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Water, climate, and social change in a fragile landscape

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Abstract. We present here and in the companion papers an analysis of sustainability in the Middle Rio Grande region of the U.S.-Mexico border and propose an interdisciplinary research agenda focused on the coupled human and natural dimensions of water resources sustainability in the face of climate and social change in an international border region. Key threats to water sustainability in the Middle Rio Grande River region include: (1) increasing salinization of surface and ground water, (2) increasing water demand from a growing population in the El Paso/Ciudad Juarez area on top of an already high base demand from irrigated agriculture, (3) water quality impacts from agricultural, municipal, and industrial discharges to the river, (4) changing regional climate that portends increased frequency and intensity of droughts interspersed with more intensive rainfall and flooding events, and (5) disparate water planning and management systems between different states in the U.S. and between the U.S. and Mexico. In addition to these challenges, there is an increasing demand from a significant regional population who is (and has been historically) underserved in terms of access to affordable potable water. To address these challenges to water resources sustainability, we have focused on: (1) the determinants of *resilience* and *transformability* in an ecological/social setting on an international border and how they can be measured and predicted; and (2) *the drivers of change* . . . what are they (climate, social, etc.) and how are they impacting the coupled human and natural dimensions of water sustainability on the border? To tackle these challenges, we propose a research agenda based on a complex systems approach that focuses on the linkages and feedbacks of the natural, built/managed, and social dimensions of the surface and groundwater budget of the region. The approach that we propose incorporates elements of systems analysis, complexity science, and the use of modeling tools such as scenario planning and back-casting to link the quantitative with the qualitative. This approach is unique for our region, as are our bi-national focus and our conceptualization of “water capital”. In particular, the concept of water capital provides the basis for a new interdisciplinary paradigm that integrates social, economic, and natural sectors within a systems framework in order to understand and characterize water resources sustainability. This proposed approach would not only provide a framework for water sustainability decision making for our bi-national region at the local, state, and federal levels, but could serve as a model for similar border regions and/or international rivers in arid and semi-arid regions in the Middle East, Africa, Asia, and Latin America.

Key words: climate change; desert rivers; social change; Special Feature: Sustainability on the U.S./Mexico Border; sustainability; transboundary aquifers; water resources.

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INTRODUCTION

Background

The Rio Grande stretches almost 2000 miles and drains about 182,000 square miles in the U.S. and Mexico. A little more than half of the river's course runs through arid and semi-arid, mountainous terrain, dominated by the Chihuahuan Desert in the southwestern U.S. and northern Mexico. About 1000 miles of the river is the international border between Mexico and the U.S.

We define the Middle Rio Grande region as the area drained by the stretch of river between Elephant Butte Reservoir in southern New Mexico and Fort Quitman, TX (Fig. 1). This region includes portions of southern New Mexico and Far West Texas in the U.S. and a significant portion of the state of Chihuahua in Mexico. This border region is challenged by: (1) limited surface and groundwater supplies that are becoming increasingly saline; (2) increasing water demands from a growing population in the El Paso/Ciudad Juarez area on top of an already high base

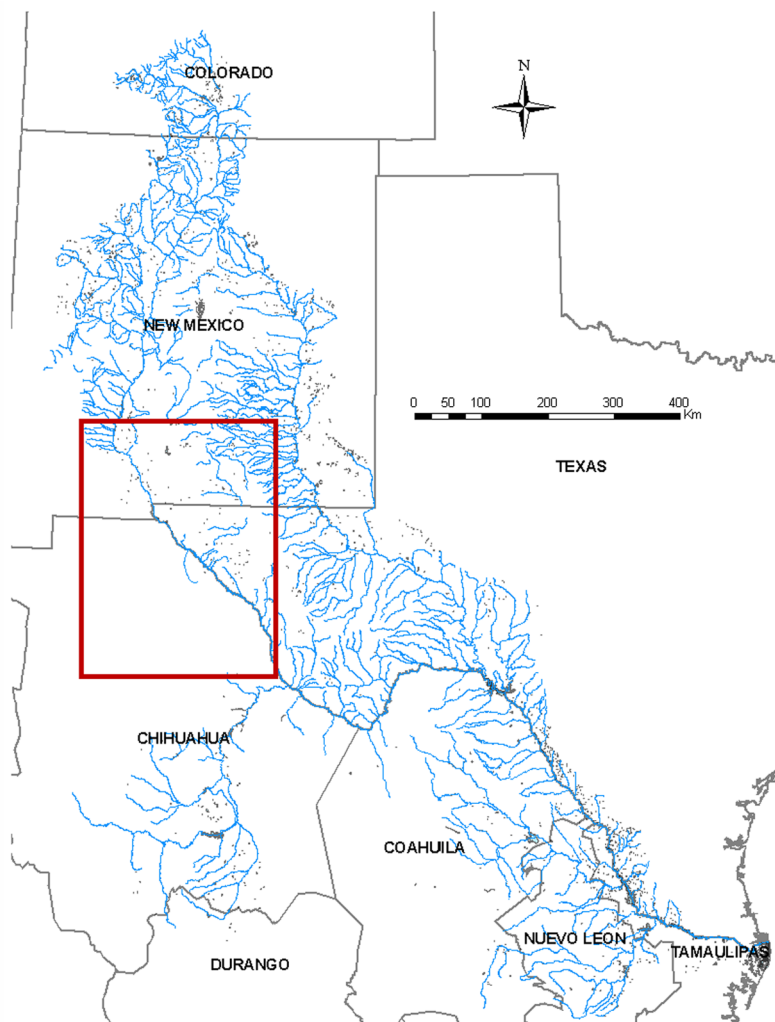


Fig. 1. Map of Rio Grande basin showing region of interest. Modified from: Patino-Gomez et al. (2007).

demand from irrigated agriculture; (3) water quality impacts from agricultural, municipal, and industrial discharges to the river; (4) changing regional climate that portends rising temperatures, increased frequency and intensity of drought, and increased frequency of extreme weather events; and (5) disparate water planning and policy structures that lack coordination and integrated management. Planning and policy structures are of great importance because the quantity and quality of water in the Middle Rio Grande are impacted by the management of water in upstream reservoirs, irrigation practices, and the dynamic groundwater/surface water relationships in the landscape. In addition to these challenges, there is an increasing demand from a significant regional population who is (and has been historically) underserved in terms of access to affordable potable water. *Colonias* are mostly rural communities in the border region that have developed without basic water and sanitation infrastructure. There are about 4000 households in El Paso County that lack complete indoor plumbing and potable water piped into their home.

