

# Conceptual modeling for improved understanding of the Rio Grande/Río Bravo socio-environmental system

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## Abstract

Social processes are essential components of human-environment systems and their dynamics. However, modeling a tightly coupled socio-environmental system over a large area and across wide social and environmental diversity presents several challenges, given the complexity of the interactions and their spatial heterogeneity. The transboundary Rio Grande/Río Bravo (RGB) Basin is an excellent case study to address these challenges. Water scarcity and over-allocation of water are present in a highly engineered system with extensive damming and a complex structure of agreements and compacts that govern the distribution of hydrological resources among users. Since no basin-wide approaches to modeling the RGB as a socio-environmental system exist, we attempt to close this gap. Building on data collected through extensive ethnographic fieldwork, we used a structured, collaborative, and integrative approach for documenting existing knowledge on and modeling of the RGB socio-environmental system. We assess different models for conceptualizing human behavior applied in the RGB, identify a need to redefine the (spatial) boundaries of the system and produce inductively generated knowledge about the interlinkages of social processes with environmental system components in the form of a semi-quantitative conceptual model. Our research demonstrates an alternative to ad-hoc approaches to defining “the social” in socio-environmental models and is a first step towards the development of a basin-wide computer simulation model of the RGB socio-environmental system.

## Keywords

Rio Grande/Río Bravo Basin; Socio-environmental systems; Interdisciplinary collaboration; Explanatory models for social processes

## Code availability

The conceptual model was developed using the Mental Modeler software (Gray et al., 2013), available at <http://www.mentalmodeler.org/>. The model file is available at <https://doi.org/10.17605/OSF.IO/R3MSV>.

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## 1. Introduction

Sivapalan et al. (2014) call for a new, use-inspired science addressing water-related sustainability issues through the integration of existing knowledge as well as the creation of new knowledge for improved systems understanding. Modeling – the process of developing and implementing a model (physical, conceptual, mathematical, or other) – is a methodology well suited for knowledge integration and new knowledge generation. While there is a focus on modeling for the purpose of simulation (i.e., the application of a model) and, ultimately, prediction (Epstein, 2008), modeling can also serve the purposes of documentation and integration of existing knowledge and the identification of knowledge gaps. The latter are the tasks that are urgently needed in order to use socio-environmental findings to effectively address water-related sustainability issues. These and related challenges are widely indicative of the questions that continue to permeate studies of complex socio-environmental systems in general: what are the relevant human-environment dynamics to study, and at what temporal and spatial scales (Crane, 2010; Evans et al., 2002; Fabinyi et al., 2014; Orlove & Caton, 2010; Ostrom, 2012); what kinds of knowledge (data/analytical units) to use; and how to integrate these in ways that are useful and meaningful to the questions being asked.

In a review of the emerging field of socio-hydrological studies, Troy et al. (2015) identify a need for expansion on all three of these counts – conceptualization of the socio-hydrological, kinds of data, and methods used to model them. Perspectives from the social sciences suggest that, while interdisciplinary studies of complex socio-environmental problems have made advances toward becoming more comprehensive and integrative in scope, they still tend to focus on a very limited definition of “the social,” leaving out the multiple kinds of institutions, power and other social dynamics, objectives, and meanings that influence human environmental behavior (Crane, 2010; Evans et al., 2002; Fabinyi et al., 2014; Janssen & Ostrom, 2006; Orlove & Caton, 2010).

The Rio Grande/Río Bravo (RGB) Basin is a prime example of a highly intertwined socio-environmental system (e.g., Scurlock, 1998). Freshwater in the RGB is a scarce resource, and its distribution in this transboundary basin (USA – Mexico) is organized through a complex set of infrastructure, regulations, and compacts that operate on multiple spatial and temporal scales (Everitt, 1993). Furthermore, water scarcity and over-allocation of water have led to extensive engineering of the river to maximize the benefits for human use. For example, extensive damming and reservoir-building have created water storage capacity that is used to improve the predictability and availability of water for agriculture or other human uses. This has led to hydrological and environmental changes, such as the creation of the “Forgotten Reach,” an almost 200-mile stretch of the RGB downstream of El Paso, Texas, where the river rarely has any flow (Everitt, 1993); the listing of endangered species (e.g., Rio Grande silvery minnow (*Hybognathus amarus*) and the southwestern willow flycatcher (*Empidonax traillii extimus*); sedimentation (Bay & Sher, 2008; Shafroth et al., 2008); and problems with invasive species (e.g., salt cedar (*Tamarix spp.*) (Bay & Sher, 2008; Shafroth et al., 2008) and giant cane (*Arundo donax*) (Blythe & Schmidt, 2018)). Taken together, it has been estimated that, in the northern reaches of the RGB, total annual flow is 95% lower than it would be without human intervention (Blythe & Schmidt, 2018). According to Duran-Encalada et al. (2017), the RGB is one of the most endangered transboundary rivers in the world.

Past modeling efforts of the RGB applied various modeling approaches for integrating biophysical and socio-economic processes. For example, System Dynamics (SD) models have been used to analyze the complex interaction of components governing the quantity/quality of water and their effects on social and economic conditions in twin-cities along the border (Duran-Encalada et al., 2017), as well as to compare different water management strategies on water supply and crop revenues for one of the major sub-basins of the RGB, the Rio Conchos (Gastélum et al., 2009, 2010). Another SD modeling approach was employed through a community-based, participatory process to assist water planning for a three-county region in north-central New Mexico (Tidwell et al., 2004). A water planning model was implemented in the Big Bend area of Texas, along the US-Mexico border, to test reservoir re-operation strategies for balancing trade-offs among environmental and human objectives at minimum cost (Lane et al., 2015; Ortiz-Partida et al., 2016; Sandoval-Solis & McKinney, 2014). Several integrated models coupling a hydrological model with economic optimization models were used to identify strategies related to use, storage, and management of water resources to maximize social, economic and/or environmental benefits. Integrated models have also been applied for the U.S. northern reach of the river under scenarios of climate change and population growth (Hurd & Coonrod, 2012), market-based water transfers (Booker et al., 2005; Broadbent et al., 2017; Gastélum et al., 2010; Ward, Booker, & Michelsen, 2006), water conservation subsidies for improved irrigation efficiency (Brinegar & Ward, 2009; Ward, 2014), and water pricing systems (Schmitt et al., 2004).

However, these modeling studies either focus only on a subsection of the basin and/or use *a priori* assumptions or data that are highly abstracted from real-life conditions to represent social processes. To the authors' knowledge, there is no socio-environmental modeling approach for the whole RGB. We aim to address this gap by developing a basin-wide modeling approach that includes a more complex representation of social processes related to decision-making in the management of the basin's water resources. Since this is a highly ambitious undertaking, we approach this task by collaboratively developing a conceptual model of the RGB socio-environmental system. In this paper, we describe an effort to explicitly use this conceptual modeling approach as a device for knowledge production and integration by a team of environmental anthropologists and environmental modelers to understand the RGB Basin as a socio-environmental system. We focus on the interactions among water management and hydrological function across the RGB Basin under conditions of drought, over-allocation/-use, and other stressors to improve our understanding of social processes at the basin scale. This task is complicated by the fact that the basin crosses three U.S. states and five Mexican states, and is governed by multiple political jurisdictions, international and inter-state treaties, and varying water rights regimes. In addition to the complexity of the socio-economic setting, the RGB Basin is characterized by geological, hydrological, and ecological heterogeneity, presenting daunting challenges to any effort to capture socio-environmental dynamics that are neither too simplified to produce new and useful understandings of "the social," nor too representative of just one sub-region to provide a broader systems perspective. Here, we will describe the process by which we approached our interdisciplinary collaboration, and how this collaboration led to novel considerations of how social and environmental components interact in the RGB.

## 2. Materials and methods

In this section, we introduce the study area, describe the ethnographic fieldwork that informs our social process identification, and describe the structured model development process we used to facilitate our collaborative, interdisciplinary research on the RGB socio-environmental system.

