home to more than 39 million people, has recently experienced one of the most severe prolonged droughts and high temperatures on the instrumented record, just followed by an equally extreme wet year. Mexico has also experienced extreme climatic conditions leading to critical water shortages for both irrigated and rainfed agriculture. Large cities like Monterrey, and numerous rural communities were faced with unreliable access to safe drinking water. These issues will likely be amplified by climate change in most regions presenting opportunities for research collaborations between experts in California and Mexico on various domains including agriculture, community engagement, groundwater, integrated water management, climate data science, and economics.

On top of the challenges imposed by highly variable surface water availability from precipitation, many regions have suffered the effects of massive surface water diversions and uncontrolled groundwater exploitation. This affects population relying on shallow wells both in quantity and quality, groundwater dependent ecosystems, cities future supplies, and small farming operations. In many cases, the lack of technological tools and knowledge for properly managing water resources, creates vulnerabilities in obtaining safe drinking water and sanitation services, particularly in communities with low adaptation capacity to upgrade their water supply infrastructure and their quality. However, collaborative efforts within academia provide the scientific basis to better inform water management decisions, expanding the conversation to local government agencies, industry, non-profit organizations, and others, facilitates inclusive discussions with community leaders that have lived through these circumstances and can provide historical local knowledge through broader engagement.

This paper presents insights from a binational collaborative research workshop for the project *Water Resources Management in Agriculture and Ecosystems to Improve Climate Extreme Resilience in Mexico and the United States* held in La Casa de la Universidad de California in Mexico, City on November 8-9, 2022. The project had four thematic areas to advance climate resilience namely: ***Climate Data Science, Integrated Water Resources Management, Groundwater Sustainability and Resilient Communities.*** The major research themes are enriched by comparative case studies from California and Mexico including extreme climate science data, community engagement, managed aquifer recharge, carbon sequestration, agricultural water pricing, and water supply sustainability. Major project outcomes include student and research staff research infrastructure skill development, faculty and research staff academic exchange, refereed journal articles, research reports and policy briefs.

Participant institutions include University of California campuses, Mexican academic and research institutions, government agencies, non-profit organizations, water utilities, and the private sector. Through a series of plenary sessions, guest speaker panels, and breakout sessions, the binational workshop participants were able to bring perspective on the present state and a desirable future of

climate resilience, and the major challenges around the thematic areas by identifying strengths, weaknesses, opportunities and threats. The second day of the workshop concluded with a blueprint for collaboration through binational comparative case studies and subsequent workshops to refine promising avenues for improved water management and policy for a more resilient future.

Some major policy recommendations from the workshop point to improvement of accessibility, coverage and resolution of climate data for increased identification of water supply shortage and flood risks and more informed water management decisions; identification of climate extreme vulnerable communities and hotspots, and collaborate with community partners to define resilience indicators. Promote groundwater sustainability through inclusive bottom-up approaches for manageing extraction and recharge; improved technical information and guidelines on managed aquifer recharge, water reuse, demand management and strategic land repurposing; and reintroduction of environmental water use education, water quality restoration of major water reserves of local and regional importance, and use of climate indexes to drive planning and emergency response to water supply challenges.

Further research project activities will continue to advance the scientific basis for climate extremes risks and vulnerabilities to agriculture, cities communities and ecosystems. Such an undertaking demands integration of local knowledge, and cultivation of binational experience exchange through comparative case studies. This will assemble compelling narratives of the major challenges as well as robust and promising water management and policy recommendations for a more resilient water future.

Introduction

Recent global climate extremes, which in California include among the most severe multi-year droughts on record and in Mexico extreme hurricane-forced precipitation events and droughts, have highlighted the rapidly changing conditions that affect water supply for agriculture, ecosystems, and growing populations. The varied geography in both California and Mexico provides compelling intersections of water resource availability and demand as affected by hydroclimatic extremes and anthropogenic systems shocks. Water resource managers and climate scientists in both regions have relied on incremental water management and institutional learning as building blocks to better manage water shortages and water excess. While it is recognized that flexible water allocation through markets, managed aquifer recharge and water conservation is needed, few of these insights have been shared across provincial borders. Furthermore, pervasive groundwater overdraft is omnipresent in both regions, and now the basis for policy intervention, For example, California's Sustainable Groundwater Management Act (SGMA) that requires groundwater basins to achieve balance in pumping and extractions by 2040. Such legislation can set the basis for sustainable water management in other regions, including Mexico.

Based on these common interests and regional needs to better develop collaborative research approaches on climate resiliency in water resources management, a workshop convening of academic, non-governmental, and industry representatives developed an agenda to address identified research needs and fill knowledge gaps. The workshop – held at Casa de Universidad California in Mexico City, November 10-11, 2022 – brought about 50 participants together to explore topics related to integrated water management, groundwater sustainability, and community resilience. These topics were underpinned by the fundamentals of climate data science and how such information is not only necessary for establishing the scope of needed response, but also for defining the direction and magnitude of needed response. The workshop utilized a SWOT analysis framework to articulate current research directions and approaches (Strengths), current research and management gaps (Weaknesses), future directions for advancing research (Opportunities), and identifying potential shortcomings or barriers (Threats).

Many benefits arise from collaborations between the University of California (UC) system and other participating partners in California and in Mexico, particularly in the ability for individuals to use unique experiences and guide advancements in research that are shared between collaborators. Global problems merit diverse ways of thinking, experiences, and levels of expertise, and this strategic UC Alianza MX project aims to support ground-breaking environmental research through a culture of collaboration. This strategic project brings experts in climatology, data science, economics, engineering, and sociology to highlight pressing issues in agriculture, local communities, cities and ecosystems and create well-rounded, data-driven answers that can support policy-making decisions.

The resulting research agenda explores opportunities for scientific discovery and exchange on weathering climate extremes, also driving case studies in California and Mexico highlighting shared problems for agriculture, communities, and ecosystems under climate extremes.

Purpose and Project Description

This project will explore opportunities for exchange of promising water management alternatives for agriculture, communities, and ecosystems as the primary beneficiaries of reliable water supply during climate extremes with some emphasis on groundwater. In addition, through a selection of case studies in Mexico and the California, the network of collaboration will inform robust water management and policy recommendations.

The project convenes a set of workshops in the US and Mexico both in person and hybrid formats with a group of academics, water and research agencies advocacy groups and NGOs. In addition, graduate student internships and faculty research visits to UC Merced were scheduled for 2023. In the first phase of the project, the group conceived a selection of matching case studies and this white report. The purpose of this white paper is to set a work plan for the case study phase in which, preliminary research findings will constitute the basis for management and policy insights around the four major topic areas.

The research network of this project will also explore future funding opportunities through organizations in the US such as USDA, NOAA, NSF, and others and funding opportunities in Mexico through CONAHCYT, CONAGUA, SADER, public utilities, as well as foundations or philanthropic organizations. Continued funding will facilitate partnership between research institutions, non-profit organizations, government, and stakeholders.