We present here and in the companion papers an analysis of sustainability in this critical region, drawing on a wider literature concerning the border region and other arid regions of the world, and propose an interdisciplinary research agenda focused on the coupled natural and human dimensions of sustainability on an international border. Because this landscape and its attributes are shared by many other significant river systems and border regions around the world, which also face sustainability challenges, our results are representative of and applicable to a number of similar border regions and/or international rivers in arid to semi-arid regions. This includes not only significant river systems in the Middle East, Africa, Asia, and Latin America, but also intra-state boundary areas in the U.S. where national, state, local, and tribal governance converge but jurisdiction for water policy and law is primarily at the state level.

Social-ecological context

A conceptual model of the landscape embedded in this region, including the key water features, is shown in Fig. 2. It can be characterized by:

- A predominant river feature, the Rio Grande, which is intensively managed and over-allocated in terms of its use;
- Significant riparian wetlands;
- The Chihuahuan Desert;
- Significant mountain ecosystems that include protected natural areas in national parks such as Big Bend and the Guadalupe Mountains, and a number of other state parks;
- A dry climate ranging from arid in the west (8 inches of annual rainfall) to semi-arid in the east (up to 15 inches of rainfall on the eastern edge);
- A “built environment” that includes a complex agricultural irrigation system of canals and drainage ditches, municipal wastewater treatment and discharge to the river, over-extraction and use of water for agricultural and municipal uses, and growing use of desalination technologies with challenges of concentrate re-use/disposal;
- Significant groundwater resources in alluvial and bolson aquifers, endangered by over-extraction and use and contamination by salt and other pollutants;
- Significant areas of former rangelands that have been degraded to desert shrublands due to overgrazing and droughts;
- A major urban center, El Paso/Ciudad Juarez of 2 million people and growing, surrounded by a fragile environment;
- Social issues of a growing population in the urban center, migrant populations, border insecurity, a bifurcated but also connected economy between the U.S. and Mexico, large numbers of marginalized populations living below the poverty line with poor infrastructure, and significant environmental health and environmental justice issues.

The majority of intensive hydrological and geochemical work on the Rio Grande has focused on the sections north of El Paso and north of Elephant Butte Dam (Phillips et al. 2003, Hogan et al. 2007). Our analysis is different in that we focus on the section of the Rio Grande stretching from Elephant Butte Dam (in southern NM) to Amistad Dam in Western Texas and Coahuila. This stretch of river is unique and deserves our focus for several reasons:

