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Managing Complex Water Resource Systems for Ecological Integrity: Evaluating Tradeoffs and Uncertainty

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DISSERTATION

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Dedication

To my parents for their support and encouragement. Aren't you glad I'm not an ornithologist?

Acknowledgments

I would like to thank my friend and advisor, Mark Stone, for his trust and encouragement during my PhD program. I would not have moved to New Mexico without knowing you would be an excellent mentor and beer-drinking companion.

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Finally, I still can't believe the encouragement given by my wife, Leslie, even while we lived 1,000 miles apart for two years. Thank you, Sweetie.

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Abstract

Water resource systems often contain numerous components that are intertwined or contradictory, such as power production, water delivery, recreation, and environmental needs. This complexity makes it difficult to holistically assess management alternatives. In addition, hydroclimatic and ecological uncertainties complicate efforts to evaluate the impacts of management scenarios. We need new tools that are able to inform managers and researchers of the tradeoffs or consequences associated with flow alternatives, while also explicitly incorporating sources of uncertainty. My research addresses this limitation using two modeling approaches: stochastic system dynamics modeling and Bayesian network modeling. Specifically, the objectives of my research were 1) evaluate the impacts of environmental flow alternatives on other water users within a complex managed basin using stochastic system dynamics modeling; 2) assess the benefits of environmental flow alternatives on select ecological processes using stochastic system dynamics modeling; and 3) demonstrate the

unique benefits of combining fine-scale hydrodynamic and Bayesian network models when assessing ecological responses to water management alternatives. I developed a stochastic system dynamics model to evaluate the impacts of environmental flow alternatives on multiple water users in the Rio Chama basin, New Mexico. This work examined the influence of flow alternatives on cottonwood recruitment, reservoir storage, hydropower production, and whitewater boating. In addition, I coupled two-dimensional hydrodynamic and Bayesian network models to assess the impacts of management scenarios on cottonwood recruitment on the Gila River, New Mexico. The Bayesian network approach explicitly incorporated spatial variability, as well as hydrologic and ecological uncertainties. These methods are useful for more thoroughly assessing the tradeoffs of management decisions, integrating system components within a holistic framework, and evaluating ecological consequences of management scenarios at fine spatial scales.

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Chapter 1

Introduction

> *"The 20th century approaches used to deal with water challenges are now failing, and new thinking and management approaches are needed....current approaches have had serious ecological side effects that were either ignored or unanticipated when our original water systems were designed and built."*
>
> – Peter Gleick, 2010

1.1 Motivation and Objectives

The importance of incorporating ecological needs in our water resources management is widely accepted (*Naiman et al.*, 2002). The field of environmental flow science has experienced rapid growth in the past two decade as researchers, policy makers, resource managers, and other interested parties search for ways to meet human water demands while minimizing ecological impacts. As recognition of environmental water needs has grown, methods for determining flows needed to sustain riverine ecologies have evolved from simple hydrologic metric approaches to more holistic techniques (*King et al.*, 2003; *Petts*, 2009; *Poff and Zimmerman*, 2010; *Tharme*, 2003).

Integrating environmental flow needs into existing management frameworks can be difficult because ecological needs are typically at-odds with other uses of the water in the basin, including hydropower, irrigation and municipal water delivery, recreational uses, and flood control. Recent multiple-use models use Pareto-optimization and genetic algorithms to find the optimal balance between human and ecological needs (*Shiau and Wu*, 2007; *Suen*, 2011; *Suen and Eheart*, 2006), or to simply minimize deviations from baseline hydrologic conditions (*Yin et al.*, 2011). These approaches find one or more optimal solutions based on specific operational rules and hydrologic boundary conditions and are therefore difficult to use when incorporating flexible operations. In addition, these techniques fail to consider system uncertainties—both hydroclimatic variability and ecological responses to management—as well as the myriad of water needs within a single basin.

There are several advantages to explicitly considering system uncertainty in environmental studies. Incorporating uncertainty in environmental flow studies allows us to recognize the complexity of systems (*Harris and Heathwaite*, 2011) and the extent of our knowledge gaps (*Beven and Alcock*, 2012). In a more practical sense, including uncertainty into environmental decision-making allows use to hedge against negative impacts resulting from wrong decisions (*Reckhow*, 1994). Although these advantages are broadly recognized, uncertainty is rarely explicitly incorporated into environmental flow studies.

Thus, my research goal is to integrate hydroclimatic and ecological uncertainties into modeling methodologies of environmental flow analyses. Hydroclimatic uncertainty pertains to variability in hydrologic conditions within the basin, such as frequency of flows and climate change impact. Ecological uncertainty refers to variability in ecological responses to hydrologic conditions (*Bunn and Arthington*, 2002), such as recruitment reposes of riparian plant species. I have completed the following three objectives in order to meet this goal:

1. Evaluate the impacts of environmental flow alternatives on other water users within a complex managed basin using stochastic system dynamics modeling

2. Assess the benefits of environmental flow alternatives on select ecological pro-

cesses using stochastic system dynamics modeling

3. Demonstrate the unique benefits of combining fine-scale hydrodynamic and Bayesian network models when assessing ecological responses to water management alternatives

The next three chapters address each of these objectives in detail. Each chapter is a stand-alone publication. Chapter 2 describes the development and implementation of a stochastic system dynamics model to evaluate the impacts of environmental flow alternatives on hydropower, reservoir storage, and whitewater boating in the Rio Chama, New Mexico (*Morrison and Stone*, in review). Chapter 3 builds off work from the previous chapter and includes probabilistic routines for assessing the benefits of environmental flow alternatives on riparian vegetation recruitment, as well as consequences for other water uses on the Rio Chama (*Morrison and Stone*, in press). I shifted my research methods in Chapter 4 by combined two-dimensional hydrodynamic and Bayesian network models to spatially examine the consequences of water diversions on cottonwood recruitment within the Upper Gila Basin, New Mexico (*Morrison and Stone*, in review).

1.2 Broad Contribution of this Research

Land use practices, climate change, regulatory constraints, and increased human demands threaten water allocations for environmental flows. As engineers and policy makers struggle to distribute water supplies, pressures on environmental needs are sure to increase, especially in the arid southwestern United States (*Gleick*, 2010). The approaches for assessing environmental flows need to evolve to include the uncertainties associated with water management. My research provides a critical link between contemporary environmental flow science and available tools for considering system uncertainty.

Specifically, my research addresses three limitations of previous environmental flow studies. First, scientific literature contains innumerable environmental flow studies that use deterministic methods of examining impacts of flow alternatives on ecological health. Rarely do these studies include system variability or impacts to other water users in the basin. My research include both these components. System variability is explicitly considered using probabilistic representations of system variables and stochastic simulations, and other important water user in the basin, such as hydropower and recreation, are also considered. This limitation is addressed on Chapter 2.

Second, representations of ecological processes are seldom components of water management models. Implications of management alternatives to ecosystem health are determined outside of management decision tools. My research directly incorporates an ecosystem process into a stochastic model that also includes other water uses in a basin. This approach makes it easier to assess the practicality of multiple flow alternatives based on improvements to ecological health and impacts to other management priorities. Chapter 3 addresses this contribution.

Third, a noted limitation of the Bayesian network modeling approach is its inability to consider spatial factors within a system. As a result, single network models are typically applied to evaluate large geographic regions without consideration of small-scale spatial variables that may influence environmental processes. My research addresses this limitation by coupling two-dimensional hydrodynamic and Bayesian network models to explicitly account for effects of small-scale spatial variability on ecological systems. Specifically, I focused on the implications of water diversion scenarios on cottonwood and willow species recruitment potential. The benefits of this approach, as described in Chapter 4, include a detailed consideration of topographic and hydrologic variability on the riparian recruitment process, visual representation of model results that facility the identification of worst impacted areas, and more informed implications of water management scenarios.