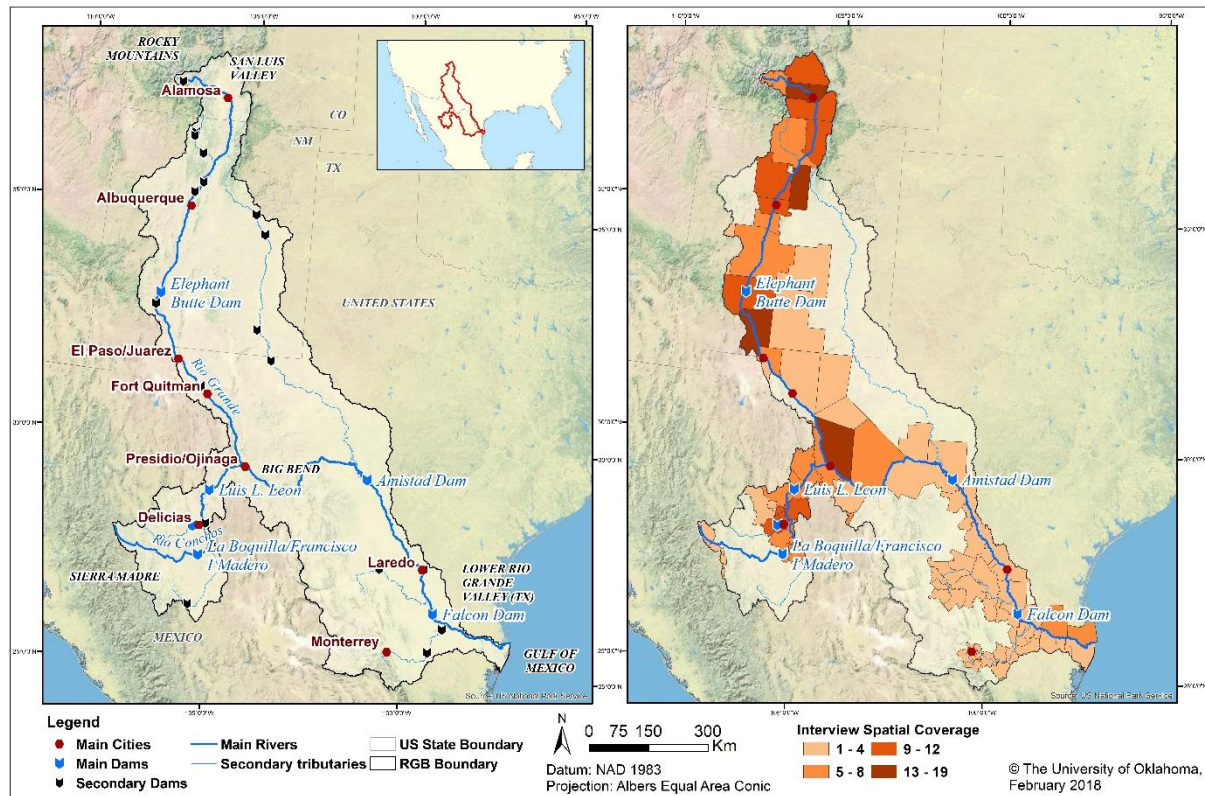
### 2.1 Study region

The RGB Basin covers an area of 552,382 km<sup>2</sup>, divided almost equally between the U.S. and Mexico (Figure 1). The 3,059 km-long river originates in the Rocky Mountains of the state of Colorado, flows southward through the state of New Mexico, and from the city of El Paso, Texas, tracks southeastward to the Gulf of Mexico, forming the international border between the U.S. and Mexico. The river crosses a climatically diverse area: mountainous in the headwaters, semi-arid to arid for most of its run, and subtropical in the estuary portion at the Gulf of Mexico. The precipitation in the basin ranges from 200 mm to 1,120 mm (Schmitt et al., 2004), resulting in spatially and temporally variable streamflow. In the upper RGB (here defined as Colorado to Fort Quitman, Texas), inflow is dominated by snowmelt from the Rocky Mountains, peaking in May or June. Between Fort Quitman and the twin border cities of Presidio, U.S. and Ojinaga, Mexico, there is a stretch of river, often called the "Forgotten Reach," where streamflow is infrequent and limited to extremely high-rainfall years. In the lower RGB (here defined as Presidio/Ojinaga to the Gulf of Mexico), two U.S. and eight Mexican tributaries replenish the river (Schmitt et al., 2004). It is the Mexican tributaries, particularly the Conchos River in the state of Chihuahua, that provide the majority of streamflow supplying both U.S. and Mexican water users in the lower RGB.

According to the 2010 GlobeLand30 land-cover dataset (Jun et al., 2014), shrubland and grassland cover 83 % of the basin, whereas cultivated area covers only 3.5 %. However, the majority of the basin's surface water and groundwater withdrawal is used for agricultural activities (83 % of total surface and groundwater use; estimate based on U.S. Geological Survey, 2010 and National Water Commission of Mexico, 2010). Industrial and municipal water supply for an estimated population of 10.5 million is, at 10 %, the second largest withdrawal (population estimate based on Llewellyn & Vaddey, 2013).

The RGB is highly engineered; irrigation canals, diversion dams, berms, and international boundary structures line large sections of the river and its floodplain. Dams and reservoirs (Figure 1) have been built over many decades to store water for irrigation and municipal uses, for flood protection and hydropower production, and to meet the obligations of international and inter-state water agreements for water sharing (Llewellyn & Vaddey, 2013). Three main agreements, in particular, heavily influence basin-wide management of the RGB's surface

waters, each guided by separate institutions and rules: (1) The Convention of 1906 obligates the U.S. to deliver a specified quantity of water from the upper RGB to Mexico at Ciudad Juarez/El Paso. (2) The inter-state 1938 Rio Grande Compact specifies the percentages of upper RGB flow to be distributed among the states of Colorado, New Mexico, and Texas. Elephant Butte Dam plays a key role in assuring water deliveries to southern New Mexico, Texas, and Mexico under these first two agreements. (3) The 1944 Water Treaty specifies how the waters of the lower RGB, including the inflows of Mexican and U.S. tributaries that supply this section, are to be distributed among the two countries. One tributary, the Conchos River, provides about 54 % of the historical Mexican water deliveries obligated to the U.S. under the 1944 International Treaty (Gastélum et al., 2009). Three dams, Luis L. Leon (located upstream of the confluence of the Rio Conchos with the Rio Grande), Amistad, and Falcon (binational dams along the border) play key roles in the distribution of Conchos water in the lower RGB.



**Figure 1:** Our study covers the entire Rio Grande/Río Bravo (RGB) Basin. The map on the left displays the basin boundary and the location of major cities, streams, and dams. The map on the right shows the relative density of ethnographic information obtained for different areas of the basin, drawn to the county/municipio level. A darker color indicates a higher number of interviewees provided information for that region, resulting in more ethnographic “data points,” but not necessarily the total number nor spatial distribution of interviewees. This is because the spatial coverage of individual interviewees’ information varies from large subsections to more localized areas of the basin.

## 2.2 Ethnographic fieldwork

We collected ethnographic data through traditional anthropological fieldwork approaches. Co-author Paladino relocated to live for 13 months in the RGB Basin (November 2015 – December 2016) in order to conduct interviews, participant observation, and other data gathering that *in situ* research affords with stakeholders, such as water resource managers and other people across multiple water-use sectors. In 2017, she made multi-week visits to the Conchos River Basin, Chihuahua, Mexico, and New Mexico, respectively, to conduct further fieldwork. Co-author Friedman conducted several weeks of fieldwork visits to different portions of the study region to complement Paladino’s *in situ* fieldwork.

For this study, we defined the water managers of primary interest as people who manage water either on behalf of a collective grouping of people (e.g., municipal water systems, irrigation districts, rural well-user associations,

government agencies) or as individuals managing water on their own land (e.g., farmers, ranchers). Recruitment of research participants began with purposive sampling (Tongco, 2007) of key informants (federal, state, municipal and agricultural water managers and decision makers) and development of a list of recommended informants (i.e., snowball sampling). In each region of the RGB, we identified agricultural/ranching organizations, agricultural co-ops, public agencies, and private and nongovernmental organizations, and used snowball sampling from other local informants, to identify farmers, ranchers, and other people with either individual or collective water management roles. We also drew on local contacts and online research to identify environment- or water-focused NGOs and other businesses that relied on the RGB (e.g., river rafting tourism). Figure 1 shows the spatial coverage of the ethnographic fieldwork, where the darker the color, the greater the density of information obtained for those areas.

Fieldwork methods included semi-structured interviews (~104 hours of recorded, one-on-one interviews, resulting in over 2,500 pages of transcribed documents), participant observation averaging from 4-8 hours spent with each interviewee (~300 hours), and participant observation and informational interviews with dozens of actors who were not formally recruited into the study, but who became key informants in both the U.S. and along the Rio Conchos in Mexico (~500 hours). This fieldwork resulted in a total of 68 recorded and 13 unrecorded formal interviews. Semi-structured interviews focused on a set of themes meant to capture not only behavior directly relevant to water management and water use decisions, but, also, the deeper personal, professional, and contextual background for each interviewee in order to understand the reasons for the interviewees' behaviors. Semi-structured interviews included a number of shared themes across all interviews, including: a) personal/professional background; b) observed changes in climate and natural ecosystems; c) local and institutional memories of drought; d) change/response/adaptation in water and land management and workplace decision-making over time; e) drought-specific questions; and f) perceptions of own and institutional roles related to water decision-making, of availability of information for water decisions, and of wider RGB Basin dynamics. Participant observations and informal discussions were also documented in written and/or audio-recorded fieldnotes (23 hours of audio recorded notes), and included such data as landscape observations, public meetings and events, the contexts of formal interviews, and, importantly, extensive visits to irrigation systems, water transport systems, local ecosystems, water treatment plants, and farm fields, all of which illustrate actual water management and use practices among research participants.

### 2.3 Conceptual modeling of the RGB socio-environmental system

According to Kragt et al. (2013), the structured process of model development is well-suited for the facilitation of interdisciplinary research. They suggest expanding the technical focus of the modeling process by discussing the multiple roles of the modeler in the context of integrative research projects and recommend that modelers move beyond being technical specialists to take on the role of knowledge brokers and facilitators. Given the interdisciplinary nature of our research, we followed the recommendations of Kragt et al. (2013) and approached our collaboration by making use of modeling as a framework for integrative research.

Frequently, modeling studies are carried out for the purpose of prediction (Epstein, 2008). This means generating new knowledge in these studies is related to running a model and analyzing the simulation results. However, Epstein (2008) lists many other reasons to model, besides prediction. We agree with Epstein (2008) and emphasize that, while prediction is a valuable output from a modeling exercise, just as critical is the fact that modeling (especially interdisciplinary approaches) always begins with the struggle over the generation of and meaning of knowledge about a system that must be captured in the conceptual modeling phase – something that is often overlooked or not given sufficient attention.

Integrated environmental modeling literature provides descriptions of approaches that lend themselves to being applied and adjusted in the context of socio-environmental systems modeling. In their position paper on the development and evaluation of environmental models, Jakeman et al. (2006) describe ten model-building steps intertwined with eight potential iteration pathways. We argue that, of those ten steps, the first three, in particular, are a natural connection point to facilitate collaborative research on socio-environmental systems through conceptual modeling, and that these steps should be carried out in close collaboration among both social and physical/natural scientists.

We started the model development process in June 2016 and met, on average, twice per month for an average of two hours per meeting until October 2017. The meetings consisted mainly of group discussions involving the

modelers and environmental anthropologists that included updates on research activities around the RGB system and introductions on approaches and methods applied in the respective fields of research. Over the first months, the meetings and discussions helped us to develop a shared terminology. They also helped to establish the level of trust that is often considered to be crucial for successfully conducting team research (Adams, 2014). We then used the model building steps described by Jakeman et al. (2006) to structure our collaborative research. In the following text, we provide a short overview of the first three modeling development steps as introduced by Jakeman et al. (2006) and describe how we applied these steps to socio-environmental model development – facilitated by modelers – to structure the analysis and conceptualization of the RGB system, focusing on key social and behavioral processes. The modelers guiding through this process had extensive experience in modeling of socio-environmental systems, which was helpful for facilitating the collaboration.

