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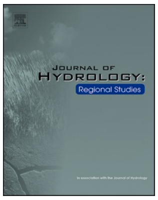

The future of water in a desert river basin facing climate change and competing demands: A holistic approach to water sustainability in arid and semi-arid regions

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ABSTRACT

Study region: The Middle Rio Grande (MRG), defined by the portion of the basin from Elephant Butte Reservoir in New Mexico to the confluence with the Rio Conchos in Far West Texas, U.S.A. and Northern Chihuahua, Mexico.

Study focus: The future of water for the MRG and many other arid and semi-arid regions of the world is challenged by a changing climate, agricultural intensification, growing urban populations, and a segmented governance system in a transboundary setting. The core question for such settings is: how can water be managed so that competing agricultural, urban, and environmental sectors can realize a sustainable future? We synthesize results from interdisciplinary research aimed at "water futures", considering possible, probable, and preferable outcomes from the known drivers of change in the MRG in a stakeholder participatory mode. We accomplished this by developing and evaluating scenarios using a suite of scientifically rigorous computer models, melded with the input from diverse stakeholders.

New hydrological insights for the region: Under likely scenarios without significant interventions, relatively cheap and easy to access water will be depleted in about 40 years. Interventions to mitigate this outcome will be very costly. A new approach is called for based on "adaptive cooperation" among sectors and across jurisdictions along four important themes: information sharing, water conservation, greater development and use of alternative water sources, and new limits to water allocation/withdrawals coupled with more flexibility in uses.

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1. Introduction

This research is focused on the future of water in the transboundary Middle Rio Grande (MRG) basin, defined by the portion of the basin from Elephant Butte (EB) Reservoir in southern New Mexico (NM) to the "*Junta de los Rios*", the convergence of the Rio Grande (RG) with the Rio Conchos in far west Texas (TX)/northern Chihuahua (CH)). This part of the RG basin faces water scarcity characterized by limited and dwindling supplies of water, increasing demands for water from multiple sectors, and a segmented governance system spanning three states in two countries (Hargrove et al., 2013). The basin faces several drivers of change (Hargrove and Heyman, 2020), including: 1) climate change that is impacting both water supply and demand (Garfin et al., 2018; Llewellyn et al., 2013); 2) agricultural intensification, characterized by increasing production of high value, high water-demand crops (Hargrove et al., 2021); 3) urban growth, impacting water demand and quality (Hargrove et al., 2021); and 4) demand for environmental services, such as riparian habitat and environmental flows (Llewellyn et al., 2013). These converging drivers are resulting in dwindling surface water supplies and groundwater depletion, not unlike many other basins, especially in arid and semi-arid regions (Gleeson et al., 2012; Wada et al., 2010; Dalin et al., 2017; Aeschbach-Hertig et al., 2012; Jasechko et al., 2021). Furthermore, the water governance system in the region, developed over 100 years ago, is characterized by rigid water institutions, weak stakeholder participation outside the direct beneficiaries of water allocations, division by artificial borders and political jurisdictions, and growing conflicts among the primary water users and other legitimate stakeholders (Hargrove and Heyman, 2020; Hargrove et al., 2021), resulting in what can be characterized as a wicked water resources problem (Rittel and Webber, 1973).

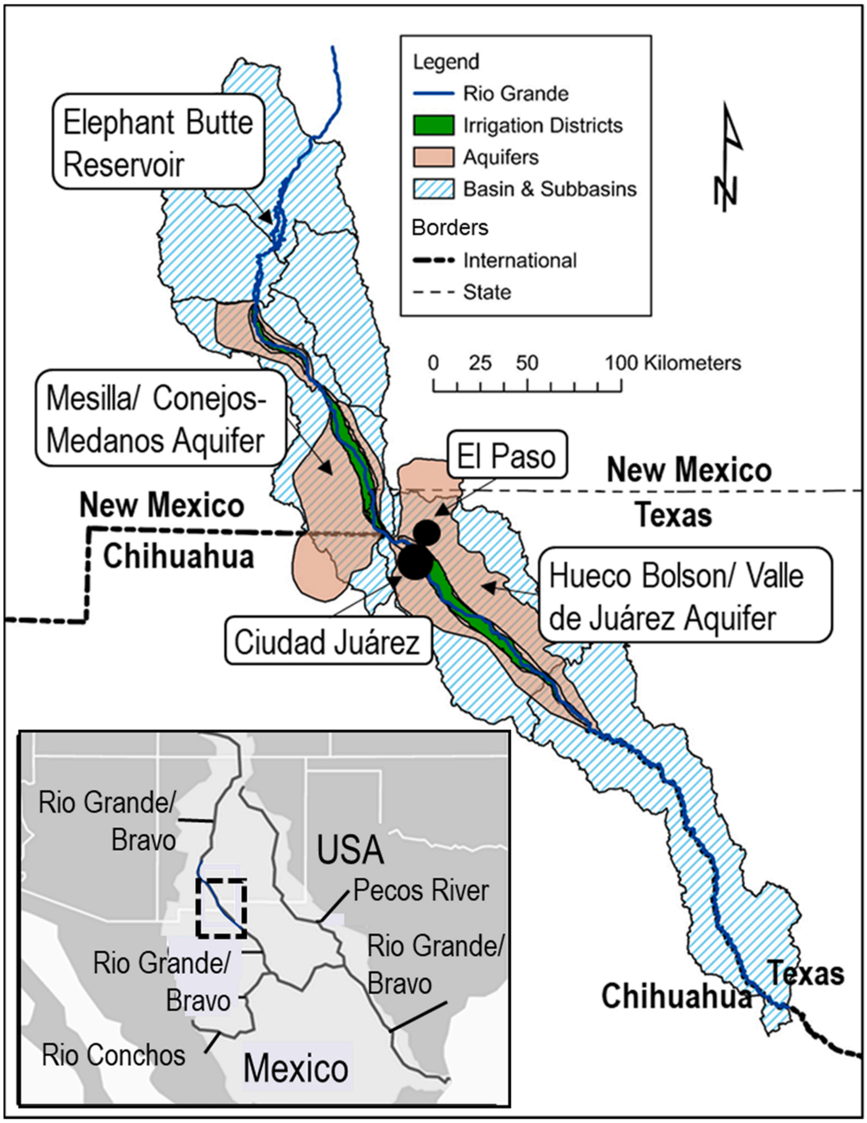

Fig. 1. Location of Middle Rio Grande, freshwater aquifers, cities of Ciudad Juarez and El Paso, and irrigation districts.

Comprehensive reviews on the state of knowledge of water resources in the region from about ten years ago (Gutzler, 2013; Hargrove et al., 2013; Hogan, 2013; Johnston, 2013; Scott and Buechler, 2013; Sheng, 2013; Walsh, 2013) showed that models have been developed for partial components of this system, but modeling approaches in the MRG generally have paid limited attention to system feedbacks and non-linear behavior, human and climatic drivers of change, and connections between surface and subsurface water, all factors that have been shown to be important in other locations (Ahn and Kim, 2016; Ahn et al., 2016; Kim et al., 2017; Lamontagne et al., 2014; McCallum et al., 2013). In the MRG and many other locations, integrated analyses that result in holistic management strategies have been broached rarely. Talchabhadel et al. (2021) provided a more recent and extensive review of one vital component of the system, the Hueco Bolson (HB) aquifer, concluding that modeling systems and research efforts to date are still inadequate to address the challenges of understanding and managing transboundary water, challenges that include technical, social, political, and jurisdictional issues (Sanchez and Eckstein, 2020; Sanchez et al., 2020).

The challenges of this region are relevant because some, if not most of them, are faced by other river basins in arid and semi-arid regions of the U.S. and the world, where societies are dependent on a desert river basin and its associated aquifers to meet the needs of irrigated agriculture, as well as growing urban populations, while facing environmental needs as well (Castle et al., 2014). Thus, the core question for the MRG and similar regions is: how can water be managed so that the three largest competing sectors—agricultural, urban/industrial, and environmental—can realize a sustainable future in such challenged water systems where supplies are dwindling and demands are increasing? "Siloed", component-based research and analyses by single disciplines alone will not be able to adequately address this question. A focus on probable, possible, and preferable water futures is called for, one in which integrated science that cuts across traditional boundaries, including disciplinary, biophysical, sectoral, social, and jurisdictional ones, is combined with holistic, collaborative management to identify the probable and possible outcomes, while stakeholder-driven decision-making determines the preferable outcomes (Amara, 1981). Given the precarious position of the MRG basin's water resources under drivers of change, we addressed these challenges by synthesizing and testing a holistic vision of water sustainability challenges and proposing integrative, collaborative approaches and solutions, crossing boundaries that are not commonly breached in the scientific literature. Using a suite of models that operate at a range of spatial and temporal scales, we utilized stakeholder participatory approaches to modeling, focused on the future of water in the region in the face of several drivers of change, and evaluated possible interventions that might alter the future. Through stakeholder interactions, we also evaluated the preference of or willingness to adopt certain technologies. Our objectives were to: 1) demonstrate and test this holistic and integrated approach to address the core question above, which is also applicable to similar regions worldwide; and 2) synthesize the results into an analysis of the future of water in the MRG basin. Bridging several boundaries, including disciplinary, biophysical, sectoral, social, and jurisdictional ones, to provide an integrative narrative of the future of water in our region is a significant scientific contribution of our work.