Workshop Participants from Mexico and the US and Major Research Themes

This project relies on collaboration among various UC campuses and Mexican institutions, with the potential for new partners. From UC Merced, Dr. Medellín and Dr. Viers maintain strong collaborative links with Dr. John Williams and the UC Davis Center for Watershed Sciences (CWS) where Medellín serves as an Associate Director. The CWS is an interdisciplinary research unit covering issues around California water systems for managing rivers, lakes, and estuaries. Dr. Medellín also serves as an Associate Director for the University of California Agricultural Issues Center within UC Agriculture and Natural Resources (UCANR) covering a wide variety of agriculture related topics with an emphasis on economics and policy. Other connections to UC campuses occur through ongoing multi-campus research project initiatives (MCRPI, PI Harmon, with Davis, Merced, Riverside and UCANR) involving automation of labor in agriculture, robustness in water management in agriculture (PI Viers, UC Davis, Berkeley, UCANR), and drought assessment and tools for resilience (PI Medellín, Davis, Berkeley, Irvine, Riverside).

Participant Mexican Academic Organizations	Research Interest(s)
Instituto Mexicano de Tecnología del Agua (IMTA)	Water technology
Universidad Autónoma de Chapingo (UACh)	Agronomy, agricultural and resource economics
Universidad Nacional Autónoma de México (UNAM)	Water technology and management
Tecnológico de Monterrey (Monterrey Tec)	Water technology, planning and management
Universidad de las Américas Puebla (UDLAP)	Water planning and management, climate change
Universidad Autónoma de Baja California (UABC)	Water technology, agriculture

The research network identified four major research themes and a selection of ongoing and new case studies to inform the four themes and draw water management and policy recommendations as the research progresses. Whereas the cases are largely led by academic institutions, input from other organizations including the Environmental Defense Fund (EDF), The Nature Conservancy, Agua, the Stockholm Environment Institute, and government institutions are essential to maintain research, management, and policy recommendations in line with the institutional and regulatory environmental goals and rules.

Major Research Themes and Associated Case Studies

Research Themes	Case Studies
Climate Data Science	a. Advancing understanding of the role of extremes in interannual-to-decadal variability in water resources.
Resilient Communities	a. Evaluating socio-ecological resilience to variable severity wildfires in Jalisco, México.
Sustainable Groundwater	a. Sustainable groundwater management through managed aquifer recharge (MAR): Site selection, characterization, and monitoring. b. Aguascalientes Valley aquifer in Aguascalientes, Mexico
Integrated Water Management	a. Economic valuation of irrigation water in Chinampas of Xochimilco and its effect on CO_2 fixation. b. Agricultural policy analysis in irrigation district 023, San Juan Del Río Querétaro. c. Management, productivity, and evaluation of the water of the San Juan Del Río Querétaro aquifer. d. Enhancing water sustainability for winery irrigation with treated domestic and internal wastewater: Napa, California and Valle de Guadalupe, Baja California. e. Dynamic modeling of groundwater storage in an arid zone, considering the effect of a climatic index.

Major Research Themes

1. Climate Data Science

Climate forecasting and use of climate models provide essential elements for water management in agricultural planting decisions, urban and rural domestic water systems, and emergency response to floods. At the same time, forecasting can aid in intra-season planning of managed aquifer recharge and floodplain reconnection to invigorate ecosystems and increase systemwide resilience using the natural infrastructure. Climate science helps improve understanding of the extent, frequency, and magnitude of climate impacts to water systems in regions and communities. This can not only help respond and recover to climate extremes, but to motivate the necessary production, collection, and synthesis of vital climate data needed to guide priority setting, develop resilience metrics, and implement adaptation actions.

Three initial research actions of mutual interest were identified among US and Mexican counterparts, focusing to address gaps in science, decision-making, and policy specific to climate resilience in communities and agriculture:

- **I) Development of wall-to-wall climate products for Mexico or transnational coverage to support climate and water resource science and tools to inform decision-making.**
- **II) Advancing understanding of the role of extremes in interannual-to-decadal variability in water resources.**
- **III) Advancing understanding of climate extremes and risks specific to natural resources.**

2. Climate Resilient Communities

The intersection of water, climate, and communities motivates solutions that expand equitable access to clean water for communities, ecosystems, and agriculture, through improved water quantity and quality. It opens the question of how a resilient community looks like, and what structure is needed for bouncing back in terms of governance, decision-making frameworks, and awareness. The binational group also brought the potential of technological tools to spatially visualize and track change in communities for a set of wellbeing indicators. Deliberations also highlight the need to define a role of a community in managing a watershed and recognizing the diversity of issues per geography. Some research and policy promising actions include:

- **I) Find ways to visualize "hotspots" of overlapping water, climate, and social indicators - for future climate failure and need for resilience development.**
- **II) Identifying community partners to help defining indicators, factors and elicit patterns in larger systems.**
- **III) Employ a cultural approach for identifying and measuring climate risk and how it relates to social vulnerability.**

Additionally, there is a pressing need to recognize why community resilience matters, especially in the scope of California and Mexico relations. There are both similarities and distinct variabilities in geographical issues per region determined by indicators or factors. These indicators or factors can assist in developing a tool to assess and track changes in communities. Indicators of vulnerabilities either static or changing should be captured to track climate resilience change in communities.

3. Sustainable Groundwater

As a common property resource, groundwater is often subject to overexploitation which has effects on availability, water quality, land subsidence, and deterioration of its dependent ecosystems. Groundwater serves as the main source of water for many rural water systems and cities worldwide which are often compromised due to increased over-pumping particularly during droughts.

Numerous challenges to sustainably manage water resources in Mexico are identified, which are common to other parts of the world. Availability, water quality issues, and disparities in decision making and access are commonalities found. A disconnection between academic research and government have also contributed to the conundrum of groundwater management with science and stakeholder-based objectives. Government agencies require simplified, and consumable summaries of academic research, and feasible projects. Lack of data and repositories undermine the potential for academia and other organizations to contribute to improve groundwater management.

Some research themes undertaken by the project point to:

I) **Development of guidelines for managed aquifer recharge projects.**
II) **Development of frameworks to quantify the economic impact of regulation on agricultural and urban systems.**
III) **Examine the potential of economic incentives to reduce over pumping in critically overdrafted areas.**

4. Integrated Water Management

As water supply systems in cities grow in demand and complexity, new layers of management and policy instruments are required. Expansion paths to support population and ecosystems in a sustainable way are the traditional way of conducting planning in major cities worldwide. Yet the potential of conservation, reuse and recycling, and storm water capturing provide a fertile ground for research, management, and policy. This research is aimed to identify research gaps common to Mexico and California involving climate resilience and water resources management for communities (both rural and urban) and agriculture considering the integration of climate forecasting, groundwater management as well as supply augmentation and demand management alternatives as these impact extreme climate resilience for agriculture and communities.