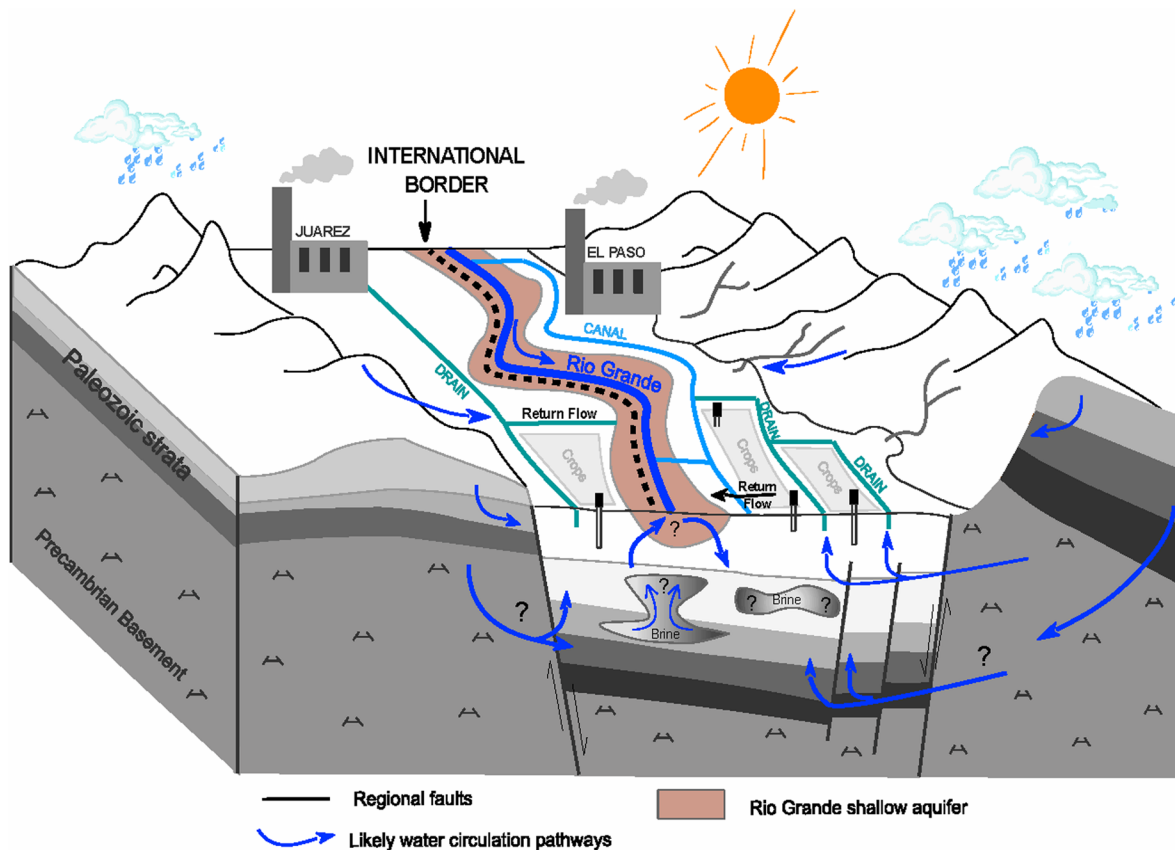


Fig. 2. A conceptual model of the Middle Rio Grande River landscape. From: Ana Szienkiewicz, UTEP.

- It includes the first stretch of the river that acts as the International Boundary between Mexico and the U.S.
- Both Mexico and the U.S. share surface and groundwater resources.
- The salt loads in the river are problematic for municipal and irrigation purposes.
- The Rio Grande becomes a losing stream over most of the stretch from Elephant Butte Reservoir to El Paso, TX, which impacts groundwater quality and quantity.
- South of El Paso, the Rio Grande is fed by salt-rich groundwater and salt-rich springs feeding the Pecos River; the hydrology and chemistry of these interactions have not been studied in detail (Hibbs and Merino 2006).

There is a plethora of component research in the region that addresses hydrology, ecology, economics, social interactions, and the impacts of the built environment on water resources in the

area (see Literature Cited in this and other papers in this Special Feature). However, our goal is to integrate this information on a landscape scale at the U.S./Mexico Border, with an aim of an improved understanding of sustainability on the border.

Water quality is a particular threat to water resources sustainability in the border region and similar arid and semi-arid regions. In particular, salinization of surface water and shallow groundwater in desert river basins like the Middle Rio Grande represents a significant global environmental problem. The problem has intensified as population growth in desert areas has increased and more water is needed to support agriculture and municipalities (Phillips et al. 2003, Farber et al. 2004, Oren et al. 2004, Hogan et al. 2007, Szykiewicz et al. 2008). The highest water use in the Rio Grande Valley is for irrigation to support agriculture (Ellis et al. 1993). The negative economic impact of excessive salt

concentrations in the Rio Grande was recently estimated by the Rio Grande Project Salinity Management Coalition (RGPSMC, a group that brings together the Colorado, New Mexico, and Texas Rio Grande compact commissioners with interested federal, state, local, and university partners) at \sim \$11,000,000/year, with municipalities like El Paso, TX, shouldering the largest fractions of these costs (Michelsen et al. 2009). In addition to the possible impact from agricultural sources, previous investigations have demonstrated that salt loads in the Rio Grande increase in part because of (1) the increasing annual temperatures southward which leads to higher evaporation and evapotranspiration rates in the irrigated fields, (2) the high geothermal gradient of the Rio Grande Rift, which may enhance upwelling of highly mineralized groundwater from deeper parts of basins, and (3) the dissolution of salt-rich sedimentary rocks in the central and southern parts of the Rio Grande Valley (Eastoe et al. 2008, Phillips et al. 2003, Hibbs and Merino 2006, Hogan et al. 2007, Witcher et al. 2004, Moore et al. 2008). These complexities are highlighted in Fig. 2. Understanding the complex dynamics of hydrology and geochemistry coupled with the sociopolitical framework in a binational setting is a goal of our analysis.

The social science component of our analysis builds on the approach of political ecology (Blaikie and Brookfield 1987, Greenberg and Park 1994, Robbins 2004, Paulson and Gezon 2005). Political ecology combines understanding of ecological settings and processes with the social science of power and meaning. An important assumption of our analysis is that biophysical science related to the Rio Grande will never be simple and undisputed. Water is a matter of fundamental existence and thus deep contention (Donahue and Johnston 1998). We are aware of, and specifically interested in, the ways that the scientific information about water are differently interpreted, valued, and used in the social and political life of the basin; and how this recursively informs the sort of biophysical science done in the basin (Escobar 1999).

Climate change portends changes in the biophysical regime of the river basin, as do human transformations, such as urban growth and irrigation (Liverman and Meredith 2002). Because demographic and economic expansion

affect aggregate water demand as well as built environment requirements, the impacts of these factors in light of climate change need to be considered in concert with conservation and environmental protection. Policy tools, like pricing decisions, and public outreach campaigns can impact per capita and total municipal consumption trends. But, such changes are scientifically complex and debated, are politically contentious, and will have differential effects on segmented and unequal social systems (Conca 2005). Previous research has highlighted the importance of a number of social factors, in both impacts of and resilience to climate change. These include: (1) differential access to economic and social capital, (2) knowledge and technology, and (3) political processes and institutions (Vásquez-León et al. 2003, Vásquez-León 2009, and more generally see Adger 2003, Pelling and High 2005, Langridge et al. 2006, Nelson et al. 2007). All of these factors need to be understood, especially in a project that brings together social and natural scientists to integrate water and climate knowledge. Key questions need to be addressed, such as: (1) what water and climate knowledge are available and to whom; (2) why certain information is contentious and how; (3) how knowledge affects people and sectors differently; and (4) how to make it most accessible and usable by all social sectors, including disadvantaged ones (Adger et al. 2006).