2. Methods

2.1. Our study area: the Middle Rio Grande Waterscape

Our study area is illustrated in Fig. 1 and includes the MRG and two aquifers that contain good quality freshwater, the Mesilla Bolson (MB; called Conejos Médanos in MX) and Hueco Bolson (HB; called Valle de Juárez in MX), plus the associated alluvial aquifer

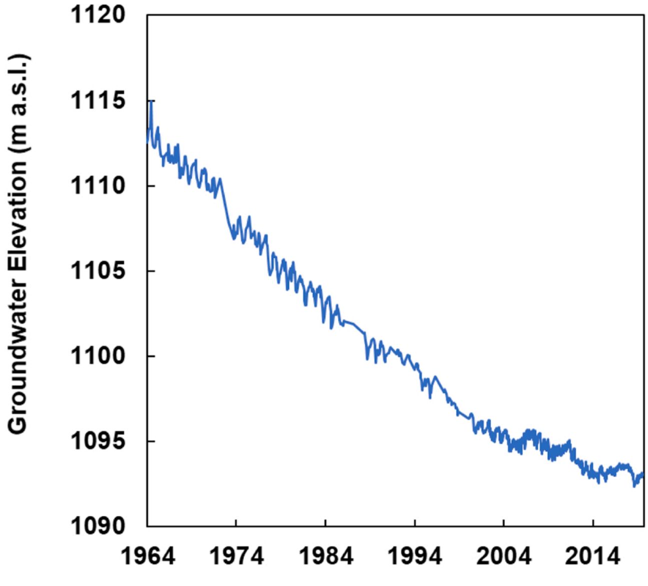

Fig. 2. Groundwater elevations in meters above sea level (m a.s.l.) in Texas Water Development Board State Well Number 4913301, located near Biggs Field, El Paso, TX.

connected to the river.

The river is the only significant source of surface water, and the two aquifers are the primary sources of fresh groundwater for users in NM, TX, and CH, which are dominated by three municipalities with a combined population of over 2 million people (Las Cruces, NM, El Paso, TX, and Ciudad Juárez, CH), and a productive irrigated agriculture in the alluvial plain of the river on both sides of the border.

Irrigated agriculture is confined primarily to the river corridor and is a highly managed system with little riparian habitat, connected to a network of irrigation canals diverting water to agriculture, and a network of drains to return unused water to the river. The amount of surface water is dictated primarily by snowfall, snowmelt, and runoff in the RG headwaters in Colorado (CO) and northern NM. Streamflow in the upper part of the basin is partitioned under the Rio Grande Compact of 1939 and the US-Mexico Treaty of 1906, legally binding agreements between upstream users and downstream users, with the water for downstream users collected and stored in several reservoirs, of which the largest is Elephant Butte (EB) Reservoir (Fig. 1).

The primary sources of good quality groundwater are contained in the HB and the MB. The deeper HB and large portions of the MB, both shared by the US and MX, are primarily "fossil" deposits of water with little or no recharge. Thus, drawdown represents withdrawals against current and future reserves of freshwater, as well as growing threats of increasing salinity in those reserves. Both aquifers contain both fresh and brackish water, with salinity levels ranging from $<$ 1000 mg/L total dissolved solids (TDS) in the freshwater to brackish concentrations of up to 3000 mg/L and higher. There is much more brackish water than freshwater.

In Mayer et al. (2021), the current rate of depletion for the HB was estimated to be 191 MCM/yr. This estimate is supported by decreases in published groundwater elevations, which have accelerated over the past 50 years (Fig. 2). We estimate that a total of more than 9000 MCM of freshwater have been removed from the HB over the past 100 years through 2013. Based on the volume of freshwater remaining and the depletion rate, Mayer et al. (2021) estimated that the recoverable freshwater will be completely depleted in approximately 42 years, with serious economic outcomes (Hurd and Coonrod, 2012), unless there are significant interventions to alter supply and/or demand. Business as usual without significant decreases to pumping is clearly not sustainable.

At the same time, both EP and CJ have experienced increasing salinity in the water being pumped, because high pumping and depletion rates have caused brackish water intrusion into freshwater zones of the HB. For example, salinity increased from 750 mg/L to 1200 mg/L from 1979 to 1993 in an El Paso Water (EPW) monitoring well, an increase of 30 mg/L per year (Mayer et al., 2021). Thus, usable freshwater might be depleted even sooner than 42 years due to saltwater intrusion.

The situation is further exacerbated by changes in the agricultural sector, where growers have transitioned away from annual crops with limited profit margins, such as cotton, to higher value perennials, such as pecans, which require comparatively much more water (Hargrove et al., 2021). The result is that while a warmer, drier climate is reducing water supplies from the river, agricultural users are driven to pump more groundwater to meet irrigation needs. This is compounded by urbanization of agricultural land due to population growth and urban sprawl (Mubako et al., 2018), resulting in increased water demand overall (Hargrove et al., 2021). Thus, finite and relatively cheap freshwater supplies are dwindling.

Some steps to augment water supplies have been taken by the two primary urban water utilities, EPW and Junta Municipal de Agua y Saneamiento (JMAS) in CJ, such as desalination and use of brackish water, increased water recycling and reuse, and importation of water. Plus, efforts to reduce demand through conservation also have been made with some success. But in sum, these efforts to augment supply and reduce demand have made and in the future, are likely to make, only relatively small changes in the regional rate of groundwater pumping and aquifer depletion, as out results will demonstrate.

2.2. Stakeholder engagement and participation

Our process of stakeholder engagement and participation is described in Hargrove and Heyman (2020) and was based on methods of participatory modeling (Morua-Robles et al., 2014; Kelly et al., 2013). Our target audiences were all stakeholders concerned about the future of water in the MRG region, and their involvement was an iterative process that built upon each encounter over the course of five years. From our work with stakeholders, including those representing agriculture, urban users, environmental concerns, social justice, and government/policy interests, we summarize below important challenges to sustainable water futures, organized into four key themes (Hargrove and Heyman, 2020), which also provided focus for our modeling work.

2.2.1. The spiral of climate change, prolonged drought, groundwater depletion, and salinization

Predicting, planning, and managing for "prolonged drought" was the top concern of most stakeholders, both agricultural and urban, coupled with concerns about the future of aquifers. Stakeholders agreed that identifying and quantifying the impact of future climate scenarios, including the depletion of groundwater reserves, was a prerequisite to planning and managing for what they termed "prolonged drought". At present, agricultural stakeholders' response to the growing unreliability of water supplies from the river is to pump more groundwater, and the response to the concomitant dropping water tables is to dig deeper wells.

2.2.2. Agricultural intensification, urbanization, and lack of conjunctive management

In brief, agricultural intensification is leading to greater extraction of groundwater as surface water supplies become increasingly unreliable. The net result is aquifer depletion and deterioration of water quality, primarily from brackish groundwater intrusion combined with return flows that are more saline than what was extracted. Components of the conjunctive water system in the basin have been modeled, but generally the connection of the surface and groundwater is poorly understood, though some progress has been made (Fuchs et al., 2019). A better understanding of the interaction of surface and groundwater to support better conjunctive management remains a research challenge. Stakeholders desire to know the limits of groundwater pumping for the future. At present, both agricultural and urban stakeholders' solution to dwindling supplies and increasing demand is to augment supplies through technology, management, and/or importation. On the other hand, environmental and social justice stakeholders tend to define the problem through the need to reduce demand by the big water users through conservation, which would allow expanded access for environmental uses and for thousands of vulnerable border residents who lack access to potable water (Hargrove et al., 2018).

2.2.3. The complexity and obsolescence of the water governance framework

The water governance framework for this binational, multi-state region was described in detail in Hargrove et al. (2021). A major deficiency is that the relevant treaty and interstate compacts were established prior to the development of a full understanding, hydrologically, of the connectivity between surface water and groundwater. Due to the fragmented jurisdictional boundaries, diverse sectoral uses, and weakly acknowledged surface/subsurface interactions (first termed "hydroschizophrenia" by Llamas (1975), applied to transboundary waters by Jarvis et al. (2005), and applied more generally to the situation in the MRG by Hargrove et al., 2021), interested parties often conceptualize the water system in divided, non-integrated ways, and therefore place blame on some other part of the system (other users or jurisdictional areas) when faced with undesirable outcomes. This has led to numerous ongoing legal challenges/lawsuits currently within NM and between TX and NM. As we will report in our results, we tried to breach these boundaries through our holistic approach.

2.2.4. Land ownership, water rights, and threats

Agricultural stakeholders, particularly in the U.S. and to a lesser degree in Mexico, have a strong feeling of ownership of water rights as part of land ownership, coupled with the concomitant sense of threat to those water rights emanating from the current

Table 1

List of models used, brief descriptions, scale of analysis, and primary benefits and limitations. Development, calibration, validation, and analysis methods for each model are provided in the given references. Additional details are provided in a Supplementary Material file.