In this research thrust, the necessity for data and long-term planning was discussed. Issues with water quality are pervasive. Community involvement is often missing. Some actions identified include:

I) **Reintroduce water (ecological/environmental) education**
II) **Consider reuse and recycling of water for irrigation of higher value commodities such as vineyards.**
III) **Restoration of surface water problems (eutrophication) via treatment and IWRM**
IV) **Basin water management (i.e. Puebla Atoyac River)**
V) **Exploration water management alternatives in large cities.**

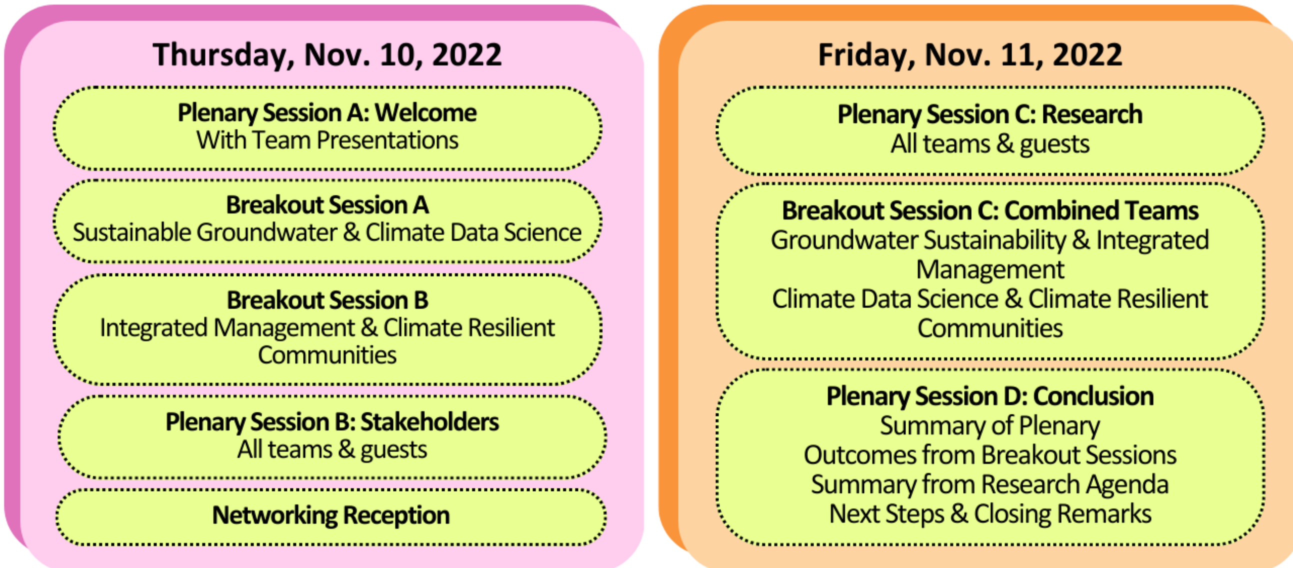
Research and Engagement Workshop Synapsis

A two-day, in-person workshop for the UC Alianza MX strategic project *Water Resources Management in Agriculture and Ecosystems to Improve Climate Extreme Resilience in Mexico and the United States*, brought nearly 50 participants from both countries. The event hosted by UC Merced at the Casa de la Universidad de California was led by co-principal investigators Medellín Azuara, Viers, Abatzoglou, Harmon and Beutel. Other participants included faculty and students from the UC system and Mexican universities, as well as representatives from government agencies, non-profit organizations, and industry, a summary of participating organizations by sector is provided below.

Participant Affiliations by Sector	
Academia	**Government**
• Instituto Mexicano de Tecnología del Agua • Tecnológico de Monterrey • University of California, Davis • University of California, Merced • Universidad Autónoma de Baja California, Ensenada • Universidad Autónoma de Baja California Sur • Universidad Autónoma de Chapingo • Universidad de las Americas Puebla • Universidad Nacional Autónoma de México	• California Department of Water Resources • Comisión Nacional del Agua • Consejo Consultivo del Agua • Secretaría de Agricultura y Desarrollo Rural • Instituto Nacional de Ecologia • International Boundary & Water Commission
Non-Profits	**Industry/Utilities**
• Environmental Defense Fund • The Nature Conservancy • Fundación Gonzalo Río Arronte • Somos Agua • Stockholm Environment Institute	• CESPE (Utility Ensenada, MX) • CESPT (Utility Tijuana, MX) • FEMSA (Monterrey, MX) • Agua y Drenaje Monterrey

The workshop allowed brainstorming around the aforementioned four major research themes as well as ongoing and potential case studies from Mexican and US institutions with common interests through breakout groups and plenary sessions on binational research, management and institutional reform on climate resilience in water resources for agriculture, communities and the environment. The workshop participants proposed a series of case studies for potential collaboration between faculties sharing common interests, that eventually could lead to research publications, policy briefs and technical reports.

An opening plenary session delivered various flash presentations from UC Merced, UC Davis and UCLA for each research themes, their respective research area innovations in the field and promising avenues for collaboration. This was followed by two breakout sessions led by UC members and Mexican collaborators where attendees could participate in discussions on individual core topics in each session. The day was closed with a final plenary session where non-academic stakeholders from different sectors led a panel to provide perspectives on current water management policies, and regulations, as well as proposed ways to engage research to support decision makers and provide solutions to vulnerable communities.



The group conducted a SWOT analysis for strengths, weaknesses, opportunities, and threats identified around each one of the four research topics. Some of the case studies were solidified with the benefit of the feedback from participants. Given the diversity of attendees, this summary is not reflective of a collective group opinion, but rather a collection of diverse viewpoints through aimed to: 1) Identify major needs to be covered on case studies and policy briefs, and 2) highlight plausible range of opportunities to pursue in future research collaboration.

1. Climate Data Science

Moderator: John Abatzoglou, UC Merced Management of Complex Systems

Attendees: Aldo Ramírez, Carlos Patiño, John Williams, Joshua Viers, J. Andrés Morandé, Yosune Miquelajauregui, Vanessa Moreno, D'Angelo Sandoval, Alejandro Jaramillo, Maria Piña, Jose Rodríguez

Strengths	Weaknesses
• Repositories exist at state level • Temperature datasets available • Commonality in water resource variability in MX/CA driven by climate	• Sparse precipitation data • Lack of quality in spatial data • Uncertainty in records and data availability
Opportunities	**Threats**
• Creating a National Repository (Water Quality and Quantity) • Embrace statistical / machine learning techniques for reducing uncertainty	• Change in public administration (policies); no cohesion or learning from policy continuity perspective.

• Develop products that can be used by water managers • Mapping strategy for changing course	• Lack of investment in monitoring (data collection) and data curation/distribution • Increasing variability in precipitation – and non-linear impacts to society. • Large scale problems difficult to tackle (e.g., Colorado, Grande/Bravo transnational basins)

2. Resilient Communities

Moderator(s): Josh Viers, UC Merced Civil & Environmental Engineering; John Williams, UC Davis Research Scientist

Attendees: Mariana Rivera, Chantelise Pells, Clara Medina, José Manuel Rodríguez, Fernando Elizundia, Anne Hansen, Ramiro Barrio, Alejandro Jaramillo, Josué Medellín-Azuara, D'Angelo Sandoval, Marina Mautner, J. Andrés Morandé, Marjorie Zatz, John Abatzoglou, Anne Hansen, Yosune Miquelajauregui, Maria Pina, Garrett Gietzen,