River basins and their associated landscapes offer an extraordinary opportunity to combine biophysical and social science (Ingram et al. 1995). There are tensions between upstream and downstream users, between groundwater users and surface water users, and among competing uses, such as wildlife, agriculture, and urban. There is also conflict between social groups within these categories—such as low capital versus high capital farmers. Our long-term goal is to identify the determinants of resilience in the hydrological system for such a contentious and fragile environment and to relate resilience to water resources sustainability. The key outcome of our analysis is a research strategy for assessing and predicting water resources sustainability on the border. We will use the concept of resilience, as affected by climate and social change, to improve our understanding of the coupled human and natural dimensions of water sustain-

ability. We will also examine management and policy interventions that will alter water supply and/or demand when the existing system becomes untenable (defined as *transformability*).

The objectives of our analysis include:

1. Identify, collect, and summarize existing data, knowledge, and models.
2. Integrate existing data, knowledge, and models into an overall model of the ecological and sociopolitical landscape/lifescap on the border.
3. Identify gaps in information, knowledge, and understanding, from item 2 above, in relation to defining resilience, adaptability, and transformability.
4. Develop a research strategy for identifying and evaluating the determinants of resilience, adaptability, and transformability in response to climate and social change.
5. Assess sustainability based on the coupled human and natural dimensions of the landscape/lifescap on the border.

Theoretical framework

We are utilizing sustainability science approaches to guide our analysis. The theoretical basis for this emerging field was described by Kates et al. (2001), who identified a set of core questions for sustainability science. Several of these questions address issues of resilience, adaptability, and transformability of social-ecological systems. Walker et al. (2004) provides definitions of these concepts: (1) *Resilience* is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain the same function, structure, identity, and feedbacks; (2) *Adaptability* is the capacity of actors in a system to influence resilience; and (3) *Transformability* is the capacity to create fundamentally new systems when the existing system becomes untenable. We use these concepts in the context of climate and social change to address the key issues for the U.S./Mexico border region. The research questions which have guided our analyses include:

- What determines the vulnerability or resilience of the social-ecological system for the U.S./Mexico border in the Middle Rio Grande region, situated in a fragile land-

scape and a dynamic social system characterized by violence, migration, and economic disparities?

- What is the adaptability of the social-ecological system and how are long-term trends in environment and development in the region reshaping the system in ways relevant to sustainability?
- What is the transformability of the social-ecological system and what measures are likely to transform environmental decision making in ways that positively impact water sustainability on the border?

We have used these concepts to analyze water sustainability in an ecological/social system that we term “the landscape/lifescap”. The landscape/lifescap of interest for this analysis is the Middle Rio Grande region. At the heart of this region is the U.S./Mexico border metropolis of El Paso/Juarez, which presents unique challenges in a highly complex biophysical and socioeconomic environment, complicated by violence, migration, and social inequities. Our long-term goal is to identify and elucidate the principles of sustainability in one of the most challenged border regions of the world. The outcome of our analysis is an interdisciplinary research agenda aimed at identifying and evaluating the determinants of resilience, adaptability, and transformability, and integrating known and new information into predictive models of water sustainability on the border in the face of climate and social change.

APPROACH

Our analysis consisted of: (1) summarizing the known science related to water sustainability under climate and social change; (2) identifying knowledge gaps and ways to integrate the biophysical and socioeconomic knowledge domains; and (3) synthesis into an interdisciplinary research agenda. We identified six key themes or “domains of knowledge” on which to focus our analysis. The themes can be divided into biophysical and socioeconomic domains. The biophysical domains consist of regional climate, hydrology and geochemistry, and ecology and ecosystem services; the socioeconomic domains consist of the built environment, the managed

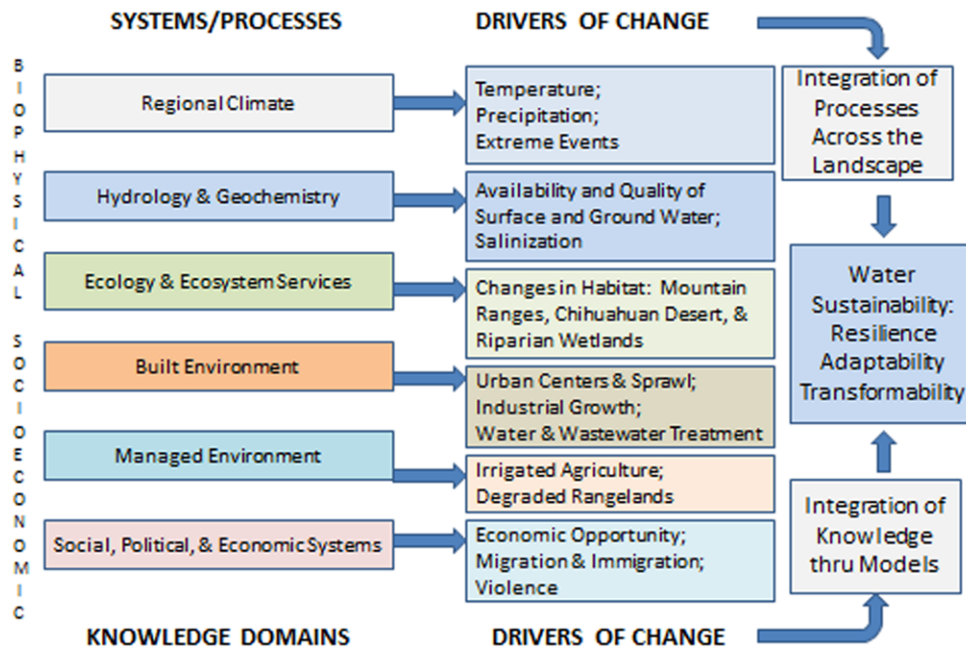


Fig. 3. Integration of knowledge domains about systems and processes to achieve water sustainability.

environment, and the social, cultural, political, and economic systems.