The remainder of this introductory chapter includes a brief history of environmental flows and short descriptions of the modeling methods used in my research.

1.3 Environmental Flows and the Natural Flow Regime

Until the later half of the twentieth century, water management strategy focused almost exclusively on providing adequate water for human needs. This focus began to shift in the 1960s as worldwide concern for protecting biodiversity and sustaining environmental systems permeated water resource policy. Research on the physical processes of running water and the riverine ecology became intricately linked (*Hynes*, 1970). The first substantial environmental flow (sometimes referred to as instream flow or e-flow) standards were developed in the late 1970s as pressure for minimum flow requirements needed for water permits under the Clean Water Act threatened fisheries (*Petts*, 2009). Abstraction limits were set to ensure enough water was present throughout specific periods of the year for fish survival, but even these standards were based on professional judgement rather than scientific evidence. *Waters* (1976) presented the need for a more holistic consideration of flows for fish, recognizing the importance of flow variability in a river system. Hence, the modern idea of environmental flows was born: the idea that river environments are dynamic systems in which aquatic species have evolved, and ensuring the natural variability of the system is vital to protecting river ecosystems (*Poff*, 2009; *Poff et al.*, 1997).

Environmental flow methodologies proliferated in the 1980s and 1990s. The most notable contributions to the field were the Indicators of Hydrologic Alteration (IHA) methodology (*Richter et al.*, 1996), Range of Variability (RVA) methodology (*Richter et al.*, 1997), and the concept of the "natural flow regime" (*Poff et al.*, 1997). The IHA method compares the hydrology of a reference pre-development scenario to a post-development scenario and calculates 32 hydrologic alteration parameters based on important flow variability indictors. The indicators represent common metrics such as median monthly flow, temporally-averaged minimum and maximum flows, hydrograph fall and rise rates, and low or high pulse discharges. The RVA method uses IHA outputs and allows researchers to determine how often a specific parameter in the post-development scenario falls within the same statistical quantile as the pre-development data. Both the RVA and IHA methodologies can be modeled using the Indicators of Hydrologic Alteration Software developed by The Nature Conservancy (*The Nature Conservancy*, 2009).

Modern techniques for implementing environmental flows (e.g. the Ecological Limits of Hydrologic Alteration (*Poff et al.*, 2010) approach) recognize the importance of the natural flow regime to sustain a rivers ecological health. There is agreement among scientists that the natural flow variability of a system should be maintained or replicated to protect the biodiversity and ecological services of a river system (*Arthington et al.*, 2006). The important hydrologic components in a system include magnitude, frequency, timing, duration, rate of change, and predictability of flow events (*Poff et al.*, 1997). The natural flow regime is important for many aspects of aquatic ecological health including water quality, energy sources, physical habitat, and biotic interactions (Figure 1.1). Not only do these facets of the natural flow regime sustain different ecological niches in a system, but each species in a riverine system evolved based on the characteristics of the naturally occurring flow regime.

The importance of environmental flows is now well established, but the institutional adoption of environmental flow standards is lagging behind the science. Furthermore, there is a wide gap between the recognition of natural flow needs and data needed to support flow-ecology linkages (*Poff et al.*, 2010). Future advancements of environmental flow methodologies will rely on strengthening our understanding of flow-ecology interactions and incorporating system uncertainties into environmental flow implementation.

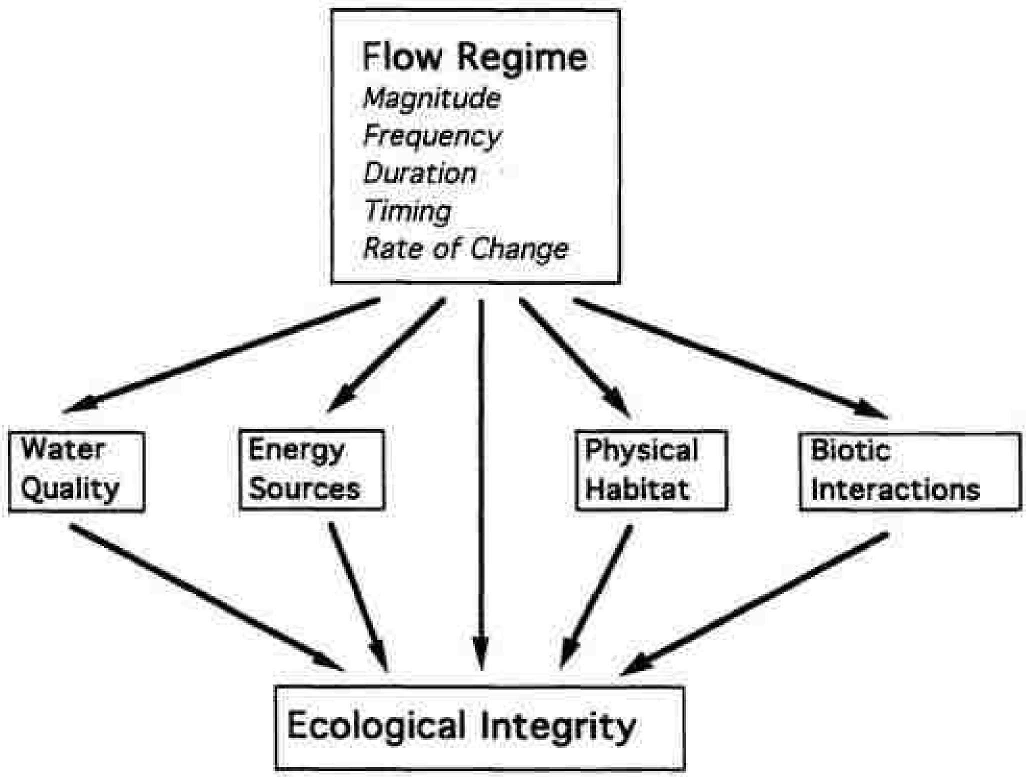

Figure 1.1: The natural flow regime effects many aspects of ecological integrity, including water quality, energy sources, physical habitat, and biotic interactions (adopted from *Poff et al.* (1997)).

1.4 Modeling Tools

My research objectives are met using a combination of modeling approaches. I use system dynamics (SD) modeling to explore hydroclimatic uncertainties related to management operations, and Bayesian network (BN) modeling to include ecological uncertainty. GoldSim (*Goldsim Technical Group*, 2012), a commercial software package, is for SD modeling purposes. I use R-code (*R Core Team*, 2013) to build and implement my unique BN model. Below is a short description of each.