Strengths	Weaknesses
• Intersection of issues – climate impacts, marginalization, • Abundant connections to different communities that could potentially inform research • Technical knowledge – some of the best institutions with innovation (urban sector) and organizations with existing capacity • Comparatively strong governmental institutions conducive to research	• Lack of direct social science engagement. • "Lip service" to communities and lack of rigor in research approaches. • Lack of needed data to support assertions. • Political and social instability create barriers to engagement (violence, fear, corruption)
Opportunities	**Threats**
• Payment for Ecosystem Services • Coordinate efforts between authorities (i.e. municipalities) • Strengthen connections between community needs & research design/plans, & with policy solutions • Adopt resilience as a dynamic property • Network theory to identify effective system change and/or maintain resilience state.	• Increasing level of contamination • Conflicts due to number of users and demands • Cascading risks (across sectors), e.g., do immediate concerns about poverty prevent focus on other issues or shift preferences to short-term solutions. • Community based approaches take time to build relationships and trust • Climate Uncertainties • Political changes

3. Sustainable Groundwater

Moderator(s): Thomas Harmon, UC Merced Civil & Environmental Engineering; Alvar Escriva-Bou, PPIC/UCLA Civil & Environmental Engineering

Attendees: Karla Carpio, Flor Gallardo, Marina Mautner, Leopoldo Mendoza Espinosa, Eduardo Ibarra, Mabilia Urquidi, Arturo Hernández, Anne Hansen, Naivy Rodal, Mariana Rivera-Torres, Marjorie Zatz, Chantelisse Pells, Clara Medina, Marc Beutel, Sergio Ramírez, Eduardo Ortegón, Angeles Jacome, Fernando Fuentes, Ramon Valdivia, Karen Lucero Cruz Herrera, Fernando Elizundia, David-Eduardo Guevara-Polo

Strengths	Weaknesses
• Utilizing interdisciplinary work for the advancement of filling gaps in research • Placing more value in community-based organizations to bring new perspectives to water problems and how they are perceived by communities • Water is a connector: opportunity to engage different actors as a society	• Lack of connection between academia and government • (In MX) Government not sharing/not willing to share data • Constraints to receive funds for projects • Aquifer resilience: little knowledge of economically acceptable measurements and models
Opportunities	**Threats**
• Tapping into historical regional practices to better understand the systems • Linking research with practical delivery products (i.e. Climate forecasting with hydrological models to generate indexes) • Water value: Existing gaps open the need to establish water value per sector according to use.	• Geopolitical policy issues • Threat of violence/retaliation within and between communities. • Data scarcity

4. Integrated Water Management

Moderator(s): Marc Beutel, UC Merced Civil & Environmental Engineering; Josué Medellín-Azuara, UC Merced Civil & Environmental Engineering

Attendees: Aldo Ramírez, Carlos Patino, Graciela Herrera Zamarrón, Tom Harmon, Leopoldo Mendoza, David-Eduardo Guevara-Polo, Karla Carpio, Mario Alberto Hernández, Mabilia Urquidi, Edgar Hernández, Alvar Escriva-Bou, Vanessa Moreno, Naivy Rodal, Sergio Ramírez, Ramon Valdivia, Karen Lucero

Strengths	Weaknesses
• Existing collaboration on water reuse, water quality, eutrophication, among others. • Variety of common needs and areas of interest • Similar water use and activities associated allow to design common strategies for increasing resilience. • Accepted needs to mitigate climate change through sustainable practices	• Uncertain capacity to develop research in extreme areas (MX) • Scarcity of data and decentralization • Slow capacity of response for changes.
Opportunities	**Threats**
• Recurring cases of polluted surface water • Promising ongoing research suitable to be extended • Exchange and application of local experience of water management in agriculture in semi-arid regions common to both countries.	• Unreliable data can be mistakenly used (MX) • Lack of fundings for long-term studies • Poor local conditions infrastructure and lack of control can deteriorate projects performance and reduce reliability.

Management and Policy Insights

The workshop once again highlighted the value and the need for research and experience exchange between Mexico and the California on water resources management to face climate extremes. Challenges in facing water shortages and floods during such extreme events transcend geopolitical boundaries and the tenure of government administrations.

More resilient water systems support thriving agriculture, urban centers, and rural communities without compromising ecosystems. A successful UC Alianza-MX strategic project should impact not only in an academic setting, but also aid in water management and policy making through policy briefs, workshops, exchange, outreach, and related for a broader audience. At the same time, the involvement of stakeholders, government, industry and other organizations, and small community leaders, involvement constitute an essential piece to accomplish the project goals.

The plenary sessions of our last Workshop provided a regional-level policy perspective on water resource management challenges and noted the importance of fulfilling some gaps. A non-comprehensive set of desirable outcomes shall include:

- Healthy water systems to support basic drinking water and sanitation needs
- Enhanced communication to better convey products to decision makers and stakeholders.
- A recognition of the role of planning in securing water in vulnerable communities.
- A close connection between researchers and water managers and administrators to support informed decision making.
- An integration of surface and groundwater in hydrologic modeling for planning purposes.
- The development of a wall-to-wall climate products for Mexico or transnational coverage to support climate and water resource science and tools to inform decision-making.
- Visualize “hotspots” of overlapping water, climate, and social indicators - for future climate failure and need for resilience development.
- Groundwater recharge projects that close the gap between extractions and recharge.
- A detailed exploration (and perhaps reconciliation) of both supply augmentation (e.g. recycling, reuse, recharge) and demand management alternatives (e.g. conservation, permanent reductions in consumptive use, via fallowing, and other), as well as water markets.
- Economic incentives conserving water, trade and delay or postpone large infrastructure investments.

The case studies will provide a broader audience management and policy recommendations to advance knowledge in various water-related areas including drought, climate resilience, groundwater sustainability and sustainable agroecosystems.

Conclusions

In recognizing the present and future challenges of climate extremes on agriculture, cities, communities and ecosystems due shortage or excess of water and chronic groundwater overdraft, opportunities exist to reconcile the dynamic anthropogenic footprint and natural systems. Academia, government, private sector, non-profit organizations, and communities bring unique perspectives on both physical and institutional hurdles that prevent sustainable use of water resources, use of natural infrastructure to increase climate extremes resilience and equitable and reliable access to water. Collaborative discussion of such challenges allows identification of the needed science and prevailing data gaps, as well as the pivotal reforms needed for a secure water future.

Whereas reliable water systems are the centerpiece and driver of the science and policy solutions pursued under this research; a concerted effort requires multi-disciplinary and multi-sectoral participation in the process. This improves the prospects for adopting the best available and economically sound science as well as locally driven approaches for planning, management, and emergency response. Sustainability frontiers go beyond major stakeholders and sectors and necessitate the expansion of the regional water user base, ensuring that people and ecosystems, which ultimately buffer overuse during droughts, are given paramount importance.

Case studies around the major themes of this research are certainly non-comprehensive, yet provide a framework that cultivates binational research exchange, collaborative learning and also educates the future generation of water resource practitioners. Regulation to protect groundwater, ecosystems and small rural water systems exists and is at various stages of implementation in California and Mexico. Furthermore, the technological solutions to restore water quality and its access and replenish aquifers and improve systemwide water connectivity and storage, allocation flexibility through markets or demand management through pricing require a careful examination of the equity implications in the various case study regions. Such considerations will gain substance through the course of the project to provide context to policy recommendations.

Over 2023, the project will produce research results and insights forming the basis for actionable recommendations and will stimulate constructive and open feedback from various sectors. Research findings will be made available through open access web-based platforms, policy briefs, and refereed journal platforms. The project leadership aims to translate science into broadly accessible, easy-to-implement tools for water users of vulnerable communities of Mexico and the US affected by long-term climate extremes. Outreach materials will be prepared to present research products and the network of collaboration will continue to engage in new rounds of extramural binational funding opportunities to build on project-supported research to advice climate resilience.