*1) Definition of Model Purpose.* The definition of the model purpose is a crucial step in the modeling process, since it forms the basis for all following steps. There is much agreement in published research that this needs to be approached in a collaborative manner, and different methods to realize the integration are suggested, ranging from stakeholder workshops and focus groups (Hamilton et al., 2015) to SWOT analysis (Ritzema et al., 2010; Voinov et al., 2016). We approached the definition of the model purpose through group discussions during our regular meetings. Meetings and discussions were facilitated by the modelers, but the content of the meetings was mainly driven by the environmental anthropologists and the findings from their fieldwork (see Section 2.2). However, the modelers provided input on the capabilities of different modeling approaches to support the definition of a feasible and realistic model purpose.

*2) Model Context Specification.* The model context specification step is required for defining the boundaries of the system under study and for describing the spatial and temporal scope/scale of the system. One key task in this step is the decision about the scale/resolution of the processes that shape the behavior of the system. The specification of the modeling context was also carried out in a collaborative manner through group discussion, gradually refining the specifications based on our improved understanding of the RGB system. While the modelers focused on the more technical parts of this step (e.g., time frame or availability of computing resources), important components related to the system under study were identified and agreed upon collaboratively (e.g., temporal/spatial scope, system boundaries, and resolution of key processes).

*3) System Conceptualization.* The system conceptualization step focuses on synthesizing and formalizing knowledge, data, and processes for the system under study. Jakeman et al. (2006, p. 608) state that this modeling step “[...] defines the data, prior knowledge, and assumptions about processes. The procedure is mainly qualitative to start with, asking what is known of the processes, what records, instrumentation, and monitoring is available, and how far they are compatible with the physical and temporal scope dictated by the purposes and objectives.” This step was the most time consuming of the three modeling steps. It was, again, facilitated by the modelers, and we applied a conceptual modeling approach during which the environmental anthropologists played the driving role. In the meetings, they verbally summarized, translated, and extracted processes in the RGB that they had learned about in their interviews, *in situ* ethnographic observations, and interactions with actors along the RGB. They, furthermore, identified links between frequently emerging topics and system components.

We formalized this process by developing conceptual models around three important themes identified during the ethnographic fieldwork: irrigation, environmental flows, and evapotranspiration. The modelers captured the discussions in the form of graphical representations on a whiteboard. In a first draft, we documented the different topics (or “nodes”) and the relationships between those through simple box-and-arrow diagrams. While the facilitation of the process was the main task of the modelers, they also supported the process by asking “outsider” questions that helped clarify what the social scientists were trying to convey and connect. The modelers furthermore supported the conceptualization step by helping to visualize the system via maps, extracting numbers from databases, or providing information on spatial heterogeneity of the biophysical environment in the RGB. This was done to contextualize the qualitative aspects of the RGB. It is important to note that we did not set a limit of nodes or connections between those to limit the development of these graphical representations. Rather, we continued this process until each of the three themes was sufficiently explored. This means that, according to the environmental anthropologists, adding more nodes to the concept map would result in opening up the discussion about an entirely new (yet connected) theme. In preparation for future analyses, and for improved visualization of the results, the modelers in the research team transferred the

diagrams captured on the whiteboard into Mental Modeler, a software for standardizing knowledge in a semi-quantitative manner (Gray et al., 2013).

Subsequently, we used the box-and-arrow diagrams, which we considered early drafts of the conceptual model, to build an influence diagram following the rules described by Bossel (2007). Following Bossel's rules, we used boxes to represent the system elements, represented direct influences between those elements via arrows, and used plus and minus signs to describe the directionality of the influence. We also added descriptions to the arrows in order to document and qualify the influences that we described. This process also included the combination of the three individual diagrams (irrigation, environmental flows, and evapotranspiration) into one conceptual model. The combination process focused specifically on the removal of redundant arrows and a refinement and quality check of the conceptual model implemented in Mental Modeler.

### 3. Results and discussion

In this section, we describe the results of the three environmental model development steps. We introduce the model purpose and the social system components of the RGB that we identified in our research as important for understanding the socio-environmental system's dynamic behavior, and we describe and evaluate our conceptual model.

#### 3.1 Model purpose definition

While we continued to iteratively circle back to further refine the purpose definition throughout our research (and will very likely continue to do so), our current definition of the modeling purpose is the following:

- 1) Document decision-making and adaptive behavior at sub-basin scale/geographic regions to compare and contrast differences among regions of the RGB.
- 2) Understand how regional decision-making and behavior affects and is affected by dynamics at the basin level.
- 3) Explore alternative future system responses resulting from different management strategies under changing social and natural conditions.

This definition of model purpose guided all of the following steps towards the development of our conceptual model of the RGB socio-environmental system. We expect to achieve the first two outcomes through modeling (i.e., the process of building a simulation model) and the third component through both modeling and computer simulation – the mid-term goal of our interdisciplinary collaboration.

#### 3.2 Specification of modeling context

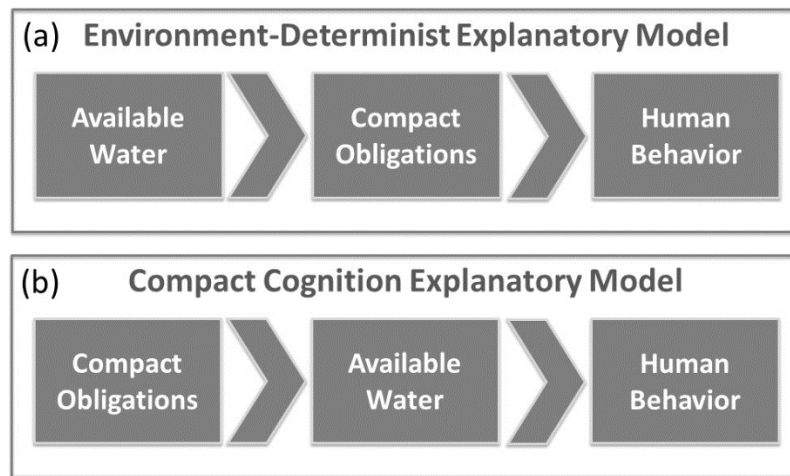
The modeling context step sets the system boundaries, processes, and their spatial/temporal resolution. Below, we discuss two explanatory models for social processes that have been applied in the RGB system and their relative explanatory power for defining human components of the RGB modeling context. We describe some key considerations in the specification of the RGB system's spatial boundaries that resulted from our collaborative process. We then discuss how using the ethnographic work to inductively derive important socio-environmental dynamics for the basin have provided us with a more robust explanatory model, with higher fidelity to "real" human behavior.

##### 3.2.1. Explanatory models for social processes in the Rio Grande/Río Bravo socio-environmental system

Within the RGB system (and, we would suggest, many other water-limited systems), two ways of thinking about the human/social system have dominated work on the socio-environmental conceptualization and modeling of the region (though there are other ways of thinking about these systems that are rarely considered). The first is what we term an Environment-Determinist Explanatory Model of Human Behavior (Figure 2). Under an environment-determinist concept, human-derived institutions and political-economic-legal frameworks emerge as a response to the physical availability of water (Rister et al., 2011). In other words, hydrological constraints (or, peculiarities) are primary drivers that shape the reactions of humans. In the RGB region, this environment-



determinist explanatory model is most clearly seen in cases where human behavior, institutions, and built environments are characterized as having been crafted in response to limitations in the availability of water or other hydrological drivers (Phillips et al., 2015; Rivera, 1998).



**Figure 2:** Schematic view of the two different explanatory models of thinking about human/social systems in the Rio Grande/Río Bravo Basin, (a) the Environment-Determinist Explanatory Model and (b) the Compact Cognition Explanatory Model.

To account for different human needs for water across the RGB Basin, treaties, agreements, and compacts have been adapted to hydrological availability. In the environment-determinist view, it is not just that humans have adapted institutions to deal with water shortages and needs, but, that those hydrological conditions caused these institutions to arise. For instance, because most, if not all, of the water from the Rocky Mountains in a typical year is exhausted to meet the allocations for users in the upper RGB (north of the “Forgotten Reach”), binational agreements establish that water from Mexico’s Rio Conchos will be used to “recharge” the lower RGB near the Big Bend region of Texas, thus providing a reliable source of water to users on both sides of the border from Amistad Reservoir south to the Gulf of Mexico (Figure 1). However, the 1944 Water Treaty specifies that Mexico’s obligations to recharge the RGB with waters from the Rio Conchos should reflect the annual variations in water availability. Thus, during a drought year, Mexico might not have to meet its usual annual obligations – instead, Mexico’s obligations to release water from the Rio Conchos to recharge the RGB are based on a 5-year average for annual water release obligations. During a drought, Mexico can hold back some water for domestic use, as long as the 5-year cumulative release of water is equal to five times the average annual obligation. As environmental conditions are projected to change due to climate change (Dettinger et al., 2015; Khedun et al., 2012), new approaches to these agreements and treaties have been proposed (International Institute for Applied Systems Analysis, 2016; Lane et al., 2015; Nava & Sandoval-Solis, 2015). Critically, in this example, “the social” is characterized as being adaptive and responsive to the hydrological drivers to the point where, even an obviously social construct (the 1944 Water Treaty, in this case) is modeled as a direct function of the environmental (hydrologic) system in which it exists.

In the RGB, this environment-determinist explanatory model of human behavior can be contrasted (or, in the best cases, supplemented) with what we call a Compact Cognition Explanatory Model of Human Behavior (Booker et al., 2005; Douglas, 2009) (Figure 2). By ‘compact cognition’ we mean the tendency to ascribe the primary explanation for resource management decisions to macro-level state, interstate, and international compacts, treaties, agreements, and obligations. At the same time, we selected the term “compact” because of its double-meaning in this model: “compact” can be a term used to describe these agreements and treaties, but, it also describes how this explanatory model of human behavior focuses on the fact that much of the decision making in the RGB region occurs in a way that draws on conveniently simplified (or “compact”) cognitive concepts of the region. Thus, when one looks at “the social” from this standpoint, human behavior is not only responding to the compacts, treaties, and agreements as a driver but is also responding through processes of cognitive simplification and reduction that drive behavior toward certain socially-sanctioned and predictable sets of choices and decisions. As the anthropologist Claude Lévi-Strauss (Lévi-Strauss, 1966) famously suggested, the reason why certain cultural artifacts — in this case, the power of compacts, treaties, and agreements —



carry such weight in the RGB region is that they not only provide a critical function but, that they are “good to think with” — they provide useful cognitive shortcuts that permit actors to simplify overly complex systems.