1.4.1 System Dynamics Modeling

Goldsim is an SD modeling software that has the ability to track information or mass balances, including feedback components of a system. GoldSim and similar SD modeling packages have been used in numerous water resource studies (*Miller et al.*, 2012; *Ryu et al.*, 2012; *Tidwell et al.*, 2004; *Vano et al.*, 2010; *Wei et al.*, 2012); however, there are no published studies of GoldSim being applied to environmental flow investigations, making my research application unique especially when paired with uncertainty analyses. GoldSim differentiates itself from other SD packages through its ability to run stochastic simulations using Monte Carlo techniques (*Kossik*, 2012). My research takes advantage of GoldSims stochastic simulation capabilities to examine the impact of hydroclimatic uncertainties on environmental flow alternatives on the Rio Chama, New Mexico. The model includes basic hydrologic variables of the basin (e.g. inflows and releases from El Vado and Abiquiu Reservoir, San Juan-Chama Project deliveries to the basin, precipitation, evaporation, and ungaged inflows) as well as accounts for various ancillary water uses, such as hydropower operations and whitewater rafting days. In addition, the model calculates hydrologic parameters important to ecological processes and commonly cited in environmental flow literature, including median monthly discharge, temporal high and low discharges, and discharge rise and fall rates. Historical daily time series data were used to develop probability distributions to perform stochastic simulations

1.4.2 Bayesian Network Modeling

Bayesian network modeling is an inference method based on Bayes theorem. Because Bayesian statistical methods are able to incorporate expert opinion and limited datasets, they have become increasingly popular among ecologists and natural resource scientists. Generally, BNs consist of three components: 1) nodes representing important system variables, 2) connections that represent causality between nodes, and 3) probabilities that a given node will be in a specific state depending on the state of the connected nodes (conditional probabilities) (*Korb and Nicholson*, 2011). My research uses BN modeling to examine the impact of water diversion scenarios on riparian vegetation recruitment in the Gila River, New Mexico. Discrete conditional probabilities for the analyses were obtained from proposed hydrologic conditions or assumed from scientific literature. I constructed the BN model using custom R-code.

Chapter 2

System Dynamics Modeling to Assess Impacts of Environmental Flows

2.1 Introduction

Sustaining aquatic ecosystem integrity is increasingly recognized as a legitimate use of our water resources. Historical water resource management approaches have resulted in alterations to natural flow regimes (*Poff et al.*, 1997)—hydrologic characteristics such as timing, frequency, magnitude, and duration of flows—and have consequently impaired riparian habitats (*Nilsson and Berggren*, 2000; *Nilsson and Svedmark*, 2002), sediment transport dynamics (*Pitlick and Wilcock*, 2001; *Poff et al.*, 2006), and overall aquatic biodiversity (*Bunn and Arthington*, 2002) in many river systems across the world. The acknowledgement of environmental water needs, and an understanding of important hydrologic drivers that maintain ecological integrity, have resulted in new challenges for water resource managers.

Integrating environmental flows into an established management structure is difficult, especially when coupled with the imminent threats of increasing water demand and decreasing supplies (*Gleick*, 2000). Numerous methods of determining hydrologic alterations, incorporating environmental flows, and assessing impacts to other water uses have been demonstrated during the last decade (see *Petts* (2009) for a thorough discussion of environmental flow history).

Indicators of Hydrologic Alteration (IHA) calculations are commonly used to assess changes to hydrologic parameters that may be important for ecological health (*Richter et al.*, 1996). Regionalized analytical methods can be applied to determine environmental impacts downstream of reservoirs (*Suen*, 2011) or to compare hydrologic conditions for ungaged sites (*Carlisle et al.*, 2010). Optimization methods are often used to minimize the degree of hydrologic alteration imposed by system operations (*Suen and Eheart*, 2006; *Yang et al.*, 2012; *Yin et al.*, 2011, 2012). Due to the large resource strain of determining environmental impacts on a basin-by-basin basis, more holistic approaches have been developed for incorporating social, environmental and economic components of water management (*King and Brown*, 2010). Two of the most recognized holistic methods of integrating environmental flows are the Downstream Response to Imposed Flow Transformation (DRIFT) method (*King et al.*, 2003) and Ecological Limits of Hydrologic Alternation (ELOHA) method (*Poff et al.*, 2010). A method that is not commonly used for assessing environmental flow impacts on existing operations, though it holds promise, is system dynamics (SD) modeling.

SD modeling can be an effective method for exploring water resource problem and management alternatives. Originating in the work of *Forrester* (1961), an SD approach focuses on the interconnectivity of system components and how the system changes over time due to perturbations. This approach is different from most water resource management methods, in which problems are separated and solved in isolation of their surrounding environment (*Mirchi et al.*, 2012). SD modeling offers numerous advantages to managers exploring water resource issues (*Simonovic*, 2008). First, SD models are typically simple to develop compared to models requiring algorithmic languages. Second, a variety of disciplines can be incorporated into a single model (e.g., economics, recreation, and operations). Third, the structure of SD modeling can allow analyses of how changes in one part of the system impact the system as a whole. And fourth, the transparency of SD models facilitates increased input and cooperation from stakeholders and provides a greater understanding of each system component. The flexibility and transparency of an SD approach are also useful for dealing with uncertainties in water resource management (*Winz et al.*, 2009).

A few studies have demonstrated an effective application of an SD approach to investigating water resource issues. *Ryu et al.* (2012) used SD modeling for collaborative water management planning in Idaho. *Tidwell et al.* (2004) showed the benefits of linking SD modeling and community-based planning for water resource management. Both socio-economic and water resource components were combined in an SD framework by *Qin et al.* (2011), and the socio-economic impacts of environmental flows in the Weihe River basin, China, were examined by *Wei et al.* (2012) within an SD model. Despite its advantages and successful implementation within these studies, however, SD modeling is still an underutilized tool in water resource management (*Khan et al.*, 2009; *Winz et al.*, 2009), especially for assessing impacts of environmental flow alternatives on other management obligations within complex systems.

Thus, my objective is to demonstrate the use of SD modeling to evaluate the impacts of environmental flow recommendations on other water users within a managed basin. I developed an SD model to assess environmental flow alternatives in the Rio Chama basin, New Mexico, with input from stakeholders, agency managers, and environmental and legal experts. Based on the advice from a collaborative workshop, three flow recommendations were tested within a stochastic framework. A fourth alternative, which attempted to mimic natural flow patterns of the system, was also tested. Impacts of the alternatives on multiple water uses in the Rio Chama basin were assessed, including water supply, reservoir releases, hydropower production and revenue, and whitewater boating.

This modeling approach does not include explicit examinations ecological responses to each flow alternative. We assumed the proposed environmental flow alternatives would benefit key ecological components of the Rio Chama, and then tested the impacts of those alternatives on other water-uses in the basin.

2.2 Rio Chama Basin and Environmental Flow Study

2.2.1 Basin description

The Rio Chama basin encompasses approximately 8,300 km^2 in northern New Mexico. As the largest tributary to the Rio Grande within New Mexico, the Rio Chama is an important water source for downstream water users, including the City of Albuquerque and farmers in the Middle Rio Grande Valley. Three dams are used to store and control releases within the basin (Figure 2.1). Heron Dam (52,996 hectare-meter reservoir volume), located off-channel on the Willow Creek tributary, stores water transferred from the Upper Colorado basin as part of the San Juan-Chama (SJC) Project and is operated by the U.S. Bureau of Reclamation (USBOR). El Vado Dam (25,820 hectare-meter maximum reservoir volume), also operated by USBOR, is used to store SJC and native Rio Chama water for downstream irrigation users. At the bottom of the basin, Abiquiu Dam (168,864 hectare-meter maximum reservoir volume) is operated by the U.S. Army Corps of Engineers (USACE) for flood control purposes but also contains easements for storage of SJC water. Although the basin is primarily managed to meet downstream water demands, reservoir operations produce other important ancillary benefits. El Vado and Abiquiu Dams contain hydropower plants (10 MW and 15 MW capacities, respectively) that are owned and operated by the Los Alamos County Public Works Department. Because Los Alamos County does not own storage easements or water in the basin, hydropower production occurs when downstream demands provide sufficient discharges to run the plants—the hydropower plants are essentially run-of-the-river facilities in which downstream water owners control reservoir releases. The Rio Chama is also a popular whitewater boating and fishing destination. When water is available, coordinated releases from El Vado Reservoir during summer weekends provide high flows for commercial and private boaters. Commercial and private anglers enjoy the river year-round. Thus, similar to many basins in the western United States, the Rio Chama is an important water resource for a variety of users.