MODEL	BRIEF DESCRIPTION	SCALE	USES/BENEFITS/LIMITATIONS	REFERENCES
Climate Scenarios	Provided future hydroclimate within the study area, and RG inflows to EB Developed from statistical adjustment to Reclamation-generated naturalized streamflow projections, derived from downscaled CMIP5 global climate model output	RG basin from headwaters to southern limits of study area	Accounts for upstream usage of water without necessitating physical models of usage High uncertainty in CMIP5 regional climate projections results in high uncertainty in streamflow projections	Townsend and Gutzler (2020)
MRG Water Balance	Systems-level model of annual surface and groundwater storage based on climate change projections (from above), surface water operating rules, and demand scenarios Accounts for all inputs, internal cycling processes, and outputs for both surface and groundwater.	MRG basin	Regional analysis of water futures/ scenarios Computationally fast Easily modifiable in real time meetings with stakeholders	Holmes et al. (2022) Mayer et al. (2021)
Hydroeconomic "Bucket"	Optimization framework using the water balance model hydrologic inputs and other external data Simulates all the major sources, sinks, uses, and losses for the MRG Identifies future water use and economic outcomes that produce the highest economic benefit summed over locations, sectors, and time periods selected by the user.	MRG basin	Explicitly incorporates a wide variety of economic, environmental, urban, surface water, groundwater, and crop variables Water quantity only is considered (not quality) Best used in paired comparisons, with and without a proposed change, to permit assessment of proposed change; otherwise, results are hard to interpret	Ward (2016) Ward et al. (2019) Torell et al. (2022)
LULC	Historical land cover change using spectral analysis of NDVI and a MARKOV change analysis	Middle Rio Grande basin	Quantifies patterns of land use/land cover change that can be used to describe broad patterns of land conversion through time Future land use projections were not simulated	Alatorre et al. (2018) Mubako et al. (2018)
SWAT-mf (SWAT integrated with MODFLOW) SWAT-Salt (SWAT with salt module)	Simulation of surface and ground water quantity and salinity at high spatial and temporal resolution	Small watershed scale, including HB and MB	Simultaneously simulates surface and groundwater; provides detailed information by sub-watershed Includes both water quantity and salinity Simulates crop production Provides analysis of interventions to reduce water use and/or adapt to reduced water availability Computationally intensive	Ahn et al. (2018) Pinales-Munguía et al. (2019) Samimi et al. (2019) Ahn and Sheng (2021) Jung et al. (2021) Samimi et al. (2022a, 2022b)
SMITUV (STELLA® -based model)	System dynamic model for field scale salinity in pecan	Field scale	Explicit analysis of causal feedback loops Simple for stakeholders to understand	Poulouse et al. (2021) Palmate et al. (2022)

situation of increasingly unreliable water supplies (Hargrove and Heyman, 2020). The sense of threat, the growing unreliability of water supplies, and the growing tension among different sectors of users and across jurisdictional boundaries converge to put farmers "on guard" against multiple threats and risks to not only their rights to water, but to their livelihood and quality of life (Brause, 2021). They tend to approach these perceived threats from a standpoint of "scarcity", commonly blaming competing users for the unreliability of water supplies for agriculture. This stance adds to the "wickedness" of the problem in visualizing and addressing water futures.

2.3. *Theory: crossing boundaries in evaluating water futures*

To address the core question and the chief concerns of stakeholders identified above, we focused our research on "water futures", considering possible, probable, and preferable future outcomes from the known drivers of change, and considering interventions that could alter those outcomes. We accomplished this by developing and evaluating scenarios, using models and with the input and participation of stakeholders. To evaluate water futures, we integrated dynamics across numerous dimensions that ordinarily are bounded and studied separately from each other (for example, Granados-Olivas et al., 2019). Our research goal was to use modeling approaches that integrate across an array of, artificial divisions (*i.e.*, surface/subsurface water, urban/agricultural/environmental uses, and international/interstate jurisdictions); use stakeholder inputs and modeling outputs to evaluate water futures; and address concerns of stakeholders about water futures, including evaluating improvements in management/technology/policy. Such connections are usually acknowledged, but less often breached in practice, because a large, interdisciplinary, binational team is needed to do so. As a result, the interacting dynamics across biophysical and sociopolitical dimensions are, in general, poorly integrated in either research or practice. The value of our integrative project was to unify all the drivers, stocks, and flows of water in one integrated vision of the regional system across conventional boundaries. Drawing on our own published work and that of others, we present here the results of our synthesis, especially results for several "boundary crossing" processes that we addressed, that inform not only the future of the MRG, but also similar desert river systems in the southwestern US and around the world. Our contribution is a holistic vision of water sustainability challenges and potential solutions for the future, based on our own and other published work on components of the system in our region.

2.4. *Modeling framework*

We developed and/or evaluated a suite of calibrated models that performed at various spatial (from agricultural field to river basin) and temporal (from daily to decades) scales, and which functioned across biophysical and jurisdictional boundaries, to address the important themes and research questions of concern about future conditions and potential interventions that could alter future conditions. Our suite of modeling tools are presented and summarized in Table 1. Below we briefly describe some of the specific uses of each model in our analyses. Throughout the modeling activities, we incorporated stakeholder participation in an iterative way as we tested scenarios, shared results, discussed interventions, and tested interventions (Hargrove and Heyman, 2020).

Scientifically sound climate scenarios for the future were fundamental to our modeling work. We developed several climate scenarios to use in simulations with the Bucket Model, the MRG Water Balance Model and the suite of SWAT-MODFLOW based models. We used a large ensemble of USBR-generated projections of naturalized streamflow along the RG, which were driven by CMIP5 Global Climate Model simulations. The USBR simulations are widely used by regional water managers, providing us with an ensemble of state-of-the-art, credible projections of future climate and streamflow, including a wide range of global climate models and future greenhouse gas forcing scenarios. Output used in our research included bias-adjusted, downscaled temperature and precipitation in the study area and associated projections of naturalized RG flow. The procedures used for statistical downscaling (BCSD) and the surface hydrological model driven by simulated climate variables (VIC) are discussed in detail by USBR (2013) and Llewellyn et al. (2013).

For our project, Townsend and Gutzler (2020) developed an adjustment algorithm to shift USBR's flow projections from EB dam to a point upstream corresponding to the San Marcial gage near the inlet to EB reservoir. More importantly, the adjustment procedure also statistically accounted for upstream anthropogenic withdrawals, by bias-correcting the simulated annual flows during a historical period to match the statistics of gaged flow at San Marcial. Preserving this bias adjustment into the future essentially assumes no change in upstream water management policy through this century (Townsend and Gutzler, 2020).

The MRG Water Balance Model was used to develop projections of the future of water resources in the region under: 1) "business as usual" conditions, 2) future climate scenarios, 3) changing demands for water, and 4) conjunctive management to include consequences of groundwater pumping, irrigation system efficiency, and seepage from the main channel of the RG and irrigation channels. This model was also enhanced or combined with other cost accounting models to project future costs for urban water, assess costs of environmental flows, and address policy questions.

The hydroeconomic optimization "Bucket" model was used in paired comparisons with and without proposed interventions to permit assessment of changes in outcomes. The annual water balance component of the Bucket Model was used to simulate storages and flows for climate scenarios in a "futures" mode. Sub-models were developed for reservoir evaporation rates, reservoir elevation-storage-surface area, irrigated agriculture evapotranspiration and return flows, urban evapotranspiration and return flows, groundwater-surface water exchanges, and groundwater elevations. It was used as a decision support framework for improving our and stakeholders' understanding of the basin, evaluating scenarios from an economics perspective, and addressing questions that were important to stakeholders.

SWIM 1.0, the user interface with the Bucket Model, enables users to graphically: a) define default or customized parameters representing human activities and climate scenarios, b) seamlessly run the Bucket Model, c) graphically explore the outputs of the model, and d) graphically explore the sources and processing (provenance) of the data (Villanueva-Rosales et al., 2017;

Garnica-Chavira et al., 2018). Links to SWIM 1.0 are provided in Table S1 in the Supplementary Material file. An improved version, SWIM 2.0, will expand its capabilities and uses, and continue to provide access to the Bucket Model and MRG Water Balance Model.

To assess land use and land cover change (LULC), we produced historical and current land use/land cover maps, and the results were used in the Bucket and SWAT models to evaluate water use implications of LULC. This required development of a methodology for improving land use classification through analyzing patterns of temporal change (Mubako et al., 2018). We successfully completed the generation of the annual LULC maps from 1990 to 2015 for the entire US-MX study area (Mubako et al., 2018) and evaluated land cover change through a MARKOV change analysis. Future projections of land use change were not made.

SWAT-mf was used in a variety of ways, including evaluation of climate change impacts, agricultural water management interventions, and adaptation to cope with warm-dry futures (Pinales-Munguía et al., 2019; Samimi et al., 2018, 2020, 2022, 2023). We also modified SWAT with a salinity module, and simulated salinity processes in the EB Irrigation District using the SWAT-Salt to assess biophysical factors that impact salinity (Samimi et al., 2019). SMITUV, a system dynamic model in STELLA®, was used for assessing field scale salinity in pecan (Poulose et al., 2021; Palmate et al., 2022).

3. Results

We synthesize and organize our results into four major themes in response to stakeholders' chief concerns and described above in Section 2.2: 1) Climate change and the future of surface and groundwater; 2) Agricultural intensification and the future of agriculture; 3) Urbanization and the future for urban water use; and 4) Implications for the future of water governance.

3.1. Theme: climate change and the future of surface and groundwater

3.1.1. Impacts of climate change on the future of surface water

USBR's CMIP5-based future climate projections range from very wet to very dry, spanning an enormous range that limits certainty in future water supply projections (Lehner et al., 2019). Assessing which projections are most likely was beyond the scope of our project. We provide here an example of some results of projections of streamflow into EB Reservoir (Fig. 3, adapted from Townsend and Gutzler, 2020). To bracket the possibilities in future climate, we chose specific simulations that included a very wet future, simulating flows that tend to increase with time (green curve in Fig. 3), a midrange projection that exhibits drier conditions after mid-century (purple curve in Fig. 3), and a very dry simulation that includes almost no high-flow years in the future (red curve in Fig. 3). This wide range of future RG inflow scenarios was used as input to many of the other modeling assessments carried out to examine potential climate change impacts on reservoir management, groundwater, and crop selection strategies, as described in the sections to follow.

The ensemble of simulations (black curves in Fig. 4) exhibits a trend toward more prolonged drought and dwindling supplies of surface water over the next 50 years, consistent with recent consensus assessments of likely future trends in streamflow and aridity in the southwestern US (Jay et al., 2018; Hicke et al., 2022). The ensemble average decline occurs despite the presence of several very wet simulations (such as the green curve in Fig. 4).