In order to summarize the known science and identify gaps, we commissioned a number of “white papers” to address some of the key themes. The white papers are presented as companion papers in this Special Feature. These white papers survey a wider literature and do not confine themselves to the Middle Rio Grande, but focus on principles applicable to the border region.

We also convened a conference in May, 2011, where the white papers were presented and a number of voluntary presentations were also shared. The conference was attended by about 150 individuals, comprised of university students and faculty; water professionals from federal, state, and local agencies; and representatives from non-government organizations from both the U.S. and Mexico. The conference combined plenary and concurrent sessions and included breakout sessions for discussion of information gaps and research needs.

A synthesis workshop was held in September, 2011, where, through small group discussions and plenary group analysis, we: (1) identified key “drivers of change” and ways in which the

drivers of change will impact the systems and processes of interest in each knowledge domain; (2) identified ways to integrate information across domains; and (3) synthesized conference and workshop output into recommended research to identify determinants of resilience and drivers of change, and integrate them into a model of sustainability on the border.

The key task of integration is illustrated in Fig. 3, including integration of change and integration across domains. This process is what sets our efforts apart from what has been done before. We are attempting to integrate the biophysical and socioeconomic domains using landscape and political ecology approaches to arrive at a new understanding of water sustainability at the border.

RESULTS

Seven white papers in addition to this one were prepared as companion papers as part of this analysis. Some of the salient findings of these white papers include:

- 1) There is an overwhelming consensus by climate scientists that average temperatures will rise in the coming decades in the Rio

Grande region; the only uncertainty is how much and how fast. There is also strong evidence to support projections of long-term reductions in winter precipitation; there is no consensus on summer precipitation. (Gutzler)

- 2) Surface water quality and quantity are experiencing change resulting from both natural and human stressors. Key natural stressors include climate (especially drought cycles) and geologic processes (such as saline groundwater discharges). Human stressors include bacterial and nutrient contamination from urban storm water, agricultural return flows, treated wastewater discharges, altered hydrology due to reservoir management and groundwater pumping, and changing water demands, especially from the El Paso/Ciudad Juarez metropolitan area. An improved understanding of the connection between surface and ground water is key to the sustainable management of water in the region. (Hogan)
- 3) Increased rates of groundwater pumping have resulted in large groundwater level drawdown, water quality deterioration, depletion of surface water, and subsidence in the El Paso/Ciudad Juarez area. Securing future groundwater availability will require minimizing net losses from the underground reservoir, developing infrastructure and managing groundwater as an integrated part of the hydrologic cycle, improving water use efficiency, improving monitoring of groundwater resources, and allocation of water in ways that balance human, environmental, and ecological goals. (Zheng)
- 4) Impacts of climate change on ecosystems and the environmental services that they provide can be viewed as sudden, patchy effects vs. incremental, homogenous effects. Sudden, patchy effects require proactive networks to help users share the risk of sudden localized impacts. On the other hand, incremental, homogenous effects require a fundamental rethinking of how ecosystem services are used and valued. Analysis of case studies from the border region suggest that the way forward is for managers and decision makers to collaborate with local users of ecosystem services to devise and implement innovative strategies for dealing with climate change regimes. (López-Hoffman)
- 5) A coupled bio/social systems approach to watershed management that prioritizes cultural health over other concerns is needed to achieve sustainability goals and address the complex and protracted conflicts that characterize river basin management. This calls for the need for greater respect for and recognition of the rights, values, and contributions of culturally diverse peoples in the management and use of river systems, and the expansion of the integrated water resource management model to include prioritized allocation of water to meet environmental and cultural demands. (Johnston)
- 6) Water infrastructures include not just physical structures but also institutions, practices, and forms of knowledge. These physical, social, and legal infrastructures for water management built in the twentieth century are not adequate or appropriate to today's challenges. Reducing and reallocating uses of surface water in the border region are called for. Future models for sustainable water management must address the social and cultural level at which water is understood and used by diverse groups. Shared knowledge and responsibility for water infrastructure and water resources management are essential to sustainability on the border. (Walsh)
- 7) Environmental and human drivers of change are also responses to earlier or simultaneous processes of change and can be understood to occur along a continuum of physical and social processes. Physical processes, like climate change, hydrology, and riparian ecosystem dynamics, are mutually conditioned by human activity, such as water and energy consumption, land use, and policy/regulation. These drivers and responses are realized at a range of scales from local to global. Adaptation strategies are also seized or missed at a variety of scales from households to nations. For the borderlands, regional scales of integration and commu-

nities of practice are called for in order to identify, monitor, and plan for human-environment interactions and their impacts. (Scott and Buechler)

Discussions at the two conferences pointed to a crucial interaction between surface water and groundwater. Surface water often provides less than the institutionalized demand, either because of annual climate fluctuations or over-allocation; both of those two elements in turn are affected by long term trends, which include climate change and growing human demand. To make up for surface shortages, groundwater is extensively used. Groundwater is to some extent (not fully known) recharged from the surface, mediated by human activity, but is also being depleted. Basically, the human system uses groundwater drawdown to re-equilibrate water supply and demand in the face of short and long term shortages of surface water. Total water supply may in the short run appear to be resilient, but this is at the expense of non-resilience in groundwater. Furthermore, the institutions governing groundwater are fragmented, while the resource itself is a complex common good, with poorly understood underground dynamics. Unlike with surface water, there is no binational (U.S.-Mexico) groundwater agreement; each nation can extract without regard to the other. Mexico treats groundwater extracted in its territory as a national resource, subject to coherent regulation—in theory, though perhaps not in reality. New Mexico has limited regulation of groundwater via regulation of well drilling. In Texas, groundwater is treated entirely as a private good owned by the surface landowner. This makes the status of groundwater—quantity and quality—central to the combined human-environmental system.