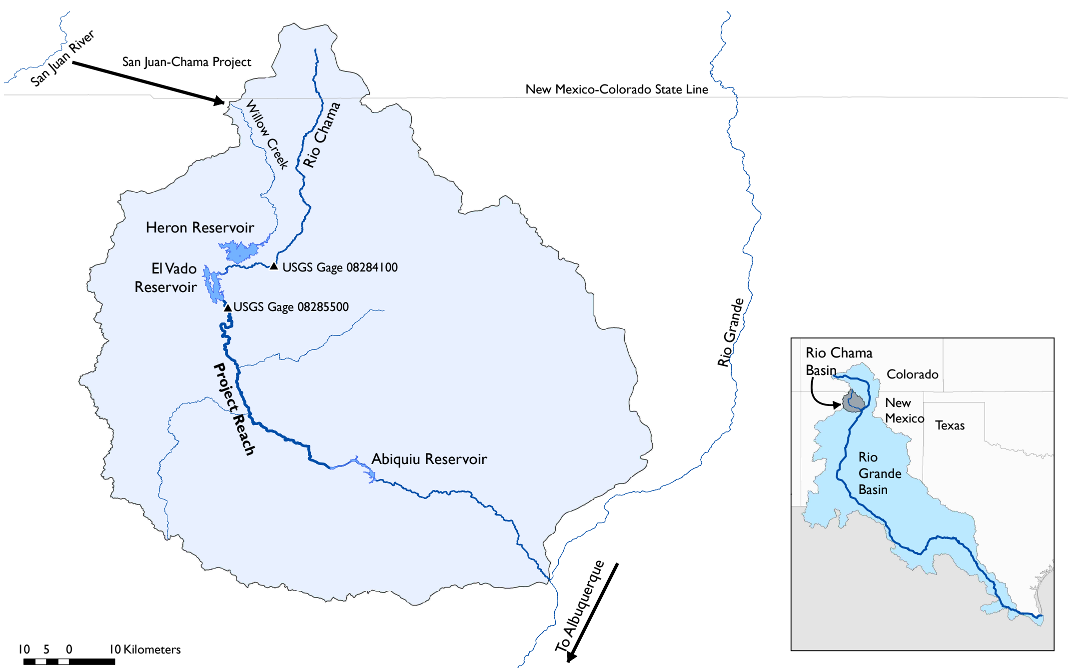

Figure 2.1: Vicinity and detailed maps of the Rio Chama basin. The project area in which environmental flows are tested is located between El Vado Dam and Abiquiu Reservoir.

2.2.2 Environmental flow study

The multi-use management of the basin has noticeably changed the hydrologic characteristics of the Rio Chama. An IHA (*Richter et al.*, 1996) analysis was performed to quantify changes to the hydrology using USGS gages 08284100 and 08285500 to represent unaltered and altered conditions, respectively (US Geological Survey, National Water Information System. Accessed January 10, 2013, `http://waterdata.usgs.gov/nwis`). The results indicate that temporal-averaged minimum flow rates (e.g., 7-day minimum discharge) have more than doubled downstream of El Vado since the construction of the dam due to downstream water delivery demands, and peak flows have been reduced by over 25% as a result of spring season water storage. The overall impact of water management has been to squeeze the natural annual hydrograph while increasing the median discharge during most months.

Various ecological components of the system have been negatively impacted by these hydrologic changes. The reduction of peak flows has limited overbank flooding and disconnected the main channel from the floodplain, restricted riparian vegetation recruitment, and prevented geomorphic work within the channel. The increase in minimum flows has possibly reduced the availability of spawning sites for brown trout (*Salmo trutta*), and sudden shifts in minimum flows during the winter months has caused the exposure and desiccation of brown trout redds.

Given the negative ecological impacts caused by current water management in the Rio Chama, a collaborative environmental flow project began in 2010 to improve ecohydrologic conditions in the basin with the cooperation of stakeholders and management agencies. Specifically, the 50 km reach between El Vado Dam and Abiquiu Reservoir has been the focus of the project. A diverse group of experts, including ecological engineers, riparian ecologists, a benthic invertebrate ecologist, geomorphologists, and environmental law experts, have been collecting geomorphic and ecological data on the river to describe baseline environmental conditions and develop flow alternatives. The project team has also been communicating with stakeholders, such as government agencies, water owners, recreationists, and hydropower owners, to encourage their involvement in the project. In March 2013 a workshop was held by the project team with other ecohydrologic experts to recommend flow conditions necessary for improving ecological conditions in the Rio Chama. The workshop resulted in three flow recommendations (Figure 2.2). First, a peak flow of around 170 $m^3\,s^{-1}$ (6,000 $ft^3\,s^{-1}$) every 10 years is needed to reconnect the main channel to the floodplain and promote off-channel habitat. Second, a discharge of 127 $m^3\,s^{-1}$ (4,500 $ft^3\,s^{-1}$) is necessary every three to five years to encourage riparian vegetation recruitment for native species such as Rio Grande cottonwood (*Populus fremontii*) and narrow-leaf cottonwood (*Populus angustifolia*). Third, every two years a discharge of approximately 71 $m^3\,s^{-1}$ (2,500 $ft^3\,s^{-1}$) is needed to provide maximum geomorphic disturbance within the channel and flush sediments downstream.

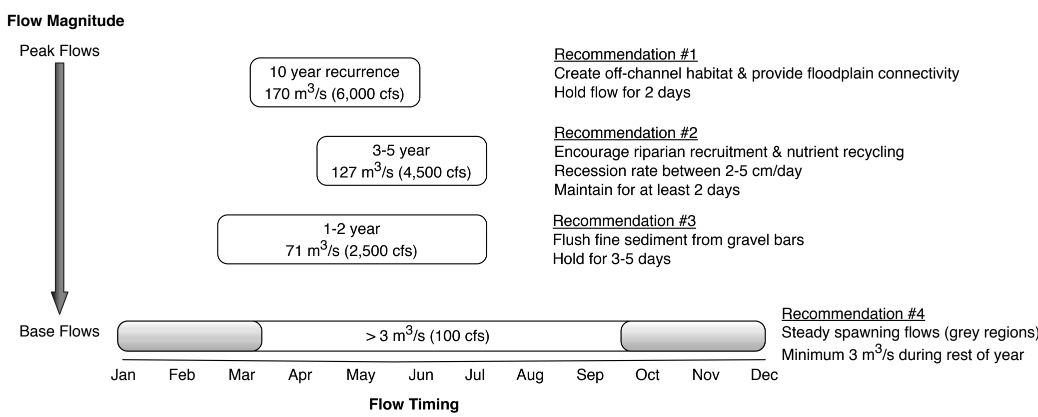

Figure 2.2: Environmental flow recommendations developed at a collaborative workshop in March 2013. The first three recommendations were incorporated into the system dynamics model.

2.3 Model Development

2.3.1 Model framework

I developed a system dynamics model using GoldSim (*Goldsim Technical Group*, 2012) to examine the broad impacts of environmental flow alternatives in the Rio Chama basin. Like all SD modeling software, GoldSim solves differential equations to determine changes to material or information stocks based on inflow and outflow rates. I specifically chose the GoldSim platform due to its stochastic simulation capability. This feature allowed us to define probabilistic variables used in Monte Carlo simulations, and to statistically assess uncertainty associated with environmental flow alternatives. The SD model included hydrologic variables required for water-budget calculations within the basin as well as water-use variables that were impacted by reservoir operations. The major hydrologic variables in the model included precipitation, evaporation, native inflows, SJC Project inflows, and reservoir releases. The impacts of environmental flow alternatives were evaluated for hydropower production, whitewater boating, and changes to El Vado operations, including reservoir storage and release patterns.