Examples of compact cognition frequently emerged during our *in situ* research. For instance, a farmer in southern New Mexico might explain some aspects of their farming practices in terms of the water limitations placed on them by New Mexico’s obligation, under the Rio Grande Compact, to release water to Texas, leaving “less” water for New Mexico farmers. This kind of thinking — this explanation that gives primacy to compact obligations — contributes to many water managers expressing that the root cause of the “the problem” is primarily one of “other people” and a legal legacy of “outdated” or “unjust” treaties, agreements, and/or compacts (Nava & Sandoval-Solis, 2014, 2015), rather than seeing problems within their own practices, or problems associated with the iterative effects of climate change and cycles of degradation within the socio-environmental system of the RGB.

When building interdisciplinary links across our research, it became clear that understanding compact cognition explanatory models of human behavior was critical to bridging the multiple levels of analysis and multiple types of data we were attempting to make sense of and synthesize in a model. For instance, in developing our broad conceptual model (see Section 3.3), we evaluated the traditional stock-and-flow management balancing that one finds in descriptions of the impact of the various RGB agreements on the river (e.g., Broadbent et al., 2017; Duran-Encalada et al., 2017; Tidwell et al., 2004). Thus, the stock-and-flow-informed understanding of the upper RGB considers, for instance: (1) the quantity of snowpack in the regions of the Rocky Mountains that feed the upper RGB Basin; (2) the amount of water measured by stream gauges at the headwaters in Colorado; (3) the proportion of the total streamflow in the RGB that Colorado is obligated to release to New Mexico; which gives us (4) the total amount of water that is available to Colorado to partition among obligations/rights for human use, environmental use, and for hydrogeological processes (e.g., evaporation or aquifer recharge); as well as (5) the total amount of water that will flow into New Mexico, where the process begins again. While environmental processes are responsible for the initial snowpack and the flow and availability of water in the RGB, it is the intervention of the distinctly social processes surrounding the Rio Grande Compact and state water rights regimes that determine how this hydrological resource is then distributed among states and water users, in turn influencing conditions of relative abundance or scarcity in each state. Thus, a compact cognition perspective can help link the social to the environmental by bringing into view the hydrological roles of these social interventions.

One of the problems with an over-reliance on a compact cognition perspective is that these political and legal agreements among states, countries, and end-users can be treated as a set of seemingly inflexible structures. In this way of modeling the socio-environmental system, one could end up portraying human behavior primarily as a function of the constraints and obligations built into the cluster of treaties, compacts, and agreements that move water along the RGB. In reality, as our field research confirms, these compacts are more flexible than often presented, being comprised of negotiated and amended political and legal agreements, evolving administrative and technical institutions to implement them, and choices made (and modified) about what scientific methodologies, accounting methods, and water monitoring and measuring procedures to employ. Another limitation of the compact cognition explanatory model of human behavior is that it tends to be based on the assumption that both collective (e.g., countries, states, cities) and individual rights-holders seek to use their maximum allotted quantities of water. However, simplified social concepts that assume that human behavior is structured primarily by compacts and laws fail to account for varied and critical aspects of behavior, as confirmed by interviews and observations while conducting fieldwork. For instance, the compact cognition explanatory model of human behavior could only tell us about how the absolute maximum available water rights allotment might be provided to an actor, but little about the range of motivations, behaviors, and practices that influenced the management of that water, the land, livestock, natural habitat, endangered or threatened species, or people themselves. Therefore, these simplified explanatory models of human behavior fail to help us understand, for instance, conservation throughout the RGB — the conscious efforts to not use the maximum amount of allotted water, and/or efforts to increase the efficiency of allotted water in order to maximize the ecological services provided by the water — as well as other non-economic, water management motivations and behaviors present in the basin.

The two discussed explanatory models of human behavior are helpful for understanding parts of the social processes that impact or drive system behavior in our modeling efforts. However, they do not have a sufficiently high explanatory power to explain all of the key dynamics in the basin. While simplified models of the role of humans as drivers on the hydrology of the RGB are the cornerstone for much of the extant scholarship on the

RGB, our ethnographic research with water managers and decision-makers showed that neither the simple environment-determinist explanatory model nor the simple compact cognition explanatory model could account for many of the real-world practices that influence the socio-environmental system. While our research supports the idea that many water managers along the RGB are guided by treaties, agreements, and compacts within the broader constraints of hydrological conditions (i.e., available water; cf. Ness et al., 2010), our empirical research has found that reducing human behavior to either/both of those simplified explanatory models (e.g., by reducing human impacts, influence, and interaction with the RGB to legal obligations or to the availability of water; Siirola et al., 2012) failed to capture critical dynamics of the system. Hence, our collaboration required our modeling efforts to include a way to find a level of simplification that does not neglect key, high-resolution social drivers of system dynamics.

### 3.2.2. Spatial boundaries of the Rio Grande/Río Bravo socio-environmental system

In addition to facing the challenge of defining an appropriate model representation of “the social” in our collaborative modeling effort, we also faced unexpected challenges defining the spatial boundaries of the RGB socio-environmental system. In the case of the RGB Basin, the hydrological basin boundary seemed to be the obvious choice for delineating the spatial system boundaries and, hence, this was proposed by the modelers during the early stages of our system conceptualization. While this was a good fit for a majority of the basin, in the Lower Rio Grande Valley of Texas (LRGV) (Figure 3), our collaborative research identified a spatial mismatch between the basin’s boundary and the actual geography of RGB water use. From the ethnographic fieldwork, we learned that the 28 irrigation districts located in the LRGV consume substantial surface water from the RGB and thereby export water outside of the hydrological basin boundary. Even though the irrigation districts cover a small area (3,129 km<sup>2</sup>) compared to the extent of the basin, the irrigation districts and their respective counties (Hidalgo, Cameron, and Willacy) are large consumers of surface water for both agricultural and municipal purposes. According to Cumming et al. (2006), the annual withdrawals of those three counties adds up to 1,073 millions of cubic meters (MCM) of surface water, which is, for example, around four times the annual surface water withdrawal of El Paso County, another big consumer of surface water in the basin.

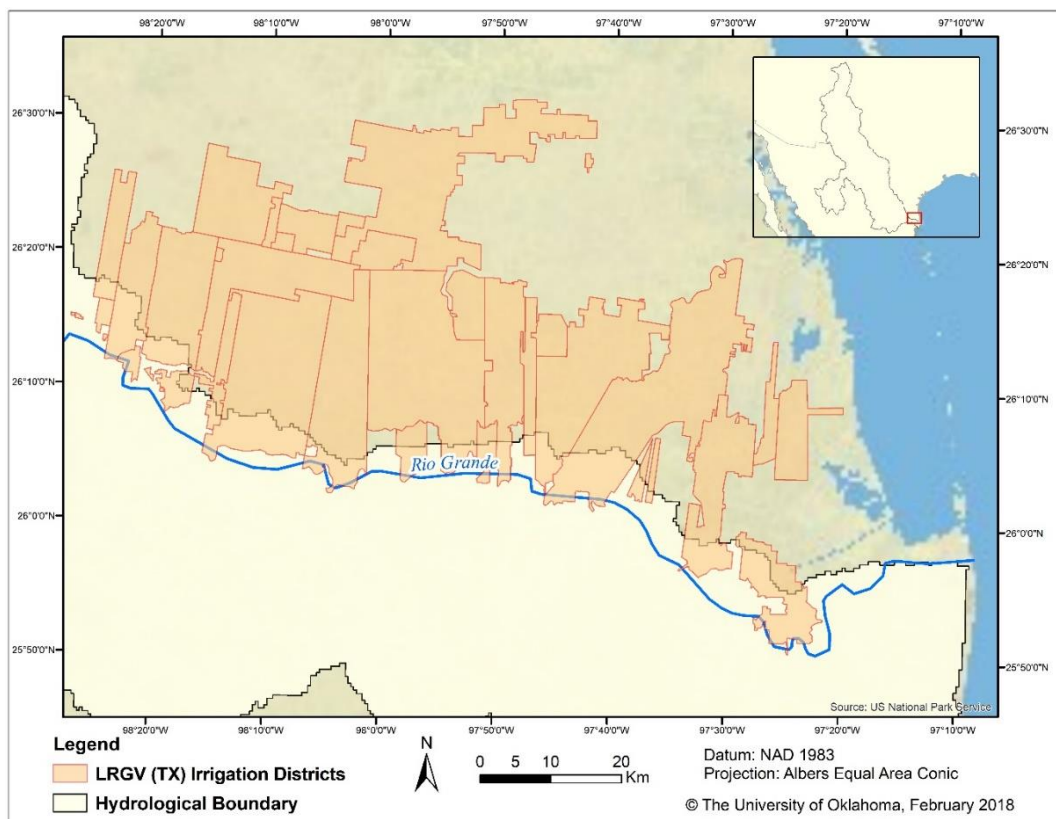


Figure 3: Spatial mismatch between the basin boundary and water management in the Lower Rio Grande Valley (LRGV) in Texas.

These findings led us to question the initial choice regarding the spatial boundaries of the RGB socio-environmental system. It became evident that the social processes of water management in the 28 irrigation districts located in the LRGV form an important part of the dynamics of the RGB system and cannot be viewed as external factors. Therefore, we decided to adjust the spatial system boundary to include the three counties (Hidalgo, Willacy, and Cameron), even though this will eventually require us to make compromises when approaching the modeling of hydrological processes in a computer simulation model. This outcome is in line with other research findings on socio-environmental systems. Delineating the boundaries of systems can be a challenging task due to scale mismatches between social and ecological processes (Cumming et al., 2006). Hence, recent research efforts have focused on developing methodological frameworks for spatial mapping of socio-ecological systems boundaries (Hamann et al., 2015; Martín-López et al., 2017).