To meet the challenges of sustainability in the face of climate and social change, we need to: (1) evaluate the future resiliency of regional groundwater supplies in the face of projected changes in demand and climate and (2) assess opportunities for transformability of the groundwater budget through policy and technology. This will require: (1) development of a multi-dimensional understanding of water resources in the border region, identifying key system variables and feedbacks; (2) development of new methodologies/tools for

monitoring and assessing groundwater resources in arid regions; and (3) targeted suggestions for changes in management frameworks, including steps, approaches, and processes that support sustainable management of regional groundwater resources. We have identified some key questions about water sustainability in our region that need to be addressed:

- Under what conditions and timetables are we likely to reach tipping points with respect to water availability, quality, and pricing among agricultural, industrial, and municipal users?
- How do key variables affecting groundwater quantity, which originate within the natural, social, and managed environments, impact demand and management?
- What management, policy, or technology changes could alter the groundwater budget, thereby transforming the overall water system and improving its long-term resiliency?

To tackle these challenges, we propose a research agenda based on a complex systems approach that will focus on the linkages and feedbacks of the natural, built/managed, and social dimensions of the groundwater budget of the region. Although we recognize that surface water is directly linked to groundwater, the groundwater budget represents the long-term water capital that the region must maintain to achieve water sustainability. We propose to develop an innovative, scenario planning/modeling tool that combines quantifiable metrics with qualitative relationships and integrates stakeholder engagement. The tool and the information it generates will result in a new framework for understanding, predicting, and transforming our water system and can be made available to decision makers to foster planning for a sustainable water future.

The approach that we propose incorporates elements of systems analysis, complexity science, and the use of modeling tools such as scenario planning and back-casting (Peterson et al. 2003, Swart et al. 2004, Liu et al. 2008) to link the quantitative with the qualitative. This approach is unique for our region, as is our bi-national focus and our conceptualization of “water capital”. The latter provides the basis for a new

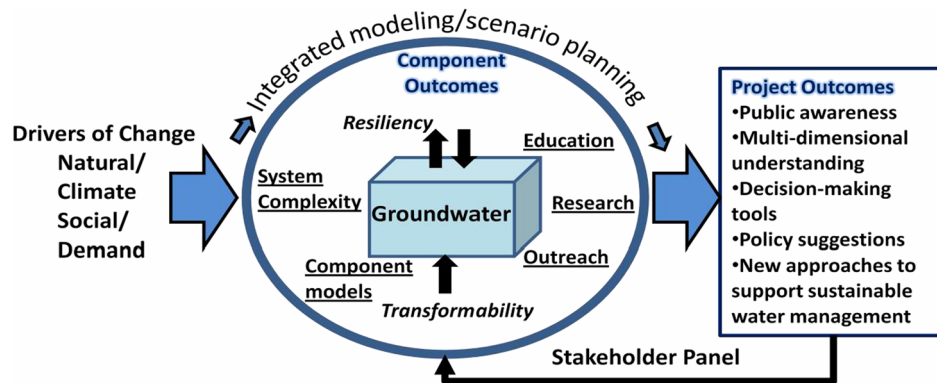


Fig. 4. Conceptual framework for coupling human and natural dimensions of water resources sustainability on the border.

interdisciplinary paradigm that integrates social, economic, and natural sectors within a water systems framework. The theoretical basis for our approach is rooted in the core sustainability questions and discussions of resilience, adaptability, and transformability presented by Kates et al. (2001) and expanded by Walker et al. (2004), and in the principles of complexity science applied to sustainability by Espinosa et al. (2008). The conceptual framework is illustrated in Fig. 4. The research goals that we have identified from our analysis include: (1) developing and using a scenario planning and analysis tool; (2) assessing the *resiliency* of the groundwater budget, the ability to maintain the quantity and quality of water “capital” over time; and (3) evaluating the *transformability* of the groundwater budget, the capacity to fundamentally change current water budget trajectories through technology and/or policy. Needed research to achieve these goals is discussed below.

Scenario planning tool

Scenario planning is the development of a set of plausible outcomes about co-evolutionary pathways of highly complex human and environmental systems (Swart et al. 2004). These plausible outcomes help us understand, bound, prioritize, and manage uncertainty and risk. Scenarios provide a framework for linking dimensional elements that are vastly different, such as the human and natural dimensions, and that may occur on different spatial and time scales. Rather than attempting to construct a single, comprehensive model of the entire sys-

tem, component models can be coupled to enable iterative, adaptive model composition, recommended by others with experience in scenario analysis of human and environmental systems (Liu 2007, Bankes 2010). To evaluate the sensitivity of plausible outcomes (and their components), a Monte Carlo approach can be used, where input for a single component is varied over a set range of possibilities. Back-casting, defined as the process of identifying desirable sustainability outcomes and identifying necessary changes to achieve those outcomes, could be a useful tool/approach (Dreborg 1996). This approach will require stakeholder engagement. Water users, including urban and agricultural users, regulatory officials, and environmental advocacy groups all need to be included in the process of identifying and testing scenarios.

Resilience of the groundwater budget

We define the resiliency of the groundwater system as a measure of its ability to maintain “water capital,” the water quantity and quality built up in the system over time. The key research tasks for assessing resiliency of the groundwater budget include:

- Reassess future estimates of monsoon rainfall and determine its impact on the surface water budget.
- Evaluate the sustainability limit of surface water flow entering our study area in light of changing snowpack conditions in the headwaters of the Rio Grande.
- Constrain the plausible variations in salt

chemistry of the Rio Grande in our study area given changes in climate, monsoon rains, and snowpack.