Because the project reach is located downstream of El Vado Dam, I simulated environmental flows by modifying releases from El Vado Reservoir and assuming storage volume was available downstream in Abiquiu Reservoir. Releases from Abiquiu Reservoir were matched to historical conditions so that downstream demands were still met.

I executed Monte Carlo simulations of environmental flow alternatives using one-day time steps for a 365-day period. Based on mean standard error calculations (less than 1%) and computation-time requirements, I found that 1,000 realizations were suitable for the Monte Carlo simulations. The initial storage levels for El Vado and Abiquiu Reservoirs were set to 17,612 hectare-meters and 22,528 hectares, respectively, to match January 1, 2008, conditions.

2.3.2 Hydrologic data sources and model calibration

A wide range of historical data was used to develop the SD model and perform stochastic simulations (Table 2.1 and Table 2.2). Given the difference in age between El Vado and Abiquiu Reservoirs, approximately 30 years of overlapping hydrologic data were available for the reservoirs. The historical data were collected from USGS stream gage records (US Geological Survey, National Water Information System. Accessed January 10, 2013, `http://waterdata.usgs.gov/nwis`) and a USACE HEC-DSS hydrological database (*United States Army Corps of Engineers*, 2011) for the Rio Grande basin.

I calibrated the SD model using a combination of approaches. First, I assessed the behavior and framework of the system by comparing historical and simulated storage values for El Vado and Abiquiu Reservoir storage. Second, I evaluated the appropriateness of the distributions assigned to each hydrologic variable by comparing simulated means produced by the distributions to the historical means. Because the primary purpose of the SD model was to study overall system responses to environmental flow alternatives rather than forecast specific operational changes, I considered these calibration approaches appropriate for this study (*Barlas* (1996) provides a thorough overview of SD model validation approaches).

The first calibration approachcomparing historical and simulated monthly reservoir storageensured the model was adequately balancing the water budget within the system. Data for all hydrologic inputs were randomly selected for 15 individual years that overlapped among variables. The data within this random selection represented my calibration dataset. I simulated one-year periods using the calibration dataset to calculate monthly volumes for El Vado and Abiquiu Reservoirs. Model and historical end-of-month volumes for each year were compared using relative error calculations. I calculated mean relative errors for each reservoir using the entire 15-year calibration dataset, and modified reservoir balance equations within the model so that daily volume calculations were adjusted based on the errors. The remaining

13 years of overlapping hydrologic data were used to validate the calibration adjustments. The simulations using the validation dataset produced end-of-month volumes that matched historical conditions within 0.5% for El Vado Reservoir and 0.2% for Abiquiu Reservoir.

After I validated the structure of the model based on monthly reservoir storage comparisons, I assigned each hydrologic variable (Table 2.1 and Table 2.2) a monthly probability distribution based on method-of-moments or maximum likelihood estimation techniques. For instance, the precipitation input for El Vado Reservoir was composed of 12 probability distributions (one for each month of the year) that were best represented by a gamma distribution. I fit a distribution to each variable using the R statistical program (*R Core Team*, 2013) and the fitdistrplus package (*Delignette-Muller et al.*, 2013). I assessed the appropriateness of each distribution by comparing the mean values for simulated and historical conditions. Monthly relative errors for mean values were less than 5% for any given month and variable.

Table 2.1: Hydrologic inputs for El Vado and Abiquiu Reservoirs. Distributions that are supported by other studies include citations.

Variable	Source	Period of Record	Fitted Distribution
		El Vado Reservoir	
Rio Chama	USGS gage 08284100	1935/10/30–2013/02/11	Gamma (*Bobée and Ashkar*, 1991); log-normal (*Loucks et al.*, 2005)
SJC Project	USGS gage 08284520	1971/01/01–2008/09/30	Exponential
Precip	USACE HEC-DSS database	1975/01/01–2007/12/31	Gamma (*Watterson and Dix*, 2003)
		Abiquiu Reservoir	
Rio Chama	Releases from El Vado Reservoir	—	—
Local inflow	Difference between USGS gages 08285500 and 08286500	Varies	Scalar
Precip	USACE HEC-DSS database	1963/02/05–2011/06/13	Gamma (*Watterson and Dix*, 2003)

Table 2.2: Hydrologic outputs for El Vado and Abiquiu Reservoirs.

Variable	Source	Period of Record	Fitted Distribution
	El Vado Reservoir		
Releases	USGS gage 08285500 or modified according to environmental flow criteria	1935/10/30–2012/01/10	Gamma; exponential
Evap	USACE HEC-DSS databasie	1975/01/01–2007/12/31	Normal
	Abiquiu Reservoir		
Releases	USGS gage 08287000	1961/08/01–2012/11/05	Gamma; log-normal
Evap	USACE HEC-DSS databasie	1975/04/01–2011/06/13	Normal
	Reservoir Storage		
El Vado Storage	USACE HEC-DSS database or determined during simulations	1947/12/31–2007/12/31	Calculated according to mass balance
Abiquiu Storage	USACE HEC-DSS database or determined during simulations	1963/02/05–2007/12/31	Calculated according to mass balance

2.3.3 Evaluation variables

I chose to evaluate the impacts of each alternative on the three largest water uses in the basin: reservoir storage and releases, hydropower production, and whitewater boating. Because the system is primarily managed to meet downstream water demands, the availability of water stored in El Vado Reservoir is vital for providing a consistent water supply. I evaluated impacts to storage by comparing end-of-year reservoir volumes between existing conditions and each flow alternative. Also, I compared daily releases from the reservoir under each alternative to existing conditions.

Hydropower production and whitewater rafting are the two largest ancillary uses of water in the basin. Hydropower energy and revenue were calculated using operational guidelines and index power prices provided by Los Alamos County Department of Public Utilities (LACDPU) (Personal and email correspondence with Steve Cummins, Deputy Utilities Manager, LACDPU, October 2012). The LACDPU does own water storage in El Vado Reservoir and therefore operates the hydropower plant based on water released by USBOR to meet downstream demands. I assessed changes to monthly energy production and annual cumulative revenue for each environmental flow alternative.

I evaluated whitewater boating, which typically occurs during summer weekends, by comparing the total (weekend plus weekday) number of days and weekend days available for rafting given an environmental flow alternative. Based on discussions with commercial and private whitewater rafters that regularly use the Rio Chama (stakeholder meeting, Santa Fe National Forest Supervisors Office, March 22, 2012), a minimum discharge of 17 $m^3\,s^{-1}$ (600 $ft^3\,s^{-1}$) is desired to navigate the river. This discharge was used as the threshold for comparing the number of days available for rafting.

2.3.4 Environmental flow alternatives

Four environmental flow alternatives were simulated in the SD model. Alternatives 1–3 (Table 2.3) were based on recommendations from the collaborative workshop held in March 2013. These three flow recommendations were tested as stand-alone alternatives so that I could evaluate the distinct impacts of each. Alternatives 1–3 target specific ecological conditions discussed previously in this article (Figure 2.2), and were incorporated into the model using probabilistic triggering criteria. Alternative 1, for example, released 71 $m^3\,s^{-1}$ (2,500 $ft^3\,s^{-1}$) from El Vado Reservoir by using a binomial distribution [P(year to release = 0.5)] to randomly select a year in which to release the environmental discharge. Once an environmental release was triggered the characteristics of the release varied according to the ecological conditions targeted by each alternative (Table 2.3).