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Appendix

Case Study Summaries

1. Climate Data Science

Case Study: *Advancing understanding of the role of extremes in interannual-to-decadal variability in water resources.*
Participants: John Abatzoglou (UC Merced) Carlos Patiño-Gómez (UDLAP)

Introduction
Our research topic was focused on climate variability and extremes given the high year-to-year variability in annual precipitation across much of the southwestern US and northern Mexico. Large interannual to decadal variability in precipitation leads to significant challenges for water management – particularly given the importance of water resources for agriculture in these areas. These regions are at the southern edge of the mid-latitude jet stream and commonly see a narrower window for cool-season precipitation to contribute to annual totals – meaning that a few number of precipitation events have an outsized impact on annual totals and variability (e.g., Dettinger et al., 2011). California and northern Baja California are heavily reliant on atmospheric rivers for total precipitation totals (Gershunov et al., 2017), while other portions of Mexico receive a large portion of their annual precipitation in tropical cyclones (Khouakhi et al., 2017). As a result, the variability of extreme precipitation events likely is a significant driver of interannual to decadal variability of water resources. Understanding how this variability plays out across the southwestern US and Mexico is critical given that these areas have existing water scarcity challenges that will be exacerbated by anthropogenic climate change (Cook et al., 2020). Further, less attention has been paid to changing hydroclimate variability which may impose significant impacts to communities. In California, there has been an increase in the variability of hydroclimatic extremes (e.g., Swain et al., 2018) with climate change expected to further increase interannual variability (e.g., Gershunov et al., 2019). The means through which has played out in Mexico and is projected to under climate change is less well known. Moreover, the influence of changes in extremes on changes in hydroclimate variability is generally not well evaluated in the region.

Objectives

- Analyze changing hydroclimate variability to understand potential impacts on communities, specifically patterns in atmospheric river events.

Hypothesis/Expected Outcomes

- Understanding the drivers of interannual variability in water resources for California and Mexico can serve as support to creating long-term, community-focused solutions for the advancement of environmental, economic and social sectors in both rural and urban regions.

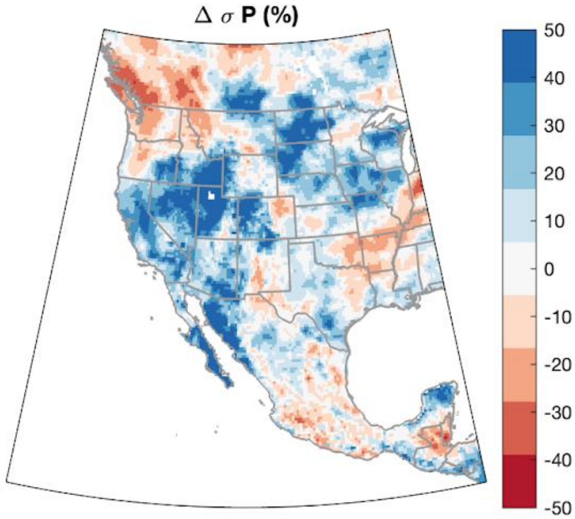


Figure A-1. Relative change in standard deviation of Oct-Sep precipitation between 1940-1980 and 1981-2022.

2. Resilient Communities

Case Study: *Evaluating socio-ecological resilience to variable severity wildfires in Jalisco, México*
Participants: Yosune Miquelejauregui (UNAM), John Williams (UCD), John Abatzoglou (UCM)

Introduction
Uncontrollable and devastating wildfires are becoming more frequent in many parts of the world. Climate change is expected to exacerbate the negative impacts of wildfires on biodiversity, public health, social wellbeing, livelihoods, built infrastructure, and on the overall stability of socio-ecological systems. Resilient responses to wildfires should aim to quickly restore the components, processes, and functionality of such systems within reasonable timeframes. Resilience to wildfires greatly depends on fire severity and its variability within the landscape. High-severity-stand-replacing fires often result in substantial physical and chemical alterations in soil properties, hydrologic responses, and ecosystem functioning. In addition, they can bring huge economic losses and human health impacts leading to negative ecological and social outcomes. On the contrary, low- to moderate-severity fires that typically leave most of the large trees alive result in structurally complex patches with different degrees of burned organic matter. These patches are more prone to restore ecosystem functioning following a fire event. Promoting resilience is central for sustainable planning and risk management. However, achieving socio-ecological resilience requires the recognition that fire severity is not only the result of biophysical feedbacks such as weather patterns, fuel type and soil drought, but it is also shaped by socio-political factors related to land-use and settlement patterns, management options, investment decisions, and stakeholders' actions and responses to wildfires. However, little is known about how social and political drivers can be conducive to variable fire severity and impact overall socio-ecological resilience. An extensive literature review will be carried out to identify the fire risk management strategies implemented in the last decade.

Objectives

- Evaluate socio-ecological resilience to variable fire severity in temperate forests of southeastern Jalisco, México.
- The study will include the temperate forested regions of La Primavera, Sierras de Quila and Tapalpa de Jalisco.
- Quantify and record fire severity in each region using the composite burn index derived from historic remote sensing data.
- Measurements of burn depths, damage to the canopy and vegetation regeneration to assess on-ground fire severity.

Hypothesis/Expected Outcomes

- Understanding the drivers of interannual variability in water resources for CA and MX can serve as support to creating long-term, community-focused solutions for the advancement of environmental, economic, and social sectors in both rural and urban regions.
- Implementation of participatory workshops with local stakeholders and community members to explore how their actions and responses are perceived to increase resilience.

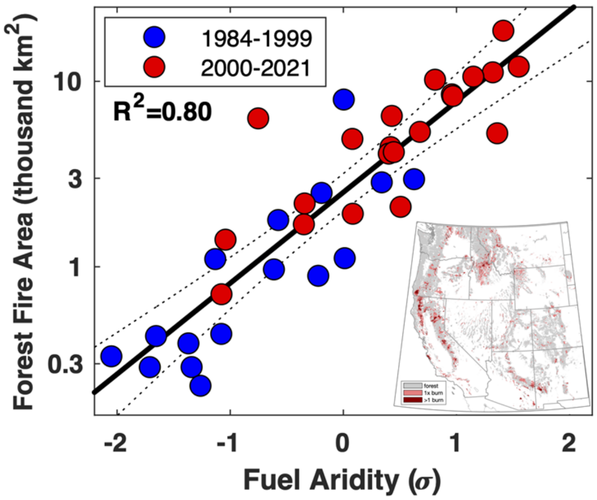


Figure A-2. Climate-Fire Relationship in the Western US Forests (Abatzoglou et al. 2021).