### 3.2.3. Socio-environmental relationships in the Rio Grande/Río Bravo Basin

The specification of the modeling context becomes an even more challenging task when conceptualizing the entire RGB Basin as a socio-environmental system. Our research takes what we consider to be an innovative approach to understanding the RGB socio-environmental system because we explicitly sought to avoid looking at only one or two regions of the RGB as proxies for the whole system. Rather, we hypothesized that different contexts exist in different parts of the river, and that to understand the RGB as a broad system — including the dysfunctional aspects of that system that might contribute to or result from fragmentation — we need to study the full length of the river (from Colorado to the Gulf of Mexico) and its main tributary (the Rio Conchos) to gather data on both the differences in regional socio-environmental interactions as well as commonalities that might cross different parts of the river system. For example, large macro-scale agreements like the Rio Grande Compact may structure water distribution across states in the RGB Basin, but sub-basins or regions within the RGB are characterized by greatly varying environmental conditions and histories of human use. Regions generate their own needs, problems, and responses to them that are not addressed by such agreements.

For instance, between the headwaters of the upper RGB in Colorado and the Colorado-New Mexico border lies one of Colorado's significant farming areas, the San Luis Valley, heavily invested in irrigation-dependent, commercial crop production. Initially, this region was reliant on surface water diversion from the RGB system. During the decades since the Rio Grande Compact was established, substantial agricultural expansion occurred based on the drilling of wells to both confined and unconfined aquifers in the valley. This has had an impact on streamflow and, particularly evident during a landmark extended drought that began in 2002, on groundwater levels. As a result, in this region, new water management subdistricts are being developed to manage groundwater withdrawal in conjunction with surface water withdrawal, adding yet another layer of water decision-making to this part of the basin. A member of the Rio Grande Water Conservation District in the Valley commented:

*"We have an over-appropriated system. We have wells that haven't been in the priority system, if you will, and there are impacts of wells on streams that we've come to know over the last thirty or forty years, and so our Board (...) came up with the idea that we could do self-governance here of our groundwater administration instead of the state coming in [with rules] (...) and so we have been about... forming groundwater subdistricts that are discrete areas, typically, that share a common thread, either it's a common aquifer, a common drainage area, primarily physical in nature. (...) Each one of those [will] have a, its own plan of water management and its own board of managers and its own operations (...) that administer, manage (...) the wells within their subdistrict and (...) be responsible for the sustainability of the aquifer and replacing any injurious depletions that wells cause to (...) water rights on that stream."*

The creation of the subdistricts introduces more complex kinds of social interactions with the hydrology of the region than had existed. Now "new" water is being imported into the system, water is being moved within the system in different ways, and water management decisions take into account both groundwater and surface water, as well as their interactions. The subdistricts also create new institutional structures and legal agreements for water governance, establish additional sets of criteria for human behavior for water management, and create the need for an intense and sophisticated amount of monitoring and administration. They also potentially create new sources of tension among different kinds of water users, which may ultimately affect how well the subdistricts' goals are realized.

Another challenge when focusing on a river like the RGB — and by extension, one of the challenges to socio-environmental modeling of the river from its source in the Rocky Mountains to its discharge in the Gulf of Mexico — is that, due to human impacts on the river and the broader basin, the RGB is constantly being “reset” hydrologically. At each point in the RGB where a significant impoundment stops the natural flow of the river — usually represented by large reservoirs that have resulted from the damming of the river — model parameters and calibrations have to be reconsidered. The hydrological understanding of the fragmented nature of the RGB (Schmidt & Wilcock, 2008) and the need to “reset” at various points along the river was paralleled in our interviews. For instance, it is common for people in the RGB basin to talk about the physical river, the “wet” river, in terms that recognize how the flow of the RGB has been divided up and re-shaped by human intervention over the years by inter-state and international agreements. As a southern New Mexico resident told us:

*“Perhaps a useful conceptual model for you is that you think of this as the Rio Grande. It’s really three rivers. There’s the river above Elephant Butte Dam, and you can call that the Rio Grande. There’s the Rio Grande Project, which is from Elephant Butte Dam down to Little Box Canyon down here, Fort Quitman. And then that river that runs into the gulf at Brownsville is not the Rio Grande at all. That’s Rio Conchos. And the Rio Grande is an occasional tributary. But, I mean, it hasn’t been a tributary for some years now, so it’s really occasional. So that’s a completely different river system. It’s got a separate treaty with Mexico.”*

The same person, however, describes divisions of the RGB in another, more political, and counterintuitive sense, based on where, geographically, the accounting for delivery of Rio Grande Compact water to Texas is done. Under the Compact, the delivery of upper RGB water to Texas is made at Elephant Butte Reservoir, over 100 miles north of the New Mexico-Texas state border. For the purposes of administering New Mexico’s obligations to Texas under the Rio Grande Compact, those 100+ miles of southern New Mexico RGB are effectively considered Texas:

*“...under that Compact, Colorado had a portion of that water to deliver to New Mexico, New Mexico had a portion to deliver to Texas. The fact that Elephant Butte was the only mainstem dam on the Rio Grande at that time, the delivery point for New Mexico was Elephant Butte. So we’re [the portion of New Mexico between Elephant Butte Dam and Texas] in Texas when it comes to the Compact. This is where it gets a little weird. It gets real weird. And it gets real complicated. And that’s why you have...we’re in lawsuits all the time. (...) We are under the (...) Compact Commissioner from Texas.”*

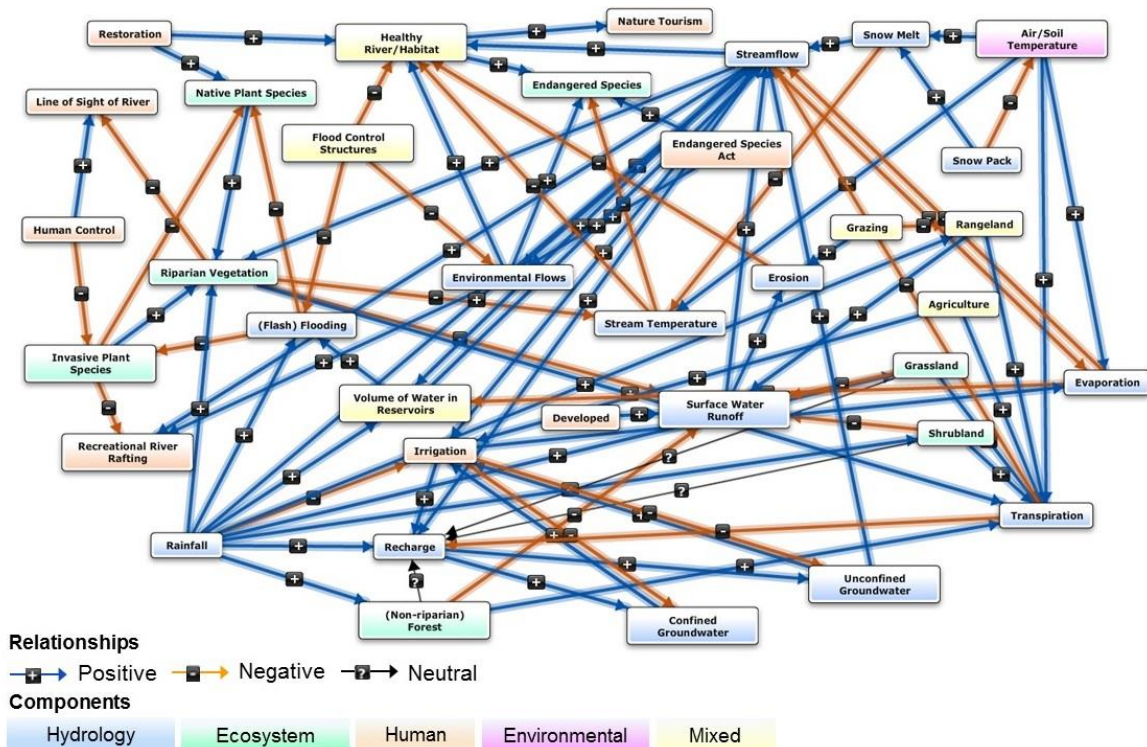
Taken together, these two narratives have important implications for the context specification of the RGB socio-environmental system. The RGB has a high density of dams distributed along the mainstem and the tributaries, which are managed by many agencies with specific rules of operation. Therefore, the choice of a basin-wide approach complicates the modeling of the reservoir operations due to the complexity of modeling all the dams and associated decision-making in a limited time frame. The collaboration between social and environmental scientists has been essential to defining the criteria to be used to specify the spatial boundaries (i.e., segments of the RGB) and reset points (i.e., impoundments and dams) that are of greatest importance to understanding the whole river system. Specifically, in addition to the size of the dams, the purpose of the dams appears to be a key criterion.

### 3.3. System conceptualization

The objective for the system conceptualization step is to synthesize and formalize knowledge, data, and processes for the system under study. Hence, we used the development of our conceptual model to synthesize and visualize, in a standardized format, how actors in the basin perceive the structure, constraints, and dynamics of the RGB socio-environmental system. Our decision regarding the modeling context — to study the full length of the river from Colorado to the Gulf of Mexico, including the Rio Conchos — made the system conceptualization step an ambitious undertaking. For this step, our priority was not to reduce the complexity, but rather, to use it to explore the complexity of the relationships within the social components of the RGB and the hydrological and other environmental system components. It is important to emphasize that we aimed to capture the main topics and concerns raised during interviews. Hence, our goal with the conceptual model was not to display some “objective,” scientific concept of how the RGB system works, but rather how actors understand/perceive the system to work, especially regarding the relationship between social and environmental components. We hypothesize that this will enable us to understand what decision makers are managing for, and ultimately, identify ways to potentially improve water management in the basin.

As described above, we began the conceptual modeling by collaboratively developing conceptual models around three important themes identified during the ethnographic fieldwork: irrigation, environmental flows, and evapotranspiration (see Section 2.3). Currently, the conceptual model does not include political and legal agreements, since we could not find a meaningful way to depict this spatially-determined component in a non-spatial modeling approach. However, we want to stress that the exclusion of the system of political and legal agreements — which in many ways, defines the flow of the RGB from segment to segment — means that the conceptual model needed to be supplemented with these external (to the model) spatially-specific drivers for understanding how and why the RGB system functions the way that it does. Within our non-spatial conceptual modeling, we combined the three themes into one conceptual model describing key components of the socio-environmental system of the RGB, as perceived by research participants during the ethnographic fieldwork. During the development of the conceptual model, we frequently circled back to the modeling purpose (see Section 3.1) to remind ourselves of the basin-wide approach of our research and to educate each other about methods and tools used in the different disciplines. We furthermore had to remind ourselves frequently to keep the conceptual model development focused exclusively on representations of the system as expressed by research participants, rather than on our own “external” understandings of it.