Table 2.3: Descriptions of each environmental flow alternative. All alternatives only impacted releases of native flows from El Vado Reservoir and did not alter SJC Project releases.

Alternative	Peak Discharge	Description
Alternative 1	71 $m^3\,s^{-1}$ (2,500 $ft^3\,s^{-1}$)	Released approx. every 2 years and held constant for 5 consecutive days between March and August
Alternative 2	127 $m^3\,s^{-1}$ (4,500 $ft^3\,s^{-1}$)	Released approx. every 5 years and decreased by 5% for 5 consecutive days between April and July
Alternative 3	170 $m^3\,s^{-1}$ (6,000 $ft^3\,s^{-1}$)	Released approx. every 10 years and held constant for 2 consecutive days between March and June
Alternative 4	—	Releases matched Rio Chama inflows when inflow was greater than assigned release for the day

Alternative 4 was developed to match the natural hydrologic patterns of the system while maintaining SJC Project releases from El Vado Reservoir. Releases from the reservoir were forced to match Rio Chama inflows on days in which releases were less than inflows. Reservoir releases were not changed in Alternative 4 when they were greater than Rio Chama inflows. Due to management constraints, SJC Project water needs to be passed through the system by the end of each year, thus SJC Project releases were not altered under any alternative.

2.4 Results

2.4.1 Reservoir storage and releases

The impacts of each environmental flow alternative on annual storage volumes and release patterns at El Vado Reservoir are shown in Figure 2.3. The plots above the dashed line in Figure 2.3 shows median storage (gray band indicates 25th and 75th percentiles) and releases for existing conditions, and plots under the dashed line are deviations from existing conditions produced by each alternative. Mean storage volumes were reduced under all four alternatives (Figure 2.3a). Alternative 1–3 did not effect reservoir volumes until the spring season due to their targeted approach, but once storage deficits were created they persisted for the remainder of the year. The small but frequent releases produced by Alternative 1 resulted in the largest decrease in storage among the three alternatives (960 hectare-meters), followed by Alternative 2 (718 hectare-meters) and Alternative 3 (230 hectare-meters). Alternative 4 created the largest end-of-year storage deficit of approximately 4,000 hectare-meters. This is not surprising given that Alternative 4 attempts to recreate some natural flow dynamics by allowing large flows to pass through the reservoir. The storage deficit peaked during the late-spring season when snowmelt runoff, which is typically captured for storage to meet irrigation demands later in the year, was allowed to pass through the reservoir.

Median releases from El Vado Reservoir increased during the spring and summer seasons under Alternatives 1–3 (Figure 2.3b). The timing during which each alternative increased reservoir releases depended on its respective targeted approach.

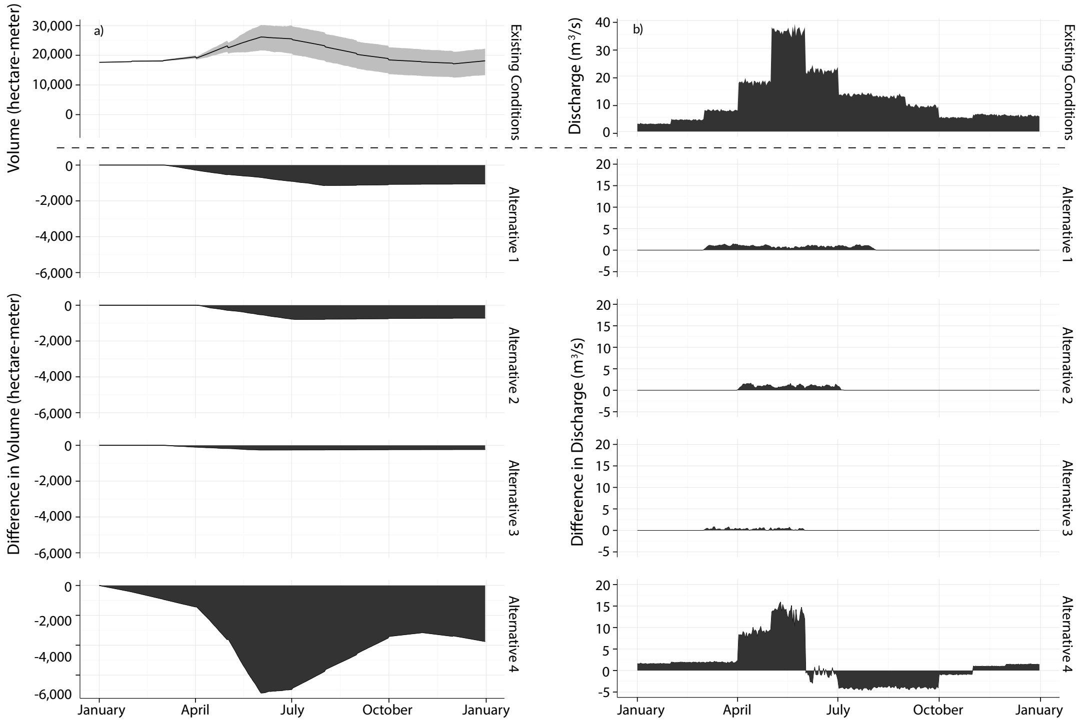

Figure 2.3: Impacts of each environmental flow alternative on median (a) volume of El Vado Reservoir and (b) releases from El Vado Reservoir. Existing conditions are shown above the dashed line. Deviations from existing conditions are shown below the dashed line. The gray band shown for existing conditions of reservoir storage represent the 25- and 75-percentiles.

Alternatives 1 and 2 increased median discharge by approximately 2 $m^3\,s^{-1}$ each day, resulting in the storage declines shown in Figure 2.3a. Median daily discharge increased by roughly 1 $m^3\,s^{-1}$ under Alternative 3. The largest shifts in reservoir releases occurred with Alternative 4, which generally produced large increases during the spring season followed by decreases later in the year. As discussed in the El Vado storage results, by forcing releases from El Vado to replicate natural flow characteristics, median discharges from the reservoir increased during the spring season—and storage levels consequently declined—but decreased later in the year when natural flows are typically less than reservoir releases.

2.4.2 Hydropower production

Because hydropower production is a function of both reservoir levels (head above the turbine) and discharge, the differences in production compared to existing conditions varied according to changes in the two driving variables. Figure 2.4 shows the monthly mean energy production at El Vado Dam (above the dashed line) and the mean differences in production caused by each alternative (below dashed line; note the difference in scale for Alternative 4). All the alternatives followed a similar pattern of production deviations from existing conditions. Production increased during the spring season for all alternatives, although Alternative 4 created nearly ten-times greater increases (approximately 60,000 kWh) compared to the others. Alternatives 1 and 2 created peaks in hydropower production of roughly 2,800 and 1,800 kWh, respectively. Peak increases in energy production among all the alternatives occurred in March or April, months when existing reservoir operations store incoming native flows and limit releases that could be used to operate the hydropower plant. Due to the decreases in storage caused by each alternative, energy production for summer and winter decreased compared to existing conditions.

The impact of each alternative on hydropower production was evaluated by comparing the annual cumulative revenue produced by each (Figure 2.5). The cumulative revenue for Alternatives 1–3 are nearly identical to existing conditions. There is less than 0.1% change in revenue for each of those alternatives. As seen in Figure 2.5, however, Alternative 4 increased revenue by more than $110,000 annually, or approximately 9% compared to existing conditions. Thus, the variability in hydropower production (seen in Figure 2.4) does not strongly influence yearly revenue except for Alternative 4. Meeting natural flow regime patterns is complementary to increased hydropower revenue in this system.