The implications for surface water supplies associated with the three individual scenarios in Fig. 3 were explored using the MRG Water Balance Model (Fig. 4, adapted from Holmes et al., 2022). In these scenarios, surface water collected in EB reservoir met

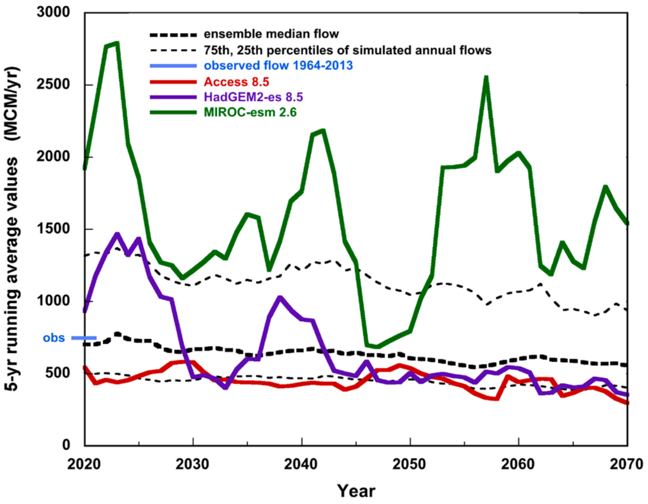

Fig. 3. Projected Rio Grande flow for 2020–2070, based on CMIP5 projections starting in 2006, at the San Marcial combined gage point. Median annual observed flow at San Marcial over 50 years (1964–2013) is shown in blue on the y-axis for comparison. Ensemble statistics of 64 simulations (25–50–75 percentile values) for each year are shown as black dashed lines, with the median (50%) line in bold. Three individual simulations used in the Water Balance model are shown as solid-colored lines. Red, very dry scenario; purple moderately dry scenario; green, very wet scenario. Each line shows 5-year running mean values for readability and to emphasize long-term fluctuations.

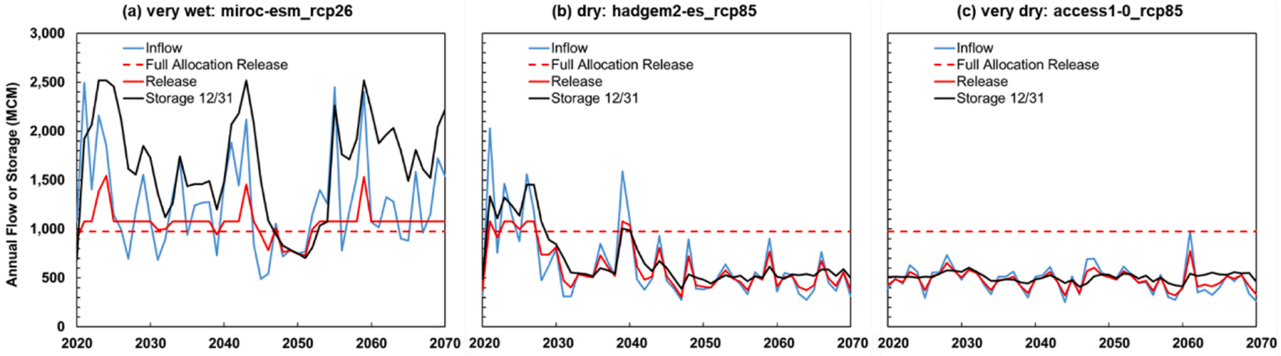

Fig. 4. Projected annual reservoir inflow (Rio Grande at San Marcial, blue curve), surface water supplies in storage (dark gray), and reservoir releases (solid red), derived from the Water Balance model driven by the three individual flow projections shown in Fig. 4: (a) MIROC 2.6 (green line in Fig. 4); (b) HadGEM2 8.5 (purple line in Fig. 4); (c) Access 8.5 (red line in Fig. 4).

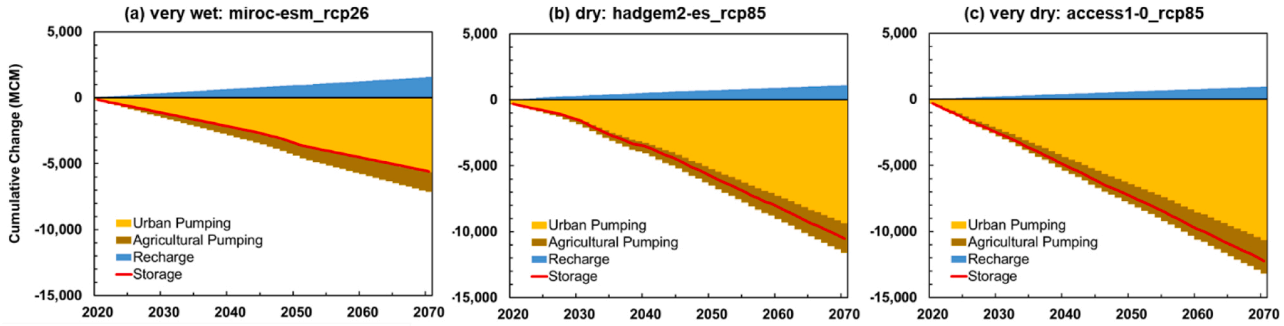

Fig. 5. Projected impacts of three climate scenarios on cumulative urban pumping, pumping for agricultural irrigation, recharge (including return flows), and groundwater storage, starting in 2020 for the Hueco Bolson aquifer. Pumping is shown as negative values and recharge is shown as positive values.

allocated demand in only about 20% of the years under the midrange drier scenario (purple curve in Figs. 3 and 4 b), and did not meet full demand at any time during the period of simulation under the very dry scenario (red curve in Figs. 3 and 4a).

3.1.2. *Impacts of climate change on the future of groundwater*

The drivers of change discussed above for surface water (climate plus growing demands), plus compensatory groundwater use to meet surface water shortfalls, portend the exacerbation of groundwater declines for the future. Projected impacts of climate change on groundwater storage in the Hueco Bolson are shown in Fig. 5 for the same climate scenarios used in Fig. 4: a very dry future, a moderately dry future, and a very wet future. Results show that for the very dry scenario, the freshwater in the HB could be depleted in only 30 years, and for the moderately dry scenario, about 40–50 years.

3.2. *Theme: agricultural intensification and the future of agriculture*

3.2.1. *Intensification of agriculture and its impact on total demand*

The results of decreasing surface supply under changing climate and increasing total demand under agricultural intensification, lead to increasingly large and sustained deficits in surface water supply, which in turn lead to more groundwater use to make up the surface water deficit.

Plus, the groundwater being pumped today is increasingly saline as the freshwater of the shared aquifers is depleted. If the current trajectory of intensification of production continues, it will have significant implications for sustainable water management in the region. Our results (Samimi et al., 2023) show that if we were to experience a prolonged drought of 8–10 years, for example, current irrigation methods/limits would fail to meet the needs of pecans unless all other crops are removed from production to save pecan orchards (Fig. 6). Relatively strong measures, such as eliminating the cultivation of alfalfa, for example, generate only moderate water savings (Samimi et al., 2023). More extreme interventions will be needed under continuing climate change as agricultural intensification continues.

3.2.2. *Potential interventions*

3.2.2.1. Alternative sources of water. Almost all treated wastewater is used already for irrigation in our region. Another potentially significant alternative source is brackish water, which is not used at this time for irrigation. Using our models, we evaluated pecan water use for two future adaptation scenarios in a dry climate future (Samimi et al., 2022): a) irrigation with river water, fresh groundwater, and desalinated groundwater; this exemplifies a dry period where surface water is inadequate, there is heavy reliance on groundwater, and desalination is available to treat brackish groundwater; and b) irrigation with river water and fresh groundwater only; this exemplifies a dry period where surface water is inadequate, there is heavy reliance on groundwater that is becoming more saline, and desalination is not available (Fig. 7). These results show that as groundwater becomes more saline, agricultural productivity decreases unless saline groundwater can be treated or replaced with alternate sources, either of which will be very costly.

We conducted a cost analysis of desalination in agriculture. We examined the potential for irrigating salt-sensitive crops (*e.g.*, pecans) with blends of desalinated brackish groundwater and fresh surface or groundwater and irrigating salt-tolerant crops (*e.g.*, quinoa) with desalination concentrate water. We used a simple cost-benefit model that estimated crop yields based on irrigation water

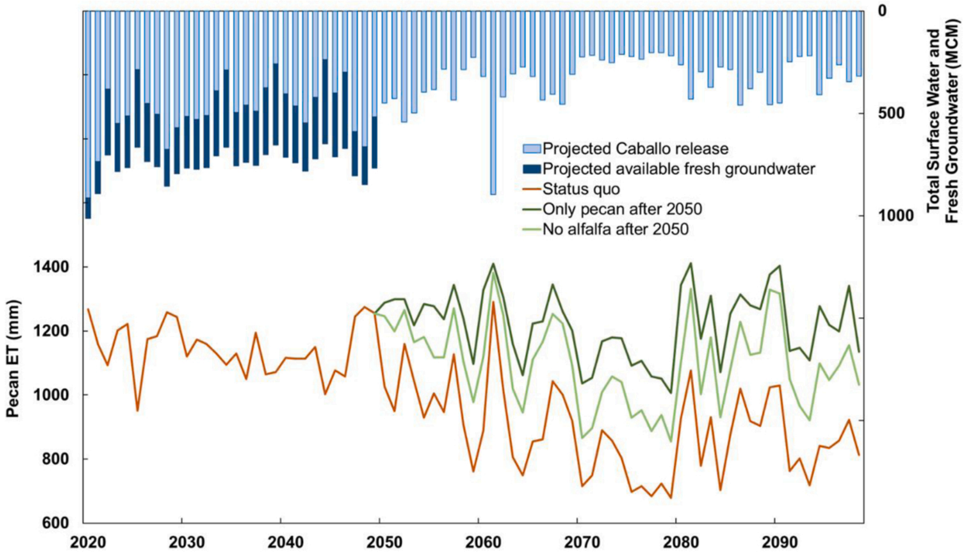

Fig. 6. Pecan ET and surface water and groundwater availability with different intervention scenarios under dry climate scenario (access 1–0_rcp85), from Samimi et al. (2022).

salinity. The net return was based on gross returns from the harvested crops minus production costs. Production costs included the net present value for purchasing and operating the desalination unit and other farm input expenses, such as labor, fertilizer, and operation of machinery. Irrigation water scheduling was based on current practices in the region.