- Characterize groundwater recharge and water quality effects of agricultural-use surface water.
- Characterize important ecosystem services
- Assess spatiotemporal dynamics of land-cover change to determine rates and/or fluctuations in desertification, urbanization, and agricultural transformation
- Parameterize observational platforms and new data collection; model for land-atmosphere water, energy and carbon balance, and groundwater recharge and exchange (latent heat) for natural, urban, and agricultural systems.
- Develop a depth-time-quality continuum model for water sustainability by characterizing flow paths, surface-groundwater interactions, and residence time distributions. Delineate the spatial and social character of water governance/distribution systems for surface water and groundwater.
- Evaluate water as a practice/technology, cultural value, and economic commodity across diverse and unequal sectors.
- Evaluate uncertainty, variability, and feedbacks in water demand models at varied time horizons.

Transformability of the groundwater budget

We define the *transformability* of the groundwater system as the capacity to fundamentally change current water budget trajectories by adding resiliency (water capital). The following research tasks need to be completed in order to evaluate transformability:

- Identify the sources, collection locations, and probable amounts of storm and waste water available in the El Paso-Juárez metroplex.
- Characterize the chemistry of storm water and industrial wastewater generated to determine necessary treatment and to model potential water quality impacts associated with different reinjection scenarios.
- Identify the feasibility for recharge of treated surface water and the likely types of reinjection systems, as well as the potential sites for reinjection within the hydrologic framework

of our water system.

- Model the impact of reinjection of high-quality water on the management of saline groundwater.
- Assign cultural and economic value(s) to the groundwater and storm and wastewater in our study area.
- Develop an urban hydrology water budget model for the El Paso-Juárez metroplex that incorporates urban vegetation landscape hydrology modeling
- Examine intersectoral transfers/net use reduction.
- Model price modifications, such as tiered pricing with low cost basic access water and higher cost high usage water.
- Model water poverty scenarios where increasing demand and access occur in the face of limited supply.
- Model basin wide, binational governance of all water, including groundwater.

Bi-national education and outreach

We are challenged to provide the next generation of scientists/leaders with the skills to address the challenges of water resources sustainability on the border. Thus, we recommend inclusion of training opportunities for students in our research agenda, as well as development of additional educational materials for use in classroom settings. We have the opportunity to train the next generation of water professionals from both sides of the border in new approaches to evaluating and achieving water resources sustainability in the face of climate and social change.

At the same time there is a need to inform and educate the citizenry on both sides of the border regarding these issues. Public outreach has to be integrated throughout. We recommend a number of outreach approaches, including field trips, public tours, community events like water festivals, public presentations, and public exhibits through museums, as means for informing and engaging the public.

CONCLUSIONS AND RECOMMENDATIONS

Climate change and population growth are placing pressure on the water resources of the Middle Rio Grande border region, challenging the sustainability of water resources in this bi-

national river basin. Despite our knowledge of individual components, we lack the system-level understanding of the river basin necessary to predict its response to these pressures. Realizing our ultimate goal of developing predictive capacity related to resilience and sustainability in a fragile landscape on an international border in the context of water, climate, and social change will require: (1) linking component-based research and models; (2) assessing the *resiliency* of the groundwater budget, the ability to maintain the quantity and quality of water “capital” over time; (3) evaluating the *transformability* of the groundwater budget, the capacity to fundamentally change current water budget trajectories through technology and/or policy; and (4) integrating education, outreach, and stakeholder engagement into the research process.

Predictive capabilities and improved strategies for protecting and managing important water resources in a fragile and threatened environment under climate and social change are desperately needed in the border region and will forge new frontiers in sustainability science. This proposed approach would not only provide a framework for water sustainability decision making for our bi-national region at the local, state, and federal levels, but could serve as a model for similar border regions and/or international rivers in arid to semi-arid regions in the Middle East (the Jordan River, for example), Africa, Asia, China, and Latin America. The results also would be applicable to many major river systems and international border areas throughout the world.

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LITERATURE CITED

- Adger, W. 2003. Social capital, collective action, and adaptation to climate change. *Economic Geography* 79:387–402.
- Adger, W., J. Paavola, and H. Saleemul. 2006. *Fairness in adaptation to climate change*. MIT Press, Cambridge, Massachusetts, USA.
- Bankes, S. 2010. Robustness, adaptivity, and resiliency analysis. Technical report FS-10-03. Association for the Advancement of Artificial Intelligence. <http://www.aaai.org/ocs/index.php/FSS/FSS10/paper/view/2242>
- Blaikie, P., and H. Brookfield. 1987. *Land degradation and society*. Methuen, London, UK.
- Conca, K. 2005. *Governing water: contentious transnational politics and global institution building*. MIT Press, Cambridge, Massachusetts, USA.
- Donahue, J., and B. Johnston, editors. 1998. *Water, culture, and power: local struggles in a global context*. Island Press, Washington, D.C., USA.
- Dreborg, K. H. 1996. Essence of backcasting. *Futures* 28:813–828.
- Ellis, S. R., G. W. Levings, L. F. Carter, S. F. Richey, and M. J. Radel. 1993. Rio Grande Valley, Colorado, New Mexico, and Texas. *Journal of American Water Resources Association* 29:617–648.
- Eastoe, C. J., B. J. Hibbs, A. G. Olivas, J. F. Hogan, J. Hawley, and W. R. Hutchison. 2008. Isotopes in the Hueco Bolson aquifer, Texas (USA) and Chihuahua (Mexico): local and general implications for recharge sources in alluvial basins. *Hydrogeology Journal* 16:737–747.
- Escobar, A. 1999. After nature: steps to an antiessentialist political ecology. *Current Anthropology* 40:1–30.
- Espinosa, A., R. Harnden, and J. Walker. 2008. A complexity approach to sustainability—Stafford Beer revisited. *European Journal of Operational Research* 187:636–651.
- Farber, E., A. Vengosh, I. Gavrieli, A. Marie, T. D. Bullen, B. Mayer, R. Holtzman, M. Segal, and U. Shavit. 2004. The origin and mechanism of salinization of the Lower Jordan River. *Geochimica Cosmochimica Acta* 68:1989–2006.
- Greenberg, J., and T. Park. 1994. Political ecology. *Journal of Political Ecology* 1:1–12.
- Hibbs, B. J., and M. Merino. 2006. Geologic sources of salinity in the Rio Grande aquifer near El Paso, Texas. *New Mexico Journal of Science* 44:1–17.
- Hogan, J. F., F. M. Phillips, S. K. Mills, J. M. H. Hendrickx, J. Ruiz, J. T. Chesley, and Y. Asmerom. 2007. Geologic origins of salinization in a semi-arid river: The role of sedimentary basin brines. *Geology* 35:1063–1066.
- Ingram, H., N. Laney, and D. Gillilan. 1995. *Divided waters: bridging the U.S.-Mexico border*. University of Arizona Press, Tucson, Arizona, USA.
- Kates, R. W., W. C. Clark, R. Corell, J. M. Hall, C. C. Jaeger, I. Lowe, J. J. McCarthy, H. J. Schellnhuber, B. Bolin, N. Dickson, M. Faucheux, S. Gallopin, C. Gilberto, A. Gruebler, B. Huntley, J. Jäger, N. S. Jodha, R. E. Kasperson, A. Mabogunje, P. Matson, H. Mooney, B. Moore III, T. O’Riordan, and U. Svedin. 2001. Sustainability science. *Science* 292:641–2.
- Langridge, R., J. Christian-Smith, and K. Lohse. 2006. Access and resilience: analyzing the construction of social resilience to the threat of water scarcity. *Ecology and Society* 11(2):18.
- Liu, Y. 2007. Scenario development for water resources planning and management in semi-arid regions.