3. Sustainable Groundwater

Case Study A: *Sustainable Groundwater Management through Managed Aquifer Recharge (MAR): Site Selection, Characterization, and Monitoring.*

Participants: Tom Harmon (UC Merced), Roxana Nicte-Há Hughes-Lomelín (UMICH), Mario Alberto Hernández (UNAM), Graciela Herrera Zamarrón (UNAM)

Introduction

Changing global climate extremes, including some of the most severe droughts on record in California, spotlight the need to more precisely observe and allocate our water supply for agriculture, ecosystems, and growing population in semi-arid regions. The varied geography, hydroclimates, ecosystems, and system shocks that have occurred and are expected in California and Mexico provides compelling intersections of water resource availability and demand. The goal of this proposal is to collaboratively explore combinations of precision water monitoring and modeling strategies in support of integrating agriculture with managed aquifer recharge (AgMAR). In short, AgMAR has the potential to enable subsurface storage gains achieved during wet years to supplement irrigation needs in dry to normal years. As we complete our understanding of and gain the capacity to precisely monitor AgMAR processes and systems, growers and water resources manages will be more able to act decisively with respect to water allocations. We can imagine, for example, a cyber-physical system for observing and managing short-term (e.g. irrigation events) and long-term water operations on a farm (see figure below).

Objectives

- Developing and testing measurement and modeling strategies for assessing AgMAR potential on farmland, or marginal lands near farms, and identifying best practices.
- Identifying metrics for success in AgMAR and developing a pilot program for testing these metrics.
- Exploring the potential impact of widespread AgMAR implementation in vulnerable agricultural regions in California and Mexico, particularly in severely over-drafted groundwater basin.

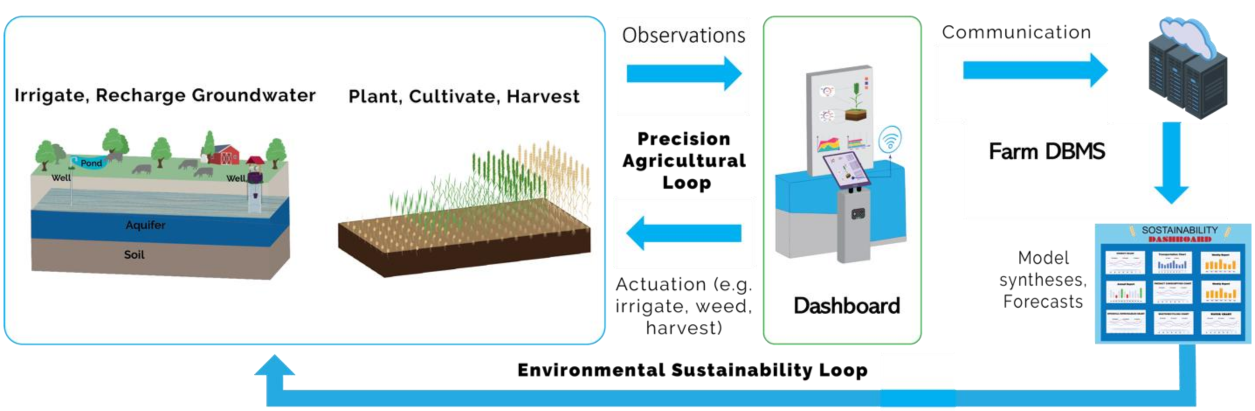


Figure A-3- Illustration of monitoring, modeling, and management technology for an agricultural managed aquifer recharge (AgMAR) system, showing optimization of short-term (irrigation event) and long-term (aquifer recharge event) operations.

Hypothesis/Expected Outcomes

- The proposed research will explore current approaches and develop new strategies for AgMAR monitoring and management in California and Mexico.

Case Study B: *Aguascalientes Valley Aquifer in Aguascalientes, Mexico*
Participants: Roxana Nicte-Há Hughes-Lomelín (UMich), Thomas C Harmon (UCM), Mario Alberto Hernández Hernández (UNAM), Marco Antonio Martínez Cinco (UMich), Sonia Tatiana Sánchez Quispe (UMich)

Introduction

Administratively, Mexico's groundwater is divided between 653 aquifers, where 105 of them are overexploited (National Water Commission [CONAGUA], 2018). One of these is the Aguascalientes Valley aquifer (Figure), located in Aguascalientes State, which supplies as much as 94% of the state's total water demand (Hernández-Marín et al., 2018). This is due to the semi-arid climate that prevails in the region, resulting in few natural surface water bodies. The mean yearly rainfall in the area is 510 mm with a yearly potential evaporation of 2,010 mm. The average temperature falls between 18 and 22 °C, and summer rains are present during the months of May-October, with the greatest incidence of rainfall occurring in the months of July and August (CONAGUA, 2020).

Aguascalientes Valley is the location of the state's capital city (Aguascalientes City), as well as other important urban centers. The state has a population of close to 1.5 million inhabitants, with about 60% of this total living in the capital (INEGI, 2021), and 95% of its economic activities are carried out within the valley limits (Sainz-Santamaria & Martinez-Cruz, 2019).

The region in which the aquifer is located is defined by important regional geological structures. It is within the Aguascalientes Graben, flanked by normal faults that run north to south (CONAGUA, 2020). However, the stratigraphy of the graben is not well-defined, as it is described mostly by lithological correlations and few reliable dating analyses. The drilling logs that are available show that the aquifer is composed by a sequence of sediments of sand and gravel, with a few intercalations of silt and clay (Pacheco-Martínez et al., 2013). On the other hand, the Mexican Geological Service (SGM) defines the general geology of the area by a large mass of alluvial material, with conglomerates and tuffs making up the southernmost part of the aquifer (SGM, 2005).

The aquifer system itself is mainly unconfined (a water table type aquifer), but exhibits confined aquifer hydraulic behavior in a few locations (Hernández-Marín et al., 2018). It extends over an area of 3,129 km2. The aquifer flows from north to south (CONAGUA, 2020), with the piezometric levels from various years confirming this (CONAGUA, unpublished data, 2015). These levels have been declining quite significantly in the last couple of decades, primarily due to the excessive pumping needed to meet the growing demand for water resources for agriculture, municipal, and industrial consumption (Pacheco-Martínez et al., 2013). Data from 2020 show that in the region of the aquifer, there are 1,468 active wells, extracting an estimated volume of 348 million m^3/year. However, natural recharge happens only at a roughly 250 million m^3 a year, indicating a serious overdraft of almost 100 millions of m^3/year at the cost of the aquifer's non-renewable storage (CONAGUA, 2020).

The Aguascalientes Valley aquifer has been the subject of much research throughout the years, due to its importance as the primary water resource of the region. The current work is an attempt to mathematically model its behavior, using the MODFLOW code (Harbaugh, 2005). This model is being carried out on the ModelMuse program (Winston, 2022), which facilitates the use of ASCII raster files as input data. Having a mathematical model of this overdrafted aquifer will allow faster and more reliable analyses on the implementation of MAR to this study case.

Objectives

- Define groundwater modeling parameters using mathematical model configurations.
- Define input data referring to the natural and anthropogenic movements in the groundwater flows
- Finalize model calibration process to determine the hydraulic conductivities and specific storage to slow the simulated flows through the aquifer

Hypothesis/Expected Outcomes

- Calibrate the groundwater model for use of the case study.