The results of this simple analysis resulted in desalination costs that are prohibitive compared to the net returns. The costs exceeded benefits over a range of sensitive variables such as the fractions of salt-sensitive and salt-tolerant crops, desalinated water/freshwater blends, energy prices, and discount rates. However, desalination costs to farmers could be reduced by offsetting the purchase price with incentives and/or by using solar power to generate the electricity required by the desalination system. Furthermore, salt tolerant crops, such as quinoa, have not been cultivated in the region, so it is not known if farmers would be willing to dedicate land to adopting these crops with no processing or marketing infrastructure in place.

3.2.2.2. Alternative methods and improved management of irrigation. Flood irrigation remains the predominant form of irrigation in the study area. In terms of water use efficiency, flood irrigation is generally in the range of 65–70%. Most of the unused 30–35% of applied water percolates below the root zone, with about 5–10% being lost to evaporation (Samani et al., 2011). We evaluated several improved irrigation methods including surge irrigation and drip irrigation (Alatorre-Cejudo et al., 2019; Ganjegunte et al., 2020). Drip irrigation can improve efficiency to 80–90% but has a significant capital cost. Furthermore, many irrigators are reluctant to adopt high efficiency irrigation methods such as drip irrigation because of salinity concerns.

We compared rootzone salinity under four types of irrigation systems with water having an electrical conductivity (EC) of 1 dS/m (Ganjegunte et al., 2020). Results showed that flood irrigation resulted in higher salinity in the root zone compared to drip or surge irrigation. The subsurface drip evaluation was in a turf field and resulted in concentrated salinity at the soil surface because salts accumulated at the drip line and migrated to the soil surface due to high evaporation rates. Surge or surface drip irrigation shows a lot of promise for decreasing total water use, especially when using groundwater as the source (Cox et al., 2018; Deb et al., 2013; Stetson and Mecham, 2011; ShalekBriski et al., 2019). Flood irrigation using surface water is not as efficient in terms of crop production, but the water lost to percolation becomes recharge to groundwater.

A time-based method of scheduling irrigation is followed by most irrigators in our region and is based on simply counting the number of days since the last irrigation. By using evapotranspiration (ET)-based irrigation scheduling, our results show that at least two irrigations per season can be saved without reductions in yield (Ganjegunte et al., 2012). For example, with an estimated 6100 ha in pecans in the El Paso County irrigation district and 127 mm/irrigation, 2 fewer irrigations translate into a potential water savings of 15 MCM per year.

3.2.2.3. Improved salinity management. As groundwater becomes more saline, soil salinity builds up over time. Gypsum as a soil amendment improves the leaching of salt in soil because calcium sulfate is very effective at replacing sodium chloride (Ganjegunte et al., 2017). Using a “sulfur burner” is also effective in converting elemental sulfur to sulfate (through oxidation) which will form calcium sulfate in soil and, in turn, leach sodium salts from the profile. This was shown to be an effective treatment for reducing salt in soil (Ganjegunte et al., 2018; Ganjegunte and Clark, 2019).

3.2.2.4. Alternative crops. We evaluated several alternative crops to pecan, such as other perennials like pistachio, pomegranate (Niu et al., 2018; Hooks et al., 2021), and switchgrass (Sun et al., 2018) and annuals such as guar, energy sorghum, forage sorghum, and canola (Suthar et al., 2018a, 2018b, 2019). Though these crops are generally adapted to the climate and soil conditions of our region, they cannot compete economically with pecan, under current economic conditions. Also, in many cases, transitioning to these crops is limited by the lack of crop-specialized infrastructure, such as processing facilities, and/or developed markets (Chaganti et al., 2020, 2021a, 2021b). In summary, though alternative crops have the potential to produce with much less water inputs, they will not be

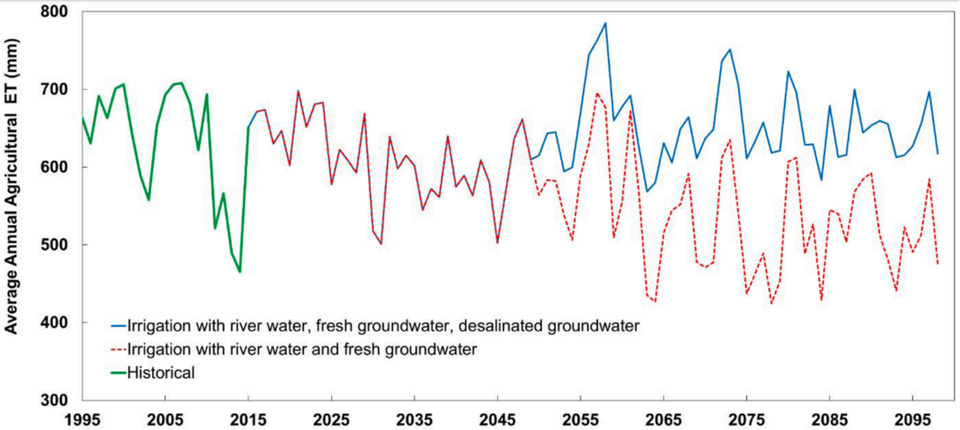

Fig. 7. Future projection for pecan ET with and without the benefit of desalinated groundwater as an additional water source for dry climate scenario (access 1–0_rcp85).

adopted under current conditions without significant financial investments in infrastructure, external incentives to farmers, or both.

3.3. Theme: urbanization and the future of urban water use

3.3.1. Current water use by EP/CJ

Though the three largest cities in the region (EP, LC, and CJ) rely primarily on groundwater from the MB and HB, it is important to recognize that the cities use other water sources as well. Fig. 8 illustrates the average volume of water from each source delivered to treatment facilities in EP and CJ. EP's water portfolio is more diverse than that of CJ. CJ's large dependence on HB freshwater makes it more vulnerable, as freshwater storage in HB is depleted. Table 2 presents water use from EP, CJ, and LC (Alger et al., 2020). These results show that CJ uses more water than EP, but since the population in CJ greatly exceeds that of El Paso, the per capita use in EP is almost twice that of CJ (CJ: 135; EP: 235 m^3). The difference in per capita use is explained mostly by the greater evaporative outdoor use in EP (more than 50% of total use in EP and only 33% in CJ).

3.3.2. The future under "Business as Usual"

We developed a baseline scenario that was meant to set the stage for choosing interventions that might alter the future. The baseline scenario assumes that urban populations and thus water demands will increase and there will be no significant change in policies that would slow depletion of the HB. Thus, it describes a future with "business as usual" (BAU). Our BAU scenario spans a 50-year period (2020–2070) and is based on the following assumptions.

a. Population will increase by 66% in CJ and 35% in EP, and per capita usage will remain the same, resulting in an average annual demand for CJ of 252 MCM/yr and El Paso of 174 MCM/yr over the 50-year period.
b. Pumping from the HB will increase in proportion to the increase in demand for the two cities.
c. Water availability from the RG will be reduced over the period due to low flows caused by climate change in the headwaters, resulting in a reduction of the availability from this source for EPW of 26–37 MCM/yr for most years.
d. Warmer temperatures will impact water demand in cities, including a lengthening growing season by at least 4–6 weeks, and more days over 38 degrees C. These changes cause greater total ET from landscaping and outdoor green spaces.
e. Other users, especially irrigators will use more groundwater for reasons described above.
f. Recharge from the river will decrease because flow will be reduced due to climate change, while recharge from canals also will diminish as irrigation districts concrete-line their ditches to enhance downstream deliveries.
g. Average salinity in groundwater pumped from the HB will increase from 500 mg/L to over 1500 mg/L as TDS.
h. Average groundwater levels in the HB will change at a rate equivalent to the depletion rate.

The result of projecting the BAU scenario 50 years into the future is shown in Fig. 9. Given a depletion rate of 258 MCM/yr and an estimate for recoverable freshwater of 8018 MCM, the recoverable freshwater would be completely depleted in 31 years (derived from Fig. 9), where compete depletion is defined by the point at which the aquifer can no longer support the water supply needs of users. Furthermore, the negative impacts of depletion could affect users well before complete depletion, since cones of depression around wells could increase faster than average, making water levels drop below the well intake, necessitating either abandonment or drilling

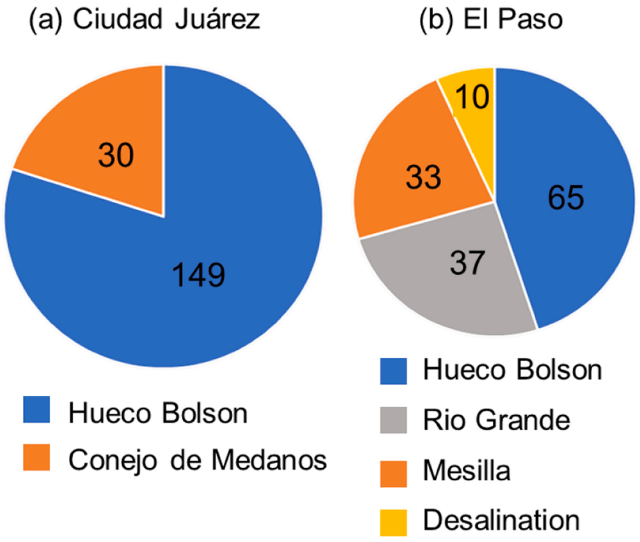

Fig. 8. Current sources of water supplies in annual volumes (MCM/yr) for (a) Ciudad Juárez and (b) El Paso; the Rio Grande source is available only when there is adequate flow, a condition that is not frequent in the past 20 years and becoming less frequent with time.