Figure 4 shows the finalized conceptual model for the RGB socio-environmental system, implemented in the Mental Modeler software (Gray et al., 2013). The model includes 36 components (displayed as boxes) with 86 total connections (displayed as arrows), resulting in a density of 6.8 %, with the density describing relationship between realized connections and possible connections. Of the components, 23 are ordinary components, which means that they have both incoming and outgoing connections (e.g., snowmelt or volume of water in reservoirs). Nine of the components are drivers, meaning that they influence components of the system but are not influenced by other components (e.g., rainfall). Four system components are receivers, indicating that they are influenced by other components but do not influence components (e.g., nature tourism or endangered species). Table 1 provides a detailed list of components and their categorization. The network metrics were derived from the Mental Modeler software (Gray et al., 2013).



**Figure 4:** Conceptual model for the Rio Grande/Río Bravo socio-environmental system. The conceptual model identifies the components of the system (boxes), categorized in five groups: Ecosystem, Hydrology, Human, Environmental, and Mixed. The Mixed category includes system components that could not clearly be categorized as solely Human or Environment system components. The connections between the components (arrows) show direction and type of influence. A positive connection (“+” in blue) describes a cause and effect relationship where the values of the component change in the same direction. A negative connection (“-” in orange) indicates that the components’ values change in opposite directions. A neutral connection (“?” in black) indicates that we were not able to identify a clear quantitative relationship between the two components.

**Table 1:** Overview of the components, their types and categories, and other indicators generated with Mental Modeler (Gray et al., 2013). Degree In gives the number of incoming relationships, Degree Out gives the number of outgoing relationships, while Centrality is calculated as the sum of incoming and outgoing relationships.

Component	Degree In	Degree Out	Centrality	Type	Category
Agriculture	0	2	2	Driver	Mixed
Developed	0	1	1	Driver	Mixed
Endangered Species Act	0	2	2	Driver	Human
Flood Control Structures	0	3	3	Driver	Mixed
Grazing	0	2	2	Driver	Mixed
Human Control	0	2	2	Driver	Human
Rainfall	0	10	10	Driver	Hydrology
Restoration	0	2	2	Driver	Human
Snow Pack	0	2	2	Driver	Hydrology
(Flash) Flooding	3	2	5	Ordinary	Hydrology
(Non-riparian) Forest	1	2	3	Ordinary	Ecosystem
Air/Soil Temperature	1	4	5	Ordinary	Environment
Confined Groundwater	2	1	3	Ordinary	Hydrology
Environmental Flows	3	3	6	Ordinary	Hydrology
Erosion	2	1	3	Ordinary	Hydrology
Evaporation	3	2	5	Ordinary	Hydrology
Grassland	1	2	3	Ordinary	Ecosystem
Healthy River/Habitat	6	2	8	Ordinary	Mixed
Invasive Plant Species	2	3	5	Ordinary	Ecosystem
Irrigation	5	4	9	Ordinary	Human
Native Plant Species	3	1	4	Ordinary	Ecosystem
Rangeland	2	2	4	Ordinary	Mixed
Recharge	4	2	6	Ordinary	Hydrology
Riparian Vegetation	4	4	8	Ordinary	Ecosystem
Shrubland	1	2	3	Ordinary	Ecosystem
Snow Melt	2	2	4	Ordinary	Hydrology
Stream Temperature	3	2	5	Ordinary	Hydrology
Streamflow	7	8	15	Ordinary	Hydrology
Surface Water Runoff	6	2	8	Ordinary	Hydrology
Transpiration	7	2	9	Ordinary	Hydrology
Unconfined Groundwater	2	2	4	Ordinary	Hydrology
Volume of Water in Reservoirs	3	2	5	Ordinary	Mixed
Endangered Species	4	0	4	Receiver	Ecosystem
Line of Sight of River	2	0	2	Receiver	Human
Nature Tourism	1	0	1	Receiver	Human
Recreational River Rafting	3	0	3	Receiver	Human

The conceptual model (Figure 4) and its components (Table 1) reflect some findings that were to be expected. Streamflow is the system component with the highest centrality value, followed by rainfall, which also has a high centrality value and is considered a major driver of the systems. We specifically used two different components — rainfall and snowpack — instead of just one component for precipitation. This was motivated by the need to represent the regional differences with regard to precipitation and its management implications, which would otherwise be lost during the non-spatial conceptual modeling. Irrigation, transpiration, and surface water runoff are also considered of high centrality to the system. Overall, 14 of the 36 identified system components are categorized as Hydrology components, and these make up 52% of the ordinary components, i.e., those that have incoming and outgoing connections. These results show the obvious — understanding or modeling the RGB socio-environmental system without a thorough representation of hydrological components and processes is not possible. More informative is the prevalence of multiple Ecosystem components in the conceptual model. Overall, the model includes seven components categorized as Ecosystem, but one could argue that environmental flows also qualifies for this category (Table 1). Except for endangered species, which is a receiver component, all other ecosystem components are ordinary components. The Ecology category mainly comprises different vegetation characteristics in the RGB. This includes the land cover component (forest, grassland, shrubland) and covers the topic around riparian vegetation including native and invasive plant species, with endangered species being specified as a receiver of the system dynamics.

Another major outcome from our conceptual modeling is that we see a pattern of the human category of system components and their placement in the conceptual model. Six out of seven components categorized as human components are either drivers or receivers, with three components for each type (Table 1) and low centrality values. Only one of the human system components (irrigation) is categorized as an ordinary component with a high centrality value. These relationships underline the findings from the ethnographic fieldwork, which describe human behavior as a reaction to the socio-environmental conditions in the basin (Figure 2). This could suggest that decision-makers in the basin may underestimate the influence they have on the conditions in the RGB socio-environmental system; it may also be a function of the non-inclusion of governance institutions and other identified or yet to be identified social processes as components in the conceptual model development process.

#### 4. Value of the conceptual model

We decided to use the process of building a conceptual model around the topic of water in a flexible and open manner, to better understand how actors in the RGB understand the system, what real-world constraints and opportunities they experience, how these influence their actions, and how these are connected to the environmental components of the basin. A similar approach is suggested by Spies et al. (2017, 2014) and Inouye et al. (2017), who describe the use of conceptual (or cognitive) mapping for the development of a simulation model. We consider our conceptual model useful in several different ways. First, the model development process was a structured way of transferring knowledge derived during the ethnographic fieldwork from the social scientists to the modelers. Second, the conceptual model identified key relationships between social and environmental components in the RGB system. A major outcome of our research is also the wealth of information behind each of those system components and relationships in the conceptual model, which will ultimately help us develop better representations of “the social” in a computer simulation model. Third, the conceptual model was helpful in converting qualitative information from the interviews into semi-quantitative information. Specifically, the analysis of the conceptual model identified the centrality of system components and revealed which components were considered drivers and receivers by the interviewees. Fourth, the identification of relevant system components and relationships is not only important for the development of a simulation model, but also for choosing those components that stakeholders consider in their decision-making regarding the management of water resources. This means that we can develop a simulation model that produces output that is specifically geared towards the interests (and maybe also knowledge gaps) of water managers in the basin. The latter is a major advantage of the application of participatory approaches to model development (Voinov & Bousquet, 2010; Voinov et al., 2016), especially in the context of water resource management (Inouye et al., 2017).

A final ethnographic example from our research, around the topic of riparian vegetation (Figure 4), describes a surprising component of high relevance to decision makers in the basin that would not have been considered without the collaboration described here. The example is illustrative of the depth of information and of the ways in which these inductively-generated social data and information are useful for better understanding the complex relationship between social and environmental system components, and the choice of process representations to include for simulation model development. We discussed how many interviewees, especially in the west Texas segment of the basin, described uncontrolled river vegetation, increased problems with sedimentation and channelization, and water quality issues as intertwined, due to what they characterized as a “lack of management” of the RGB. For example, one interviewee in west Texas, whose farming depends heavily on the availability of irrigation return flows from upstream farmers, complained that most farmers in the region were only able to farm “20 percent of their land” because of the loss of water availability due to sedimentation, groundwater seepage, and uncontrolled river vegetation. Instead, he insisted that:

*“if [the RGB] was lined, it wouldn’t matter if [others] pumped [groundwater around the river]. If they lined it, I mean, yes, I know there are some issues with environmental stuff and everything else, but, let’s be real. This is an irrigation system, and we’re trying to deliver water. And if that was lined, you don’t have the maintenance of all the weed growth. You don’t have to worry about the channel moving. You don’t have the seepage. You don’t have the pumping out from under it. You don’t ... you know. You have so many things that are avoided that cost money in the system.”*

This discussion of the multiple dimensions of “weed growth” was one that was not an obvious choice as an important system component until we began to hear more about the complications of riparian vegetation for



understanding water management along the river (cf. Brookshire et al., 2010). For instance, around Laredo, Texas, we interviewed members of a conservation group who stressed the value of the riparian habitat for various insects, especially for species of dragonfly that controlled the populations of other problem-species, like mosquitoes. At the same time, we heard from the U.S. Border Patrol, which saw the problem of “line of sight” — the fact that high riparian vegetation could often conceal people who were attempting to illegally cross the RGB from Mexico — as of paramount importance, thus advocating for unilaterally spraying herbicide to kill all vegetation along the river. A similar, but different, concern was voiced by interviewees in the LRGV portions just north of the Gulf of Mexico, who noted that heavy riparian vegetation also concealed the work of Mexican cartels who often crossed the RGB at these points. For many in the LRGV, though, the concern was less about the potential for illegal immigration, and more about the risk to Irrigation District workers who had been, in the past, mistaken for Border Patrol agents. This final example summarizes one of the main outcomes of our research: our integrative research shows that any modeling of the RGB socio-environmental system needs to take account of the complex and multiple social meanings that could lead to different ways that humans interact with the RGB socio-environmental system and make management decisions about it.