4. Integrated Water Management

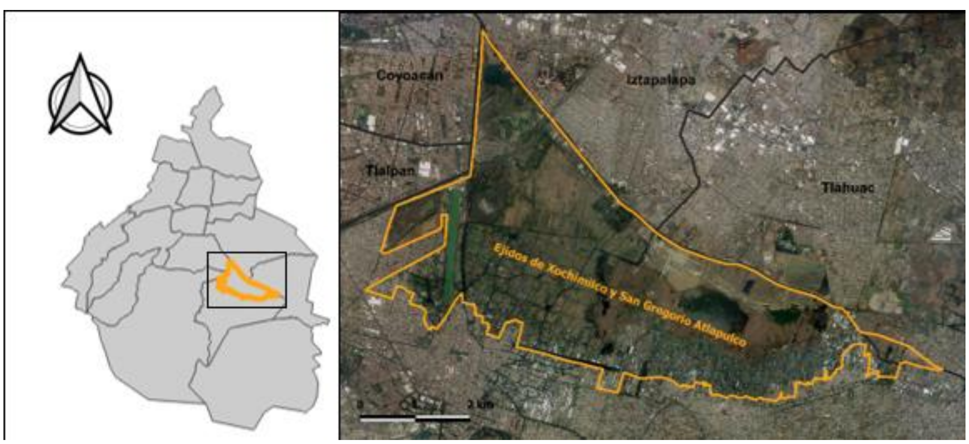
Case Study A: *Economic valuation of irrigation water in Chinampas of Xochimilco and its effect on CO_2 fixation.*
Participants: Everardo Trujillo Moreno

Introduction
The lake system in Xochimilco is characterized by chinampas, which are artificial islets delimited and stabilized by forest species. The chinampas are continuously fed with nutrients and organic matter provided by the flows of the canals (González et al, 2014), which has allowed the production of up to 3.3 million tons of vegetables per year (SIACON, 2020), which represents a contribution to food security in Mexico City. About 70% of groundwater extractions for urban supply comes from the Xochimilco-Chalco sub-basin. The supply and management of water are one of the main problems facing Mexico City, in which the drinking water service has not been able to fully cover the needs of its inhabitants (Martínez, 2016, Zapana et al, 2021, Rolland, 2010). The scarcity of water for agriculture and pollution from wastewater discharges have caused serious ecological damage and decreased yields in chinampas.

Objectives

- Determining the agricultural value of water for chinampas
- Determine the opportunity cost of Xochimilco's water instead of being used for agriculture.

Hypothesis/Expected Outcomes

- Irrigation with treated water in the chinampas produces differentiated yields depending on the concentration and type of contaminants.
- Higher concentrations of pollutants decrease the value of agricultural production, and this reduction can be quantified
- The contribution of treated water directly affects the ecosystem service of CO_2 fixation.
- 

- Figure A-4. Spatial location of the ANP "Ejidos de Xochimilco and San Gregorio Atlapulco" (Source: National Biodiversity Information System 2021 [http://www.conabio.gob.mx/informacion/gis/])

Case Study B: *Agricultural policy analysis in irrigation district 023, San Juan Del Río Querétaro.*
Participants: Karen Lucero Cruz (Universidad Autonoma de Chapingo), Miguel Angel Martinez

Introduction

The agricultural policy has an important role for the development of agricultural and commercial activities and in the well-being of the population in the country; the use of an agricultural policy guarantees in many occasions that the operation of programs and projects occurs adequately. The methodology used was mathematical programming, both at the farm level and at the regional level, modeling the implications of the guarantee price policy, fertilizer prices and access to irrigation water. Three models were built for the standard farms and one regional one with 5 scenarios each, and the impact on the indicated elements was analyzed.

Objectives

- Evaluation of the impact of the water and agricultural policy on the crop pattern of DDR 023, San Juan del Río, Querétaro on the well-being of the producers reflected in the income of one of them

Hypothesis/Expected Outcomes

- TBD

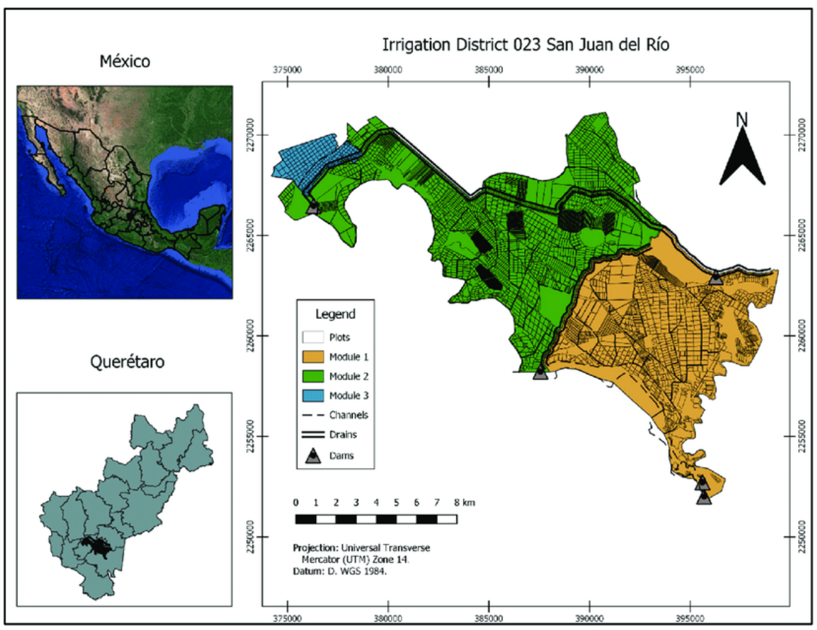


Figure A-5. Location of the Irrigation District 023 SOURCE: CONAGUA

Case Study C: *Management, productivity, and evaluation of the water of the San Juan Del Río Querétaro aquifer.*
Participants: Ángeles Suhgey Garay (Universidad Autónoma de Chapingo), Ramon Valdivia

Introduction

The current conditions of greater demand for water in Mexico and the world, due to the increase in population and economic activity, the effects of pollution and climate change, the depletion of many sources of the resource and the aging of the hydraulic infrastructure, have triggered alarm signals. In this context, the institutions of an economy are very important to manage the management of water resources, their actions are reflected in proper governance. The study analyzed the state of multilevel governance in the aquifer of San Juan del Río, Querétaro, using the OECD multilevel governance method. For this, the questionnaire (with adaptations) proposed by the OECD was used.

Objectives

- To know the productivity of the water of the aquifer of the Valley of San Juan del Río, Querétaro.
- To know the state of the water governance of the aquifer of the Valley of San Juan del Río, Querétaro.
- Determine the willingness to pay to estimate the economic value of the water from the aquifer of the Valley of San Juan del Río, Querétaro.

Hypothesis/Expected Outcomes

- The economic valuation of water from the aquifer of the Valley of San Juan del Río, Querétaro will help to manage demand and a better use of the resource.