- Pages 192–198. *in* N. van de Giesen, X. Jun, D. Rosbjerg, and Y. Fukushima, editors. *Changes in water resources systems—methodologies to maintain water security and ensure integrated management*. IAHS Publication 315.
- Liu, Y., H. Gupta, E. Springer, and T. Wagener. 2008. Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management. *Environmental Modeling & Software* 23:846–858.
- Liverman, D., and R. Meridith. 2002. Climate and society in the US southwest: the context for a regional assessment. *Climate Research* 21:199–218.
- Michelsen, A. M., T. McGuckin, Z. Sheng, R. Lacewell, and B. Creel. 2009. Rio Grande salinity management program: preliminary economic impact assessment. Report to the Rio Grande Salinity Management Coalition.
- Moore, S. J., R. L. Bassett, B. Liu, C. P. Wolf, and D. Doremus. 2008. Geochemical tracers to evaluate hydrogeologic controls on river salinization. *Ground Water* 46:489–501.
- Nelson, D., W. Adger, and K. Brown. 2007. Adaptation to environmental change: contributions of a resilience framework. *Annual Review of Environment and Resources* 32:395–419.
- Oren, O., Y. Yechieli, J. K. Böhlke, and A. Dody. 2004. Contamination of groundwater under cultivated fields in an arid environment, central Arava Valley, Israel. *Journal of Hydrology* 290:312–328.
- Patino-Gomez, C., D. C. McKinney, and D. R. Maidment. 2007. Water quality data model in GIS for the Rio Bravo/Grande Basin.
- Paulson, S., and L. Gezon, editors. 2005. *Political ecology across spaces, scales, and social groups*. Rutgers University Press, New Brunswick, New Jersey, USA.
- Pelling, M., and C. High. 2005. Understanding adaptation: what can social capital offer assessments of adaptive capacity. *Global Environmental Change* 15:308–319.
- Peterson, G. D., G. S. Cumming, and S. R. Carpenter. 2003. *Essay scenario planning: a tool for conservation in an uncertain world*. *Conservation Biology* 17(2):358–366.
- Phillips, F. M., J. F. Hogan, S. K. Mills, and J. M. H. Hendrickx. 2003. Environmental tracers applied to quantifying causes of salinity in arid-region rivers: results from the Rio Grande, southwestern USA. Pages 327–334 *in* A. S. Alsharhan and W. W. Wood, editors. *Water resources perspectives: evaluation, management and policy*. Elsevier Science, New York, New York, USA.
- Robbins, P. 2004. *Political ecology: a critical introduction*. Blackwell, Malden, Massachusetts, USA.
- Szynkiewicz, A., M. Rangel-Medina, M. Modelska, R. Monreal, and L. M. Pratt. 2008. Sulfur isotope study of sulfate in the aquifer of Costa de Hermosillo (Sonora, Mexico) in relation to upward intrusion of saline groundwater, irrigation pumping and land cultivation. *Applied Geochemistry* 23:2539–2558.
- Swart, R. J., P. Raskin, and J. Robinson. 2004. The problem of the future: sustainability science and scenario analysis. *Global Environmental Change* 14:137–146.
- Vásquez-León, M., C. West, and T. Finan. 2003. A comparative assessment of climate vulnerability: agriculture and ranching on both sides of the US–Mexico border. *Global Environmental Change* 13(3):159–173.
- Vásquez-León, M. 2009. Hispanic farmers and farmworkers: social networks, institutional exclusion, and climate vulnerability in southeastern Arizona. *American Anthropologist* 111:289–301.
- Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society* 9(2):5.
- Witcher, J. C., J. P. King, J. W. Hawley, J. W. Kennedy, J. Williams, M. Cleary, and L. R. Bothern. 2004. Sources of salinity in the Rio Grande and Mesilla Basin groundwater. New Mexico Water Resources Research Institute WRRI Technical Completion Report No. 330. New Mexico State University, Las Cruces, New Mexico, USA.