## 5. Next steps and study limitations

While beyond the scope of this manuscript, our ultimate aim is to develop an agent-based, integrated computer simulation model of the RGB Basin. The model will be implemented in the ENVISION framework (Bolte et al., 2006; Spies et al., 2017, 2014) and the model development, model component selection, and output preparation will be guided by the results presented here. Specifically, we gained important knowledge about the social processes identified by the ethnographic research that will be highly relevant for guiding the design and parameterization of the agent-based model component for water management decisions. This step is recognized as a major challenge when modeling socio-environmental systems (Filatova et al., 2013; Schlüter et al., 2017). We will use the conceptual model to direct the selection, implementation, and analysis of the model components representing environmental processes (e.g., hydrology and land use change) and their relationships to the human system components. Since the simulation model will be implemented to support decision making in the RGB, we will also use the conceptual model to guide the selection of indicators and scenarios relevant to water managers in the RGB Basin.

For the development of the simulation model, the identification of key social processes that are typically not considered in models of the RGB is of high relevance. However, the next challenge will be to describe the identified social processes in a quantitative manner, finding a suitable trade-off between the simplification required for inclusion of processes in simulation models and the need to preserve the heterogeneity observed in the behavior of systems participants. Furthermore, we identified the need to integrate governance institutions and agreements, as well as the temporal dynamics of administrative and technical institutions. However, these components are currently not represented in our conceptual model. We will address these limitations in the future. This will allow us to identify ways for better representing those processes in models of socio-environmental systems and, ultimately, improve our understanding of the structure and dynamic behavior of those systems.

## 6. Conclusions

Here, we demonstrated the application of an existing model development framework as a way to facilitate collaborative research and knowledge generation on the Rio Grande/Río Bravo Basin socio-environmental system. We were able to identify important components that characterize the decision-making of resource managers in the RGB Basin. We explored different explanatory models for the drivers of social processes often applied in RGB modeling, identified a need for redefining the (spatial) system boundaries to better connect social and environmental dynamics, and described the interlinkages of key human components with the environmental system components in the form of a semi-quantitative conceptual model. The specifics of these outcomes were unexpected and are highly relevant for the development of a computer simulation model of the system.

Since currently, no basin-wide, socio-environmental modeling efforts exist, our objective was to capture “the social” of the entire basin in a way that is neither too specific to be implemented in a large-scale simulation

model, nor so simple that it fails to capture past, present, and future unanticipated systems behavior. Using the first three steps of environmental model development in a collaborative manner, in which the modelers served as facilitators and knowledge brokers and the social scientists guided the content selection, we were able to identify several key social components of the RGB system that have often been overlooked or dismissed in existing socio-environmental system models. Our inductive approach keeps some of the advantages of both deductive and co-production methodologies typically applied in environmental modeling, while also using the open-ended and exploratory nature of inductive research to capture unexpected, unpredicted, and, often, unrecognized socio-environmental dynamics. This commitment to an inductive approach was critical, given the social and environmental heterogeneity of the RGB system and the diverse ways in which its problems are experienced and understood across the full length of the river. Many issues that appeared on the surface to be a common problem (e.g., not enough water) were in fact, viewed by different informants in different places as problems that have dramatically different implications and demand dramatically different solutions. While the described process required considerable commitment, we consider it an example of interdisciplinary research that will ultimately lead to improved understanding of socio-environmental systems and as a result, a better representation of social processes in integrated simulation models.

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## References

- Adams, L. G. (2014). Putting together a scientific team: Collaborative science. *Trends in Microbiology*, 22(9), 483–485. <https://doi.org/10.1016/j.tim.2014.05.001>
- Bay, R. F., & Sher, A. A. (2008). Success of active revegetation after Tamarix removal in riparian ecosystems of the Southwestern United States: A quantitative assessment of past restoration projects. *Restoration Ecology*, 16(1), 113–128. <https://doi.org/10.1111/j.1526-100X.2007.00359.x>
- Blythe, T. L., & Schmidt, J. C. (2018). Estimating the natural flow regime of rivers with long-standing development: The Northern branch of the Rio Grande. *Water Resources Research*, 54(2), 1212–1236. <https://doi.org/10.1002/2017WR021919>
- Bolte, J. P., Hulse, D. W., Gregory, S. V., & Smith, C. (2006). Modeling biocomplexity – actors, landscapes and alternative futures. *Environmental Modelling & Software*, 22(5), 570–579. <https://doi.org/10.1016/j.envsoft.2005.12.033>
- Booker, J. F., Michelsen, A. M., & Ward, F. A. (2005). Economic impact of alternative policy responses to prolonged and severe drought in the Rio Grande Basin. *Water Resources Research*, 41(2), W02026. <https://doi.org/10.1029/2004WR003486>
- Bossel, H. (2007). *Systems and Models: Complexity, Dynamics, Evolution, Sustainability*. Norderstedt, Germany: Books on Demand GmbH.
- Brinegar, H. R., & Ward, F. A. (2009). Basin impacts of irrigation water conservation policy. *Ecological Economics*, 69(2), 414–426. <https://doi.org/10.1016/j.ecolecon.2009.07.020>
- Broadbent, C. D., Brookshire, D. S., Coursey, D., & Tidwell, V. (2017). Futures contracts in water leasing: An experimental analysis using basin characteristics of the Rio Grande, NM. *Environmental and Resource Economics*, 68(3), 569–594. <https://doi.org/10.1007/s10640-016-0032-4>
- Brookshire, D. S., Goodrich, D., Dixon, M. D., Brand, L. A., Benedict, K., Lansey, K., Thacher, J., Broadbent, C. D., Stewart, S., McIntosh, M., & Kang, D. (2010). Ecosystem Services and Reallocation Choices: A Framework for Preserving Semi-Arid Regions in the Southwest. *Journal of Contemporary Water Research & Education*, 144(1), 60–74. <https://doi.org/10.1111/j.1936-704x.2010.00075.x>
- Crane, T. A. (2010). Of models and meanings: Cultural resilience in social–ecological systems. *Ecology and Society*, 15(4), 19.
- Cumming, G. S., Cumming, D. H. M., & Redman, C. L. (2006). Scale mismatches in social-ecological systems: Causes, consequences, and solutions. *Ecology and Society*, 11(1), 14. <https://doi.org/10.5751/ES-01569-110114>
- Dettinger, M., Udall, B., & Georgakakos, A. (2015). Western water and climate change. *Ecological Applications*, 25(8), 2069–2093. <https://doi.org/10.1890/15-0938.1>

- Douglas, A. J. (2009). Social, political, and institutional setting: Water management problems of the Rio Grande. *Journal of Water Resources Planning and Management*, 135(6), 493–501. [https://doi.org/10.1061/\(ASCE\)0733-9496\(2009\)135:6\(493\)](https://doi.org/10.1061/(ASCE)0733-9496(2009)135:6(493))
- Duran-Encalada, J. A., Paucar-Caceres, A., Bandala, E. R., & Wright, G. H. (2017). The impact of global climate change on water quantity and quality: A system dynamics approach to the US-Mexican transborder region. *European Journal of Operational Research*, 256(2), 567–581. <https://doi.org/10.1016/j.ejor.2016.06.016>
- Epstein, J. (2008). Why model? *Journal of Artificial Societies and Social Simulation*, 11(4), 12.
- Evans, T. P., Ostrom, E., & Gibson, C. (2002). Scaling issues with social data in integrated assessment modeling. *Integrated Assessment*, 3(2–3), 135–150. <https://doi.org/10.1076/iaij.3.2.135.13571>
- Everitt, B. (1993). Channel responses to declining flow on the Rio Grande between Ft. Quitman and Presidio, Texas. *Geomorphology*, 6(3), 225–242. [https://doi.org/10.1016/0169-555X\(93\)90048-7](https://doi.org/10.1016/0169-555X(93)90048-7)
- Fabinyi, M., Evans, L., & Foale, S. J. (2014). Social-ecological systems, social diversity, and power: Insights from anthropology and political ecology. *Ecology and Society*, 19(4), 28. <https://doi.org/10.5751/ES-07029-190428>
- Filatova, T., Verburg, P. H., Parker, D. C., & Stannard, C. A. (2013). Spatial agent-based models for socio-ecological systems: Challenges and prospects. *Environmental Modelling & Software*, 45, 1–7. <https://doi.org/10.1016/j.envsoft.2013.03.017>
- Gastélum, J. R., Valdés, J. B., & Stewart, S. (2009). A decision support system to improve water resources management in the Conchos Basin. *Water Resources Management*, 23(8), 1519–1548. <https://doi.org/10.1007/s11269-008-9339-4>
- Gastélum, J. R., Valdés, J. B., & Stewart, S. (2010). A system dynamics model to evaluate temporary water transfers in the Mexican Conchos Basin. *Water Resources Management*, 24(7), 1285–1311. <https://doi.org/10.1007/s11269-009-9497-z>
- Gray, S. A., Gray, S., Cox, L. J., & Henly-Shepard, S. (2013). Mental Modeler: A fuzzy-logic cognitive mapping modeling tool for adaptive environmental management. *Proceedings of the 46th Hawaii International Conference on System Sciences*, 965–973. <https://doi.org/10.1109/HICSS.2013.399>
- Hamann, M., Biggs, R., & Reyers, B. (2015). Mapping social-ecological systems: Identifying “green-loop” and “red-loop” dynamics based on characteristic bundles of ecosystem service use. *Global Environmental Change*, 34, 218–226. <https://doi.org/10.1016/j.gloenvcha.2015.07.008>
- Hamilton, S. H., ElSawah, S., Guillaume, J. H. A., Jakeman, A. J., & Pierce, S. A. (2015). Integrated assessment and modelling: Overview and synthesis of salient dimensions. *Environmental Modelling & Software*, 64, 215–229. <https://doi.org/10.1016/j.envsoft.2014.12.005>
- Hurd, B. H., & Coonrod, J. (2012). Hydro-economic consequences of climate change in the upper Rio Grande. *Climate Research*, 53(2), 103–118. <https://doi.org/10.3354/cr01092>
- Inouye, A. M., Lach, D. H., Stevenson, J. R., Bolte, J. P., & Koch, J. (2017). Participatory modeling to assess climate impacts on water resources in the Big Wood Basin, Idaho. In S. Gray, M. Paolisso, R. Jordan, & S. Gray (Eds.), *Environmental Modeling with Stakeholders: Theory, Methods, and Applications* (pp. 289–306). [https://doi.org/10.1007/978-3-319-25053-3\\_14](https://doi.org/10.1007/978-3-319-25053-3_14)
- International Institute for Applied Systems Analysis. (2016). IIASA Policy Brief #13: Managing an Endangered River across the USA-Mexico Border. Laxenburg, Austria.
- Jakeman, A. J., Letcher, R. A., & Norton, J. P. (2006). Ten iterative steps in development and evaluation of environmental models. *Environmental Modelling & Software*, 21(5), 602–614. <https://doi.org/10.1016/j.envsoft.2006.01.004>
- Janssen, M. A., & Ostrom, E. (2006). Chapter 30: Governing Social-Ecological Systems. In *Handbook of Computational Economics* (Vol. 2, pp. 1465–1509). [https://doi.org/10.1016/S1574-0021\(05\)02030-7](https://doi.org/10.1016/S1574-0021(05)02030-7)
- Jun, C., Ban, Y., & Li, S. (2014). China: Open access to Earth land-cover map. *Nature*, 514(434). <https://doi.org/10.1038/514434c>
- Khedun, C. P., Mishra, A. K., Bolten, J. D., Beaudoin, H. K., Kaiser, R. A., Giardino, J. R., & Singh, V. P. (2012). Understanding changes in water availability in the Rio Grande/Rio Bravo del Norte basin under the influence of large-scale circulation indices using the Noah land surface model. *Journal of Geophysical Research Atmospheres*, 117, D05104. <https://doi.org/10.1029/2011JD016590>
- Kragt, M. E., Robson, B. J., & Macleod, C. J. A. (2013). Modellers’ roles in structuring integrative research projects. *Environmental Modelling & Software*, 39, 322–330. <https://doi.org/10.1016/j.envsoft.2012.06.015>
- Lane, B. A., Sandoval-Solis, S., & Porse, E. C. (2015). Environmental flows in a human-dominated system: Integrated water management strategies for the Rio Grande/Bravo Basin. *River Research and Applications*, 31(9), 1053–1065. <https://doi.org/10.1002/rra.2804>
- Lévi-Strauss, C. (1966). *The Savage Mind*. The University of Chicago Press.
- Llewellyn, D., & Vaddey, S. (2013). West-wide climate risk assessment: Upper Rio Grande impact assessment. U.S. Department of the Interior, Bureau of Reclamation.
- Martín-López, B., Palomo, I., García-Llorente, M., Iniesta-Arandia, I., Castro, A. J., García Del Amo, D., Gómez-Baggethun, E., & Montes, C. (2017). Delineating boundaries of social-ecological systems for landscape planning : A comprehensive spatial approach. *Land Use Policy*, 66, 90–104. <https://doi.org/10.1016/j.landusepol.2017.04.040>
- National Water Commission of Mexico. (2010). *Statistics on Water in Mexico, 2010 edition*. Coyoacán, Mexico, D.F.
- Nava, L. F., & Sandoval-Solis, S. (2014). Multi-tiered governance of the Rio Grande/Rio Bravo Basin: The fragmented water resources management model of the United States and Mexico. *International Journal of Water Governance*, 2, 85–106. <https://doi.org/10.7564/13-IJWG23>