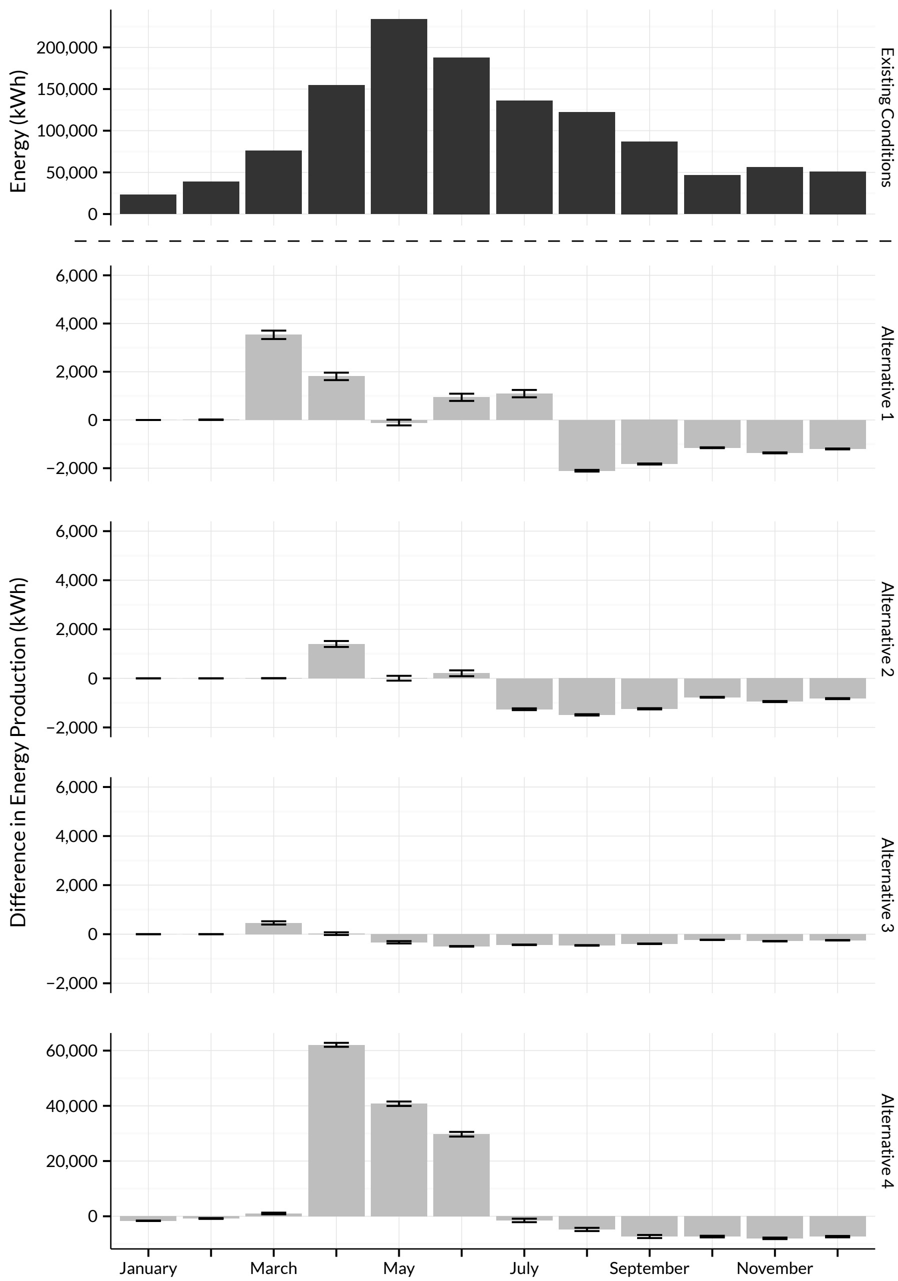

Figure 2.4: Hydropower production impacts of each environmental flow alternative. Existing conditions are shown above the dashed line. Deviations from existing conditions are shown below the dashed line. Monthly medians and standard error are represented. Note the scale difference for Alternative 4.

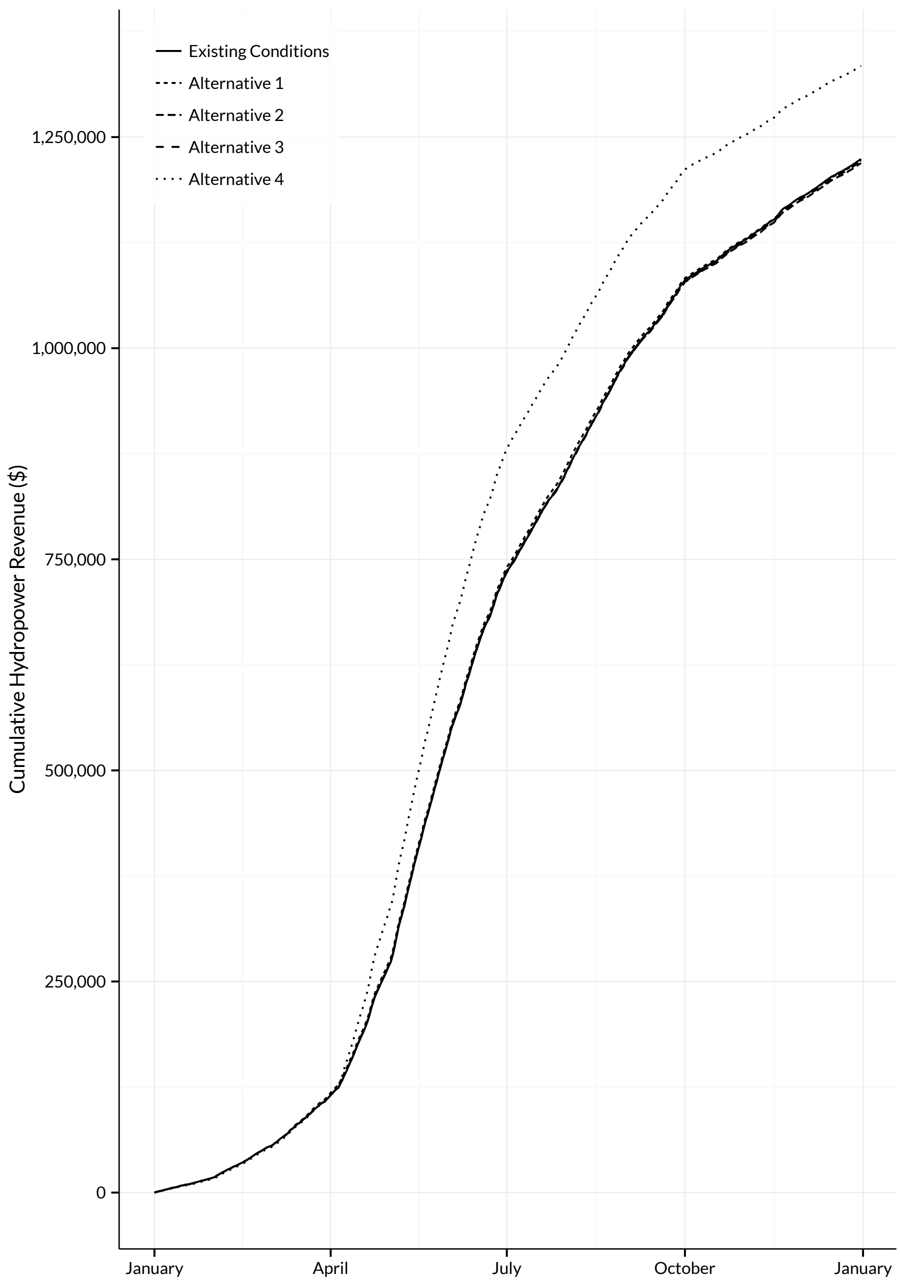

Figure 2.5: Annual cumulative hydropower revenue for each environmental flow alternative.