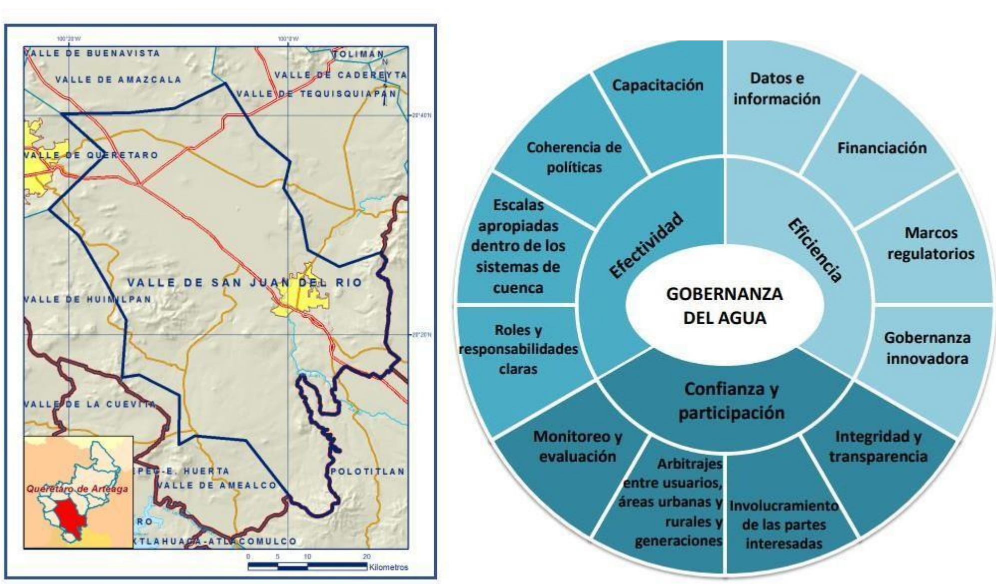


Figure A-6: Aquifer location (left), and Principles of OCDE Water Governance (right).

Case Study D: *Enhancing Water Sustainability for Winery Irrigation with Treated Domestic and Internal Wastewater: Napa, California and Valle de Guadalupe, Baja California*
Participants: Marc Beutel, Leopoldo Mendoza Espinosa, Clara Medina, Thomas Harmon, Josué Medellín, J Andrés Morandé

Introduction
With the uncertainty facing water managers in arid California and Baja California, there is a growing acknowledgement of the need to diversify water sources for crop irrigation. One potential source is recycled water from wastewater treatment plants (WWTP), and a potential user is vineyards (Chen et al. 2013). Initial social concerns surrounding the use of reclaimed water for crop irrigation may have influenced the slow adoption of the practice (Fielding et al. 2017), but increased literature supporting its use has impacted local and government acceptance (Bischel et al. 2012). The growing acceptance of this practice has sparked the research interest of farmers, engineers, and biologists alike to further understand the long-term effects of soil, water, and crop quality with prolonged irrigation (Chen et al. 2015). There are many benefits to using reclaimed water for irrigation, including soil nutrient recovery, water conservation, and lessening dependence on aquifers as a water source (Toze 2006). Vineyards are generally a less water-intensive crop than other agricultural commodities. Understanding how reclaimed water for vineyard irrigation may potentially benefit wine crops is both important for determining sustainable water management options for Baja California's Valle de Guadalupe, but also serves as a successful project influencing changes in general agricultural water resource management on a larger scale. Shifting agricultural water resources in times of climatic extremes to more sustainable options can support the long-term local economy and promote similar practices in other regions of Mexico impacted by drought.

Objectives
- Understand successful water reuse irrigation systems in Napa, CA to adapt for the vineyards in Guadalupe Valley.
- Analyze water regulations in CA and MX, compare for both regions and highlight possible disparities or obstacles in applying water reuse system in MX.
- Analyze institutional constraints at both UC Merced and the University of Baja California, Ensenada for carrying out the project.
- Analyze social constraints impacting implementation at both locations.

Hypothesis/Expected Outcomes
- The case study shows that distribution systems to transport recycled water from the WWTP to end users can be expensive, and that addressing water quality considerations are critical for stakeholder buy into use recycled water at vineyards.

Table 1. Water Quality Standards for Recycled Water Use in California

Water Type	Parameter	Quality Criteria
Disinfected Tertiary: oxidized, filtered and disinfected	Total Coliform	• Median concentration < 2.2 MPN/100 mL in any 7 days of analyses • < 23 MPN/100 mL in more than one sample in 30 days • < 240 MPN/100 mL at any time
	Turbidity for Filtration Using Natural Undisturbed Soils or a Filter Bed	• Average turbidity < 2 NTU in 24 hours

		• < 5 NTU more than 5 percent of the time within 24-hour period • < 10 NTU at any time
	Turbidity for Filtration Using Microfiltration, Ultrafiltration, Nanofiltration or Reverse Osmosis	• < 0.2 NTU more than 5 percent of time in 24 hours • < 0.5 NTU at any time
Disinfected Secondary 2.2: oxidized and disinfected	Total Coliform	• Median concentration < 2.2 MPN/100 mL using last 7 days of analyses • < 23 MPN/100 mL in more than one sample in 30 days
Disinfected Secondary 23: oxidized and disinfected	Total Coliform	• Median concentration < 23 MPN/100 mL in any 7 days of analyses • < 240 MPN/100 mL in more than one sample in 30 days
Un-disinfected Secondary: oxidized, not disinfected	None	None

Adapted from CDPH (2009)

Case Study E: *Dynamic modeling of groundwater storage in an arid zone, considering the effect of a climatic index*
Participants: David-Eduardo Guevera-Polo (UDLAP), Carlos Patino

Introduction
The water crisis is already happening. In this context, promoting integrated water management cannot be postponed in order to achieve water security. However, historically groundwater has played a minor role in it, despite the fact that in many regions it represents the main source of supply for different uses and plays a substantial role in ecosystems. The main challenge to incorporate groundwater into integrated water management is its understanding as a system and one of the aspects that is not usually considered for this purpose is its relationship with climatic processes. There is statistical evidence that suggests that climatic oscillations significantly influence the availability of groundwater. However, the statistical approach does not consider water uses and land use change in its analyses. The present study seeks to describe the storage of groundwater considering the influence of a particular climatic index, the uses of water and the use of land, using the system dynamics approach. This approach will make it possible to describe the groundwater system under different climatic, demand and land use change conditions and propose actions that allow its incorporation into integrated water management.

Objectives
- Describe the storage of groundwater, associated with a climatic index, water uses and land use, in an aquifer in an arid zone using a dynamic simulation model, to propose tactical and/or strategic management actions of the water.
- Develop a dynamic simulation model through the identification of the system's structure, the definition of its borders and the mathematical description of the processes that influence it, to understand the behavior of the system.
- Implement the model in a pilot arid aquifer to validate its results and demonstrate its usefulness for proposing tactical and strategic water management actions.
- Based on the results of the model and the use of various scenarios, propose tactical and/or strategic actions for groundwater management to ensure the satisfaction of the demands for the different uses and for environmental protection.

Hypothesis/Expected Outcomes
It is feasible to develop a dynamic simulation model to describe the storage of an aquifer in an arid zone, considering the effect of a climate index through its influence on precipitation patterns, together with water uses and soil characteristics. Furthermore, this model will be useful to propose tactical and/or strategic actions to increase the efficiency of groundwater use.

Research Questions
1. How to describe the storage of groundwater in an aquifer in an arid zone for a monthly scale considering the effect of a climate index, change in land use and groundwater extraction?
2. What are the variables to which groundwater storage offers greater sensitivity?
3. Is the influence of the climatic index significant on the recharge of the aquifer?
4. Do incidental recharges make a significant contribution to storage?
5. What tactical and/or strategic actions can be implemented in the aquifer to favor the efficient use of groundwater?
6. Do the protection of recharge zones and induced recharge represent leverage points in the groundwater system?