- Nava, L. F., & Sandoval-Solis, S. (2015). A lock-in transboundary water management regime: The case of the Rio Grande/Bravo Basin. World Water Congress, 25-29 May 2015. Edinburgh, Scotland.
- Ness, B., Anderberg, S., & Olsson, L. (2010). Structuring problems in sustainability science: The multi-level DPSIR framework. *Geoforum*, 41(3), 479–488. <https://doi.org/10.1016/j.geoforum.2009.12.005>
- Orlove, B., & Caton, S. C. (2010). Water sustainability: Anthropological approaches and prospects. *Annual Review of Anthropology*, 39, 401–415. <https://doi.org/10.1146/annurev.anthro.012809.105045>
- Ortiz-Partida, J. P., Lane, B. A., & Sandoval-Solis, S. (2016). Economic effects of a reservoir re-operation policy in the Rio Grande/Bravo for integrated human and environmental water management. *Journal of Hydrology: Regional Studies*, 8, 130–144. <https://doi.org/10.1016/j.ejrh.2016.08.004>
- Ostrom, E. (2012). Nested externalities and polycentric institutions: Must we wait for global solutions to climate change before taking actions at other scales? *Economic Theory*, 49(2), 353–369. <https://doi.org/10.1007/s00199-010-0558-6>
- Phillips, F. M., Hall, G. E., & Black, M. E. (2011). *Reining in the Rio Grande: People, land, and water*. UNM Press, Albuquerque, New Mexico.
- Rister, M. E., Sturdivant, A. W., Lacewell, R. D., & Michelsen, A. M. (2011). Challenges and opportunities for water of the Rio Grande. *Journal of Agricultural and Applied Economics*, 43(3), 367–378. <https://doi.org/10.1017/S1074070800004363>
- Ritzema, H., Froebrich, J., Raju, R., Sreenivas, C., & Kselik, R. (2010). Using participatory modelling to compensate for data scarcity in environmental planning: A case study from India. *Environmental Modelling & Software*, 25(11), 1450–1458. <https://doi.org/10.1016/j.envsoft.2010.03.010>
- Rivera, J. A. (1998). *Acequia culture: Water, land and community in the Southwest*. UNM Press, Albuquerque, New Mexico.
- Sandoval-Solis, S., & McKinney, D. C. (2014). Integrated water management for environmental flows in the Rio Grande. *Journal of Water Resources Planning and Management*, 140(3), 355–364. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000331](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000331)
- Schlüter, M., Baeza, A., Dressler, G., Frank, K., Groeneveld, J., Jager, W., Janssen, M. A., McAllister, R. R. J., Müller, B., Orach, K., Schwarz, N., & Wijermans, N. (2017). A framework for mapping and comparing behavioural theories in models of social-ecological systems. *Ecological Economics*, 131, 21–35. <https://doi.org/10.1016/j.ecolecon.2016.08.008>
- Schmidt, J. C., & Wilcock, P. R. (2008). Metrics for assessing the downstream effects of dams. *Water Resources Research*, 44(4), W04404. <https://doi.org/10.1029/2006WR005092>
- Schmitt, C. J., Dethloff, G. M., Hinck, J. E., Bartish, T. M., Blazer, V., Coyle, J. J., Denslow, N. D., & Tillitt, D. E. (2004). Biomonitoring of Environmental Status and Trends (BEST) Program: Environmental contaminants and their effects on fish in the Rio Grande Basin. In *Scientific Investigations Report 2004-5108*. Reston, VA.
- Scurlock, D. (1998). *From the Rio to the Sierra: An environmental history of the Middle Rio Grande Basin*. In *General Technical Report RMRS-GTR-5*. Fort Collins, Colorado: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
- Shafroth, P. B., Beauchamp, V. B., Briggs, M. K., Lair, K., Scott, M. L., & Sher, A. A. (2008). Planning riparian restoration in the context of *Tamarix* control in western North America. *Restoration Ecology*, 16(1), 97–112. <https://doi.org/10.1111/j.1526-100X.2008.00360.x>
- Sirola, J., Tidwell, V. C., Benz, Z. O., Stansbury, M., Richards, E. H., Turnley, J. G., Warrender, C., & Morrow, J. D. (2012). *Decision insight into stakeholder conflict for ERN*. Albuquerque, New Mexico: Sandia National Laboratories.
- Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C. A., Wescoat, J. L., & Rodríguez-Iturbe, I. (2014). Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth's Future*, 2(4), 225–230. <https://doi.org/10.1002/2013EF000164>
- Spies, T. A., White, E., Ager, A., Kline, J. D., Bolte, J. P., Platt, E. K., Olsen, K. A., Pabst, R. J., Barros, A. M.G., Bailey, J. D., Charnley, S., Morzillo, A. T., Koch, J., Steen-Adams, M. M., Singleton, P. H., Sulzman, J., Schwartz, C., & Csuti, B. (2017). Using an agent-based model to examine forest management outcomes in a fire-prone landscape in Oregon, USA. *Ecology and Society*, 22(1), 25. <https://doi.org/10.5751/ES-08841-220125>
- Spies, T. A., White, E. M., Kline, J. D., Fischer, A. P., Ager, A., Bailey, J., Bolte, J., Koch, J., Platt, E., Olsen, C. S., Jacobs, D., Shindler, B., Steen-Adams, M. M., & Hammer, R. (2014). Examining fire-prone forest landscapes as coupled human and natural systems. *Ecology and Society*, 19(3), 9. <https://doi.org/10.5751/ES-06584-190309>
- Tidwell, V. C., Passell, H. D., Conrad, S. H., & Thomas, R. P. (2004). System dynamics modeling for community-based water planning: Application to the Middle Rio Grande. *Aquatic Sciences*, 66(4), 357–372. <https://doi.org/10.1007/s00027-004-0722-9>
- Tongco, M. D. C. (2007). Purposive sampling as a tool for informant selection. *Ethnobotany Research and Applications*, 5, 147–158.
- Troy, T. J., Konar, M., Srinivasan, V., & Thompson, S. (2015). Moving sociohydrology forward: A synthesis across studies. *Hydrology and Earth System Sciences*, 19(8), 3667–3679. <https://doi.org/10.5194/hess-19-3667-2015>
- U.S. Geological Survey. (2010). *Estimated Use of Water in the United States. County-Level Data for 2010*. National Water Information System (NWIS).
- Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling & Software*, 25(11), 1268–1281. <https://doi.org/10.1016/j.envsoft.2010.03.007>

- Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., Pierce, S. A., & Ramu, P. (2016). Modelling with stakeholders - Next generation. *Environmental Modelling & Software*, 77, 196–220. <https://doi.org/10.1016/j.envsoft.2015.11.016>
- Ward, F. A. (2014). Economic impacts on irrigated agriculture of water conservation programs in drought. *Journal of Hydrology*, 508, 114–127. <https://doi.org/10.1016/j.jhydrol.2013.10.024>
- Ward, F. A., Booker, J. F., & Michelsen, A. M. (2006). Integrated economic, hydrologic, and institutional analysis of policy responses to mitigate drought impacts in Rio Grande Basin. *Journal of Water Resources Planning and Management*, 132(6), 488-502. [https://doi.org/10.1061/\(ASCE\)0733-9496\(2006\)132:6\(488\)](https://doi.org/10.1061/(ASCE)0733-9496(2006)132:6(488))