Table 2
Water use in Ciudad Juarez, El Paso, and Las Cruces by use category in millions of cubic meters/year (MCM/yr).

	Ciudad Juárez	El Paso	Las Cruces
Evaporative Use	64	91	12
Indoor Use	95	65	14
Infrastructure Losses	33	5	3
Total Water Use	192	161	29

deeper wells (also from Fig. 9). Regardless, it is certain that pumping costs will grow substantially throughout the 50-yr period of projection as a result of dropping water tables and energy costs. Under this BAU scenario, usable freshwater in the HB will be completely depleted by about the year 2050, or before, depending on the salinity dynamics. Meeting drinking and other household needs for water for millions of people on both sides of the border are compelling reasons for stakeholders to identify affordable and effective solutions to aquifer depletion. Clearly, action is called for to avert this devastating result.

3.3.3. Future supply and demand and cost of alternative sources

Fig. 10 shows the projected population growth and concomitant water demand relative to current supply. Projected demand is expected to exceed projected supply within the next thirty or so years (assuming no change in per capita consumption). As groundwater sources are depleted, alternative sources will have to be "tapped" to meet growing demand, resulting in increased cost of water to residents (Fig. 11). The least expensive alternative source is desalination of brackish groundwater, while water importation is the most expensive. Furthermore, urban centers can improve water sustainability and resiliency by reusing municipal wastewater, especially for drinking water supplies. Direct potable reuse of wastewater could reduce the amount of fresh groundwater pumping by cities, though it is a very expensive alternative and carries a certain amount of consumer stigma.

We evaluated several conservation practices at the household level for urban consumers (Capt et al., 2021). The greatest consumptive use in the urban environment, and thus the greatest opportunity for conservation, is outdoor vegetation and evaporation from bare soil (Alger et al., 2020). Reducing landscaping uses of water through practices like xeriscaping and others would be an effective way to reduce urban demand, and if incentivized, could be financially attractive to urban water users. Also, rainwater harvesting and its use for outdoor watering is an effective way to reduce use of potable water for landscaping (Hargrove et al., 2020).

Regardless, since alternative sources are several times more expensive per unit volume than current sources and reductions in per capita consumption cannot reasonably make up the difference, consumers will have to expect to pay considerably more for potable water in the future as alternative sources become necessary.

3.4. Theme: implications of water futures for water governance

3.4.1. Management of EB reservoir

We evaluated the impact of the current EB reservoir operating rules for downstream releases on the ability to account for climate change and resulting conditions in the watershed (Holmes et al., 2022). We addressed these questions: (a) under current operating rules, how will downstream surface water supplies be affected by projected climate change? (b) how resilient are the current reservoir management rules to projected climate change? (c) how will increases in temperature, which will lead to higher evaporative losses from reservoirs, compare to impacts on upstream snow-fed flows?

Results from Holmes et al. (2022) for future climate simulations with warming temperatures showed decreases in surface water

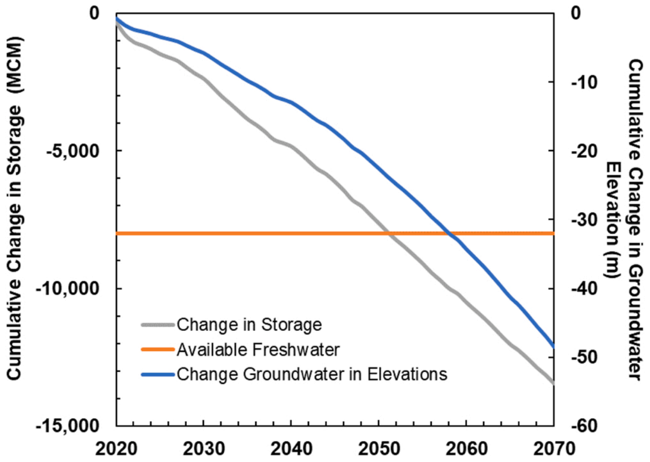

Fig. 9. The future under "business as usual:" Projected change in recoverable freshwater in storage and cumulative change in average groundwater elevations starting in 2020.

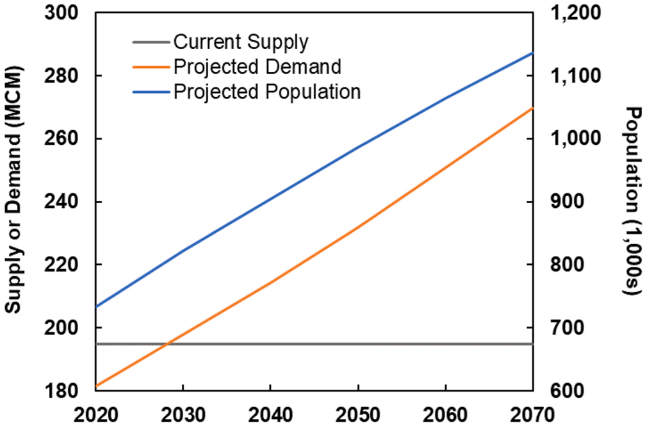

Fig. 10. Projected population growth and concomitant water demand relative to current supply.

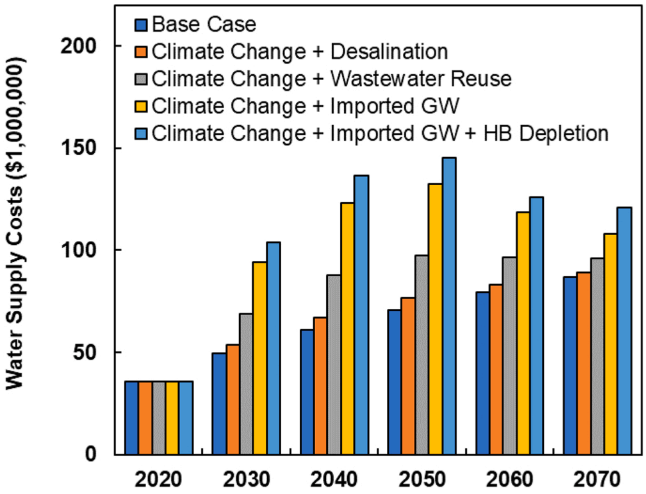

Fig. 11. Future water supply costs in millions of U.S. dollars for different water supply strategies in El Paso.

supplies across all parameters explored. Despite increasing evaporation rates associated with warmer temperatures in our climate projections, there was little change in the volume lost to reservoir surface evaporation compared to the past 50 years. This is because the operating agreement for releasing water from the reservoir results in continuously low reservoir surface area, and thus similar evaporation volumes, under low inflows. Thus, maintaining the current operating agreement for releases under a warming climate results in lower downstream water availability overall. Local precipitation and evaporation had little impact on reservoir storage, and thus, future water supply in the MRG is relatively insensitive to projected changes in local precipitation. Instead, the water supply is strongly determined by diminishing snowmelt runoff occurring far upstream. Unfortunately, this means that water managers and/or users would have limited ability to impact water supply through local water capture or changes in storage policies because such policies are unlikely to compensate for diminishing water flows into the reservoir.

Our results show that water availability will need to be addressed through changes in policies that impact reservoir releases and the related water demand downstream. For our study, reservoir management practices were held constant throughout the study period, which allowed us to isolate the hydrologic effects of climate change on water availability. But, given the high probability of reduced flows into the reservoir, managers and users will need to find ways to adapt to diminishing reliability of water availability by reconsidering reservoir operating policies and/or renegotiating water sharing agreements, to better match the water demand with a diminishing supply that the reservoir system can support.

3.4.2. Environmental flows

Historically, almost no surface water has been allocated to serve environmental needs in the region. By agreement with the USBR, all the water stored in EB Reservoir is allocated to the two irrigation districts in NM and TX, and by treaty, to the irrigation district in CH. This precludes environmental uses of RG water and remains a subject of debate for future water policy. The International Boundary and Water Commission (IBWC) has proposed periodic pulse flows in times of ample supply to flood riparian areas to encourage riparian vegetation. We evaluated the water requirements for pulse flows every 5–10 years (Table 3). For this evaluation, we applied the hydroeconomic optimization “Bucket” model to investigate cost to water users as a result of securing water for environmental flows without assigning any economic benefit to environmental flows (Torell et al., 2022). Two EB inflow scenarios were considered: 1) a baseline of historical weather (1995–2015) + a very wet scenario projection (2016–2024); and 2) 50% of inflows as prescribed for scenario 1 above.

We calculated the amounts of water and approximate costs for each of these scenarios. At best, out of any climate or pulse flow timing scenario, the total value of water is reduced by only 0.05%. At worst, the total value of water is reduced by 2.5%. This strategy would require relatively small amounts of water, amounting to generally less than 2% of the total annual flow in any one year. Yet there currently is insufficient political will to make changes to provide this amount of water for environmental flows.

3.4.3. *Agricultural interventions to improve water use efficiency and decrease total water use*

We evaluated several interventions that are technically feasible and that could change either water use efficiency and/or total water use in agriculture significantly. Specifically, “game-changing” interventions include desalination of brackish groundwater, conversion from flood to drip irrigation, and alternative crops that would require much less water. All of these either would require considerable capital expense to implement (desalination and drip irrigation) or are much less profitable than pecan production. We tested these ideas with stakeholders but found no interest or desire to implement these practices without considerable financial incentives. Other interventions that are less costly and that they are willing to implement have much smaller, but still significant impacts (like improved irrigation timing for example). Interventions that will have significant impact will require policies to incentivize their adoption.

3.4.4. *Slowing groundwater depletion*

At present, there is no shared governance of groundwater in the HB, either binationally or between states, but governed instead by the rules and regulations of the individual states and/or countries who share it. Furthermore, the hydrological fact that surface and subsurface water are connected and should be managed conjunctively is not considered in this strictly delineated governance system (Hargrove et al., 2021).

Based on these conditions, we evaluated, with stakeholders, possible and preferable changes to water governance that would prolong the life of the aquifer. We conducted a binational, multisector, serious games workshop to explore collaborative solutions for extending the life of the shared HB aquifer (Mayer et al., 2021). We evaluated several potential pumping restrictions with stakeholders including: 1) each city (EP and CJ) reduce pumping by 15%, 2) each city reduce pumping by 25MCM/yr, 3) each city reduce pumping by 35%, 4) each city reduce pumping by 50 MCM/yr, 5) each city reduce pumping by 35% plus reduce demand by 13%, and 6) reduce pumping by 50MC/yr and reduce demand by 44 MCM/yr. Since CJ relies much more on the HB and pumps much more than EP, equal percentage reductions mean that CJ has to reduce pumping by much larger amounts than EP. Stakeholder preferences spanned the range of choices with no clear consensus on preference (detailed results can be found in Mayer et al., 2021). Since the two countries come to the issue with uneven financial and technical resources and different political and social constraints, an easy and obvious solution is not possible. Even though we did not achieve a consensus, the value of the serious game workshop was building knowledge, interest, understanding, and mutual recognition among stakeholders from both sides of the border in an informal setting. The qualities of mutual respect and trust, essential for long-run convergence, were enhanced by shared learning in the games process (e.g., a key realization was the cost and necessity of ensuring water supply for the municipal utilities, especially CJ). In spite of not achieving consensus on a single path forward, frameworks for potential binational solutions emerged, including: (1) participants agreed that action to slow the drawdown of fresh water in the HB is needed because of the serious negative effects to the region of completely depleting its freshwater; (2) prolonging the life of the freshwater aquifer will require binational action because unilateral action on one side of the border is not enough; and (3) solutions all include conservation of freshwater pumping from the aquifer—the remaining differences being in the level of reduction and cost of conservation and alternative replacement to carry out that reduction. Such stakeholder consensus sets the stage for future discussions and negotiations aimed at binational cooperation in adaptive management.

3.4.5. *Affordability of and access to potable water for vulnerable populations*

The rising costs of water are expected to have undue impact on vulnerable populations in EP, a city in which 17.6% of the population lives below the poverty line. We assessed these impacts through a household level analysis in different census tracts (Heyman et al., 2022) in the context of varying water supply scenarios facing EPW, plus different climate and fresh groundwater depletion scenarios, as well as regional demographic growth scenarios. This was used then to calculate future costs to consumers, following current billing practice.

Table 3
Estimated costs of environmental flows.

	Value as DNPV* ($thousands)	
	Baseline Inflows	50% of Baseline Inflows
No Pulse Flow and Baseline Inflows	$20,932	
Best Performing Pulse Flow Scheduling	$20,922	$20,413
Worst Performing Pulse Flow Scheduling	$20,913	$20,405

[*] Discounted Net Present Value, 5% Discount Rate

All future supply models were dramatically more costly. Fig. 12, from Heyman et al. (2022), shows significant impacts of higher costs on poor areas of the city, seen in deeper orange and red. They show profound cost of living impacts on low-income households even for a minimal human need for water and cooling, with potential for widespread debt and shutoffs. These results show the need for future policy discussions to address social justice concerns related to the much greater cost of water.

4. Discussion

4.1. Approach

Our project focused on the future of water in our region, a region that is characterized by increasing water scarcity as supplies dwindle and demands rise. Addressing our objective of demonstrating and testing a holistic and integrated approach to addressing the core question regarding the future sustainability of water in the region, required us to breach several common boundaries: surface and subsurface water; water quantity and quality (primarily salt); agricultural, urban and industrial, and ecosystem services sectors; and the political jurisdictions of three states (TX, NM, and CH) in two nations (the US and MX). Our research results and products were directed toward issues and questions identified at the start of the project by stakeholders. Several researchers have proven and/or reviewed the positive results of stakeholder engagement and participatory approaches to water resources management (Robles-Morua et al., 2014; Megdal et al., 2016; Basco-Carrera et al., 2017), but few have included the wide range of stakeholders that we did and focused stakeholder engagement on projections of the future (Hargrove and Heyman, 2020). The research required a large and diverse team from six institutions in the US and MX. In particular, the work of our modeling team culminated in making major models like the Bucket Model and MRG Water Balance model available through SWIM, and the results from more computationally demanding models (like SWAT-Modflow, SWAT-Salt, and others) available to stakeholders. Our approach was built on working in interdisciplinary teams, focused on the problems identified by stakeholders, and cutting across sectors of users and political boundaries. Our research team, representing a range of disciplines and the range of geographies of the region, functioned as a whole rather than siloed components, breeching a chief challenge of wicked water resources problems (Freeman, 2000). This required frequent and regular communications and in-person working meetings. In addition to stakeholders, we also engaged students at every level of this important work, and thereby modeled interdisciplinary, problem-solving research approaches as part of their training and education. The result is that we brought together many of the challenging pieces of the wicked water resources problem in the MRG and at least provided a coherent and holistic view of the water future, though the preferred interventions are not yet agreed upon (Mayer et al., 2021).

4.2. Implications of results for the future of water in the MRG

Our results show that there is a high probability of declining surface water inflows due to climate change in the Rio Grande headwaters, found also by Christensen et al. (2004), Hurd and Coonrod (2012), and Garfin et al. (2018). Our contribution is that we provide some quantification of these deficits for fifty years into the future using future climate projections. Our results show that there is increased risk of prolonged surface water shortages, since EB Reservoir will frequently be below 10% and 50% full under current water release protocols and will meet irrigation demands only 20% of the time under a plausible, drier future climate scenario. In spite of these deficits, relatively low volumes of water would be required for environmental pulse flows, a need emphasized by Llewellyn et al. (2013), and would result in relatively small reductions in the total value of water in the region while meeting important environmental goals.

Increased groundwater extraction is now, and will continue to be, the response to decreased surface water, as is the case for many other similarly challenged basins (Lamontagne et al., 2014; McCallum et al., 2013; Famiglietti, 2014). Most of the groundwater pumped and the surface water delivered for irrigation in agriculture or used outdoors in urban areas is consumed via ET. Extreme interventions will be needed in agriculture in order to sustain agricultural intensification under continuing climate change. Some

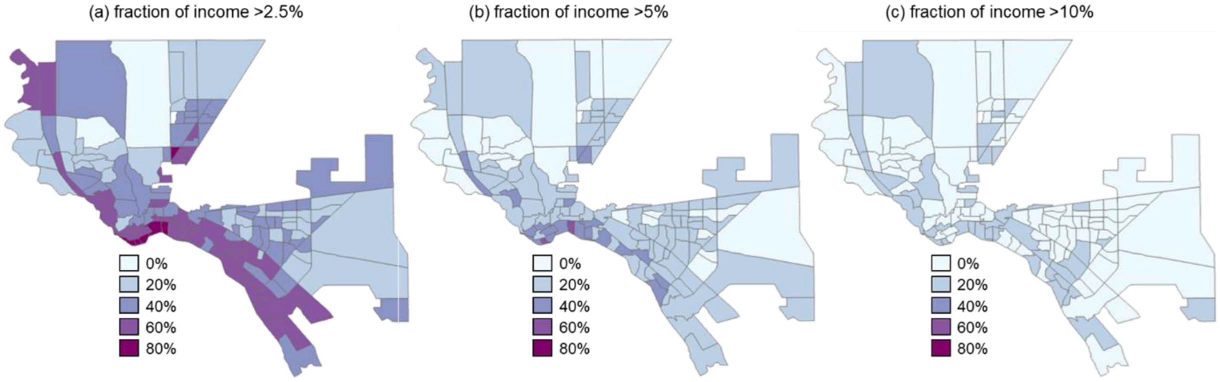

Fig. 12. Fractions of households in census tracts (indicated by color shading) with fractions of income spent on municipal water of (a) $\geq 2.5\%$, (b) $\geq 5\%$, and (c) $\geq 10\%$ for the Climate Change + Imported GW + HB Depletion scenario in 2070.

examples of potential technologies that hold promise include desalination of brackish groundwater for irrigation, developing water markets to increase flexibility in water use, and transitioning to high-value crops that are relatively drought- and salt-tolerant to increase the resiliency of irrigated agriculture (Samimi et al., 2022b). These measures need to be combined with improvements in agricultural irrigation methods, such as drip irrigation, and improved management, such as ET-based irrigation scheduling, to reduce demand through conservation. In addition, these water-saving practices need to be combined with policies to limit water use, since savings at the farm level paradoxically can lead to expansion of production, a phenomenon known as Jevon's Paradox and proven worldwide in large-scale projects aimed at improving irrigation efficiency (Perry et al., 2017). Without a concomitant change in water policy to "capture" savings through conservation, farmers tend to use saved water to expand production.

In urban settings, most of the water indoors is recycled through the wastewater system. Thus, the greatest savings at a household level is through outdoor water conservation, including more xeriscaping, improved landscape irrigation, and reduced reliance on water cooler-based air conditioning (though its replacement would be costly to financially marginalized households).

There is very little aquifer recharge in this desert river basin; much more is pumped (about 230 MCM/yr, primarily by cities) than is replaced (about 40 MCM/yr, from a combination of natural and agricultural recharge). Flood irrigation using surface water does provide some recharge to groundwater, but flood irrigation using groundwater provides only return flow, not really recharge. Total fresh groundwater depletion is likely well before the end of the century (in about 40–50 years) without changes in management, technologies, and/or policies. This result would be catastrophic to the economic health of the region (Hurd and Coonrod, 2012).

Stakeholders throughout the basin agree that interventions to prevent this probable outcome (fresh groundwater depletion) are called for, but they do not agree on which possible interventions might be preferable. The situation of stakeholders "pointing of fingers at others" expresses the fragmentation of water governance, rights, and responsibilities in the basin (across nations, states, and other jurisdictions; urban/agricultural conflicts; and surface/subsurface water boundaries). While stakeholder consensus did not emerge, a basis for a common understanding of the problem was developed and for building knowledge and rapport for future shared decisions was established (Mayer et al., 2021).

Policy, management, and/or conservation changes could extend the life of aquifers, but not indefinitely, and will come at a high cost. There is much more brackish groundwater compared to fresh groundwater, but it is not useable as is and is expensive to treat. These realities are what lead Bierkens and Wada (2019) to conclude that "physically non-sustainable withdrawal of groundwater is a global problem that is a slowly ticking time bomb for food security" and related economic sustainability of civilizations worldwide.

Our results show that greater systemic efforts at conservation, use of brackish water (via desalination), increased reuse through water treatment, artificial aquifer recharge, and possibly water importation will all be necessary to meet growing demands of urban centers in challenged basins such as the MRG. The net result is not that the region will "run out" of water, but that water will be much more costly in the future. Within the next 3–4 decades, the relatively cheap water will be consumed. A significant social justice question needing serious research and policy debate is "how will water needs be prioritized as supplies dwindle, and who will bear the cost of developing and using new water sources to meet those needs?" (Heyman et al., 2022).

4.3. *Limitations of our study*

We faced a number of limitations related to data gaps for: 1) groundwater extraction in Mexico (We were forced to use how much was licensed, not how much was actually pumped, in our analyses.); 2) private well pumping, especially in Texas where it is not reported; 3) spatially specific data for recharge and return flows and water quality data for same; 4) information on the distribution of crops year to year, which impacts modeling results; and 5) land cover change, which was incompletely modeled and depended largely on extrapolation from historical data.

Another limitation of our study was that we chose (out of necessity with respect to limited resources) to focus on water quantity primarily, and much less on water quality. Increasing salinity is a growing problem in surface water, groundwater, and agricultural soils, in both urban and agricultural sectors, and will have significant consequences for the future. This issue has received some attention in the literature but until now has not received the rigorous study that it deserves in the MRG; a large-scale salt mass balance approach is called for to understand the dynamics of salinization of our soils and water, both surface and groundwater. Other water quality issues such as arsenic and nutrient loading are also deserving of attention.

Finally, our modeling of future decision-making was based totally on hydroeconomic optimization, which perhaps works fairly well for the agricultural sector but might not work as well for other users/sectors. Our SWIM online platform needs to continue to be enhanced to enable modelers to easily add their models to the platform, allowing stakeholders to run diverse models through a single interface. The technical objective is to lower the barriers to learning how to run different models that may provide alternative perspectives on water issues. Ultimately, the primary goal is to support stakeholders at all levels (individual, institutional, policy) in envisioning plausible future scenarios, identifying those that are most desirable, and considering interventions that could be made to reach desirable future outcomes.

4.4. *Future research needs*

Additional research is needed to address some of the limitations above, especially analyzing and modeling the medium-term dynamics of salinization in both agriculture and urban water supplies. Understanding the complex dynamics of water quantity and salinity in desert river basins in conjunction with aquifers containing both fresh and brackish water is paramount to sustaining useable water supplies (Pauloo et al., 2021).

The lack of water available for and allocated to environmental flows remains a challenge for the MRG. It is necessary to better understand the feasibility and hydrologic and economic tradeoffs of environmental water allocation to support ecosystem services in this water-scarce region under scenarios of climate change. Future research can explore a dynamic environmental water allocation scheme by adjusting the amount and cost of environmental flows based on water availability during wet or dry periods, and economic value of water to minimize the effects of environmental water allocation on agricultural water availability and other water uses.

With regard to the future of water in the MRG, there is a particular need for social science research to support adaptive management to arrive at preferred solutions and interventions that will promote sustainability. The MRG presents a special challenge for transboundary water management based on collective goal setting rather than continuing the current fragmented approach to depletion of the common pool resource of freshwater. Adaptive cooperation could provide a useful framework for meeting this challenge. What discursive and governance approaches could strengthen a shared common pool vision and practical governance system, especially for transboundary situations (Heyman, 2023)? How can this be applied to the MRG and other transboundary, conjunctive river/aquifer settings? The answers to these and other related questions could provide a way forward to a more sustainable water future.

5. Conclusions

“Business as usual” in the MRG is not sustainable. Climate is becoming warmer and drier now, and this trend is expected to continue. The situation will become perilous as it continues. If change accelerates and it becomes much drier, the situation can become even catastrophic. The probable outcomes for the future of water in the region include: 1) trends in agricultural intensification and the shift to perennial crops are “locking in” water demand, combined with an increasing reliance on groundwater; 2) growing urban populations are increasing overall demand, forcing cities to more expensive sources of water; 3) a warmer, drier climate in the Rio Grande headwaters will result in less reliable surface water supplies and increasing reliance on groundwater; 4) surface water is over-allocated, and the current governance structure does not allow flexibility in allocations that could result in more efficiency as supplies become less reliable, nor is it likely to in the near future; and 5) governance of groundwater is fractured between three states in two countries, but stakeholders are interested in seeing voluntary binational cooperation on groundwater management moving forward.

We evaluated possible interventions (technologically possible, but not necessarily economically viable). For agriculture, possible interventions center around: 1) alternative sources of water, especially desalination of brackish water; 2) alternative methods of irrigation, especially drip irrigation; 3) improved water management, especially ET-based irrigation management; 4) improved salinity management, especially gypsum application or use of sulfur burner technologies; and 5) alternative crops, none of which are as profitable as pecans, so their adoption would have to be subsidized. We evaluated possible interventions that rely on alternative water sources for urban water use as well. These include: 1) more desalination, 2) direct potable re-use, and 3) imported water. All of these would make water much more expensive for urban consumers. Conservation, especially related to outdoor water use, also could be efficacious to a degree, at much less cost. The question of which of these is preferable in terms of efficacy, cost, and social justice is a question to be answered by stakeholders, informed by policy-oriented scientific research, and would require much more public engagement and civic discourse than is now practiced typically. However, water management across all sectors and jurisdictions must be improved to realize a more sustainable future.

We faced several limitations including data gaps for a number of important parameters such as groundwater extraction in Mexico, private well pumping in Texas, spatially specific data for recharge and return flows and water quality data for same, information on the distribution of crops year to year, and detailed land cover change. In addition, a significant limitation of our study was that we did not focus as much attention on water quality issues, especially salt, as was probably warranted. Other water quality issues such as arsenic and nutrient loading are also deserving of attention. Finally, our modeling of future decision-making was based totally on hydro-economic optimization, which perhaps works well for the agricultural sector but might not work as well for other users/sectors.

Additional research is needed to address some of the limitations above, especially analyzing and modeling the medium-term dynamics of salinization in both agriculture and urban water supplies. There is a need for a better understanding of the hydrologic and economic tradeoffs for water allocation to environmental flows. Regarding the future of water in the MRG, there is a particular need for social science research to support adaptive management to arrive at preferred solutions and interventions that will promote sustainability. The MRG presents a special challenge for transboundary water management based on collective goal setting rather than continuing the current fragmented approach to the depletion of the common pool resource of freshwater. Adaptive cooperation could provide a useful framework for meeting this challenge. The answers to these and other related questions could provide a way forward to a more sustainable water future.

Our work has several broader impacts for the scientific community, as well as a broad range of stakeholders, especially water managers and users. For the scientific community, we have demonstrated a viable process of identifying and engaging stakeholders in identifying problems, evaluating modeling results that characterize the future, identifying potential solutions or interventions, and responding to modeling results that evaluate the outcomes of interventions. Our process formed the basis upon which we were able to synthesize a holistic vision of the future of water for the MRG, though much work still needs to be done to identify stakeholder-preferable interventions to achieve a sustainable future. Our interdisciplinary research team functioned as a whole, rather than siloed components, breeching a chief challenge of wicked water resources problems.

For water managers and users to meet the challenges of the future, a new approach is called for, one based on “adaptive management” (Pahl-Wostl, 2007) and cooperation among sectors and across jurisdictions. The challenges to achieving a more sustainable water future are many but among the greatest threats is aquifer depletion since groundwater is the most important source for urban uses and a growing source for agricultural uses. Because the aquifers are shared between the US and MX, the problem of depletion is also shared; thus, the responsibility for the solutions also must be shared. Adaptive cooperation could provide a useful framework for meeting this challenge. Adaptive cooperation is needed across four important themes (plus additional research and outreach in support of these themes): 1) information sharing, especially regarding groundwater pumping, trends in total water demand, use of alternative sources, and conservation measures; 2) conservation, especially regarding outdoor water use in urban settings and improved irrigation management in agricultural settings; 3) greater development and use of alternative water sources, especially desalination, wastewater reuse, and imported water; and 4) new limits to water allocation/withdrawals coupled with more flexibility in uses. A major policy question is how will the cost of these actions be borne?

CRediT authorship contribution statement

W.L. Hargrove: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Roles/Writing – original draft, Writing – review & editing. **J.M. Heyman**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Roles/Writing – original draft, Writing – review & editing. **A. Mayer**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing. **A. Mirchi**: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing. **A. Granados-Olivas**: Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing. **G. Ganjegunte**: Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. **D. Gutzler**: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing. **D.D. Pennington**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing. **F.A. Ward**: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing. **L. Garnica-Chavira**: Data curation, Formal analysis, Methodology, Software, Validation, Visualization. **Z. Sheng**: Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing. **S. Kumar**: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing. **N. Villanueva Rosales**: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization. **W.S. Walker**: Data curation, Formal analysis, Investigation, Software, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2023.101336.

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