2.4.3 Boating availability

Releases from El Vado Reservoir between May 1 and September 30 each year support whitewater boating on the Rio Chama. Using a minimum flow threshold of 17 $m^3\,s^{-1}$ (600 $ft^3\,s^{-1}$), the accumulation of days suitable for rafting was evaluated for each alternative. Because rafting typically occurs during the weekends, the impacts were separated according to weekend days (Friday–Sunday) and total days throughout the summer months.

As shown in Figure 2.6, the median number of days available for rafting under each alternative was nearly identical to existing conditions. Between May 1 and September 30 approximately 65 days were available for rafting—roughly half the number of days during the summer. The number of weekend days suitable for rafting varied between alternatives, however. For both existing conditions and Alternatives 1–3, roughly 28 days were available for rafting. Alternative 4 increased the median number of weekend days to 32, essentially adding an extra weekend of whitewater rafting to the summer season. This is due to the pass-through of large native flows provided by Alternative 4.

2.5 Role of SD Modeling in Water Resource Management

The benefits of using an SD modeling approach to assess environmental flow alternatives apply to other basins besides the Rio Chama. In particular, SD models can fit into larger collaborative modeling frameworks that are being used more frequently to address water management challenges. Also, when SD models are constructed so that hydroclimatic variables are defined using probabilistic functions, they are well suited to examine flow alternatives in conjunction with changing climate conditions. In addition, results from SD models can be applied to address larger economic concerns that extend outside of a basin.

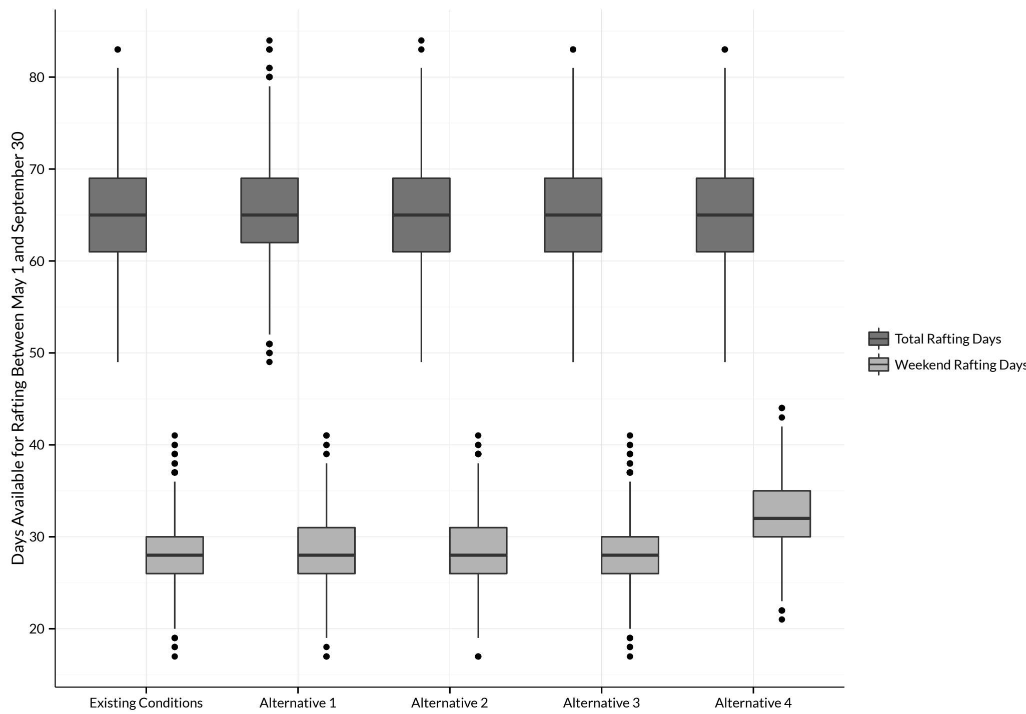

Figure 2.6: Bar plots of the total and weekend days available for whitewater rafting during the summer season (May 1–September 30). The bar plot lines represent median, 25 and 75percentiles, and 10 and 90percentiles. The dots above and below the bars are outlier data.

2.5.1 Collaborative modeling and adaptive management

Increasing pressures on our water resources require agencies and researchers to examine new methods of evaluating management scenarios. As managers face new water-use demands and strong interest from stakeholders, collaborative modeling and adaptive management approaches can play an integral role in developing successful management strategies. *Bourget et al.* (2013) defined collaborative modeling as building models with rather than for participants," which compliments the process of adaptive management, especially in the context of river management (*Prato*, 2003).

In complex systems where stakeholders are amenable to working together, collaborative modeling within an adaptive management framework can be useful for solving water resource challenges (*Williams*, 2011). *Langsdale et al.* (2011) gives an excellent description of collaborative modeling and the advantages to using this approach to engage stakeholders and develop decision tools. In particular, collaborative modeling can help participants gain consensus regarding water resource challenges, increase knowledge about a system, and push difficult management negotiations beyond gridlock circumstances (*Langsdale et al.*, 2011).

When coupled with adaptive management, collaborative modeling may help our social-ecological systems become more sustainable (*von Korff et al.*, 2012) in the long-term due to the frequent learning and management adjustments that can occur as part of the collaborative process.

I see the use of SD modeling as a natural fit within adaptive management and collaborative modeling frameworks. This is particularly true given the advantages of SD modeling, such as the transparency and flexibility of SD models, and the ease with which the models can incorporate stakeholder input. According to *Williams* (2011), these benefits are key for models that are used in conjunction with adaptive management. These benefits are also aligned with the principles of collaborative modeling presented by *Langsdale et al.* (2013), particularly using models that are accessible and transparent to all participants (principle 3) and can easily accommodate new information (principle 5). In addition, SD modeling is ideal for Shared Vision Planning Models (*Palmer et al.*, 2013), which are interactive, emphasize the system dynamics that are important to stakeholders, and are specifically built to address stakeholder concerns. Although this has been demonstrated through a few studies (e.g. *Tidwell et al.* (2004)) I feel that SD modeling is a promising tool to use in larger collaborative modeling frameworks and integrated water resource management.

2.5.2 Incorporating future basin conditions

Climate change is predicted to cause significant impacts to the hydrologic conditions and ecological processes in many water resources systems, particularly in the western United States (*Archer and Predick*, 2011; *Cayan et al.*, 2010; *Gleick*, 2010; *Gutzler and Robbins*, 2011). A recent study by *Llewellyn and Vaddey* (2013) highlights the hydrologic impacts of climate change in the Upper Rio Grande Basin, including the Rio Chama. The study reports that native inflows within the Rio Chama basin may decrease by one third, peak flows may occur up to one month sooner, and median temperature may increase nearly 8 degrees Fahrenheit by the year 2100.

Although I used historical data to develop probability distributions for hydroclimatic variables, the model can be easily adjusted to explore the conjugate impacts of climate change and environmental flow alternatives on water uses. Probability functions of hydroclimatic variables can be adjusted using data from literature (such as *Llewellyn and Vaddey* (2013)) that evaluates the consequences of climate change on hydrologic processes.

This application of SD modeling to evaluate climate change impacts is transferrable to other basins where sufficient data is available to represent shifts in climate conditions. In addition, this approach is compatible with management frameworks proposed by key federal water management agencies, such as the U.S. Army Corps of Engineers (*Brekke*, 2011).

2.5.3 Economic considerations

In systems that include hydropower production, SD model results can be useful for examining economic impacts that extend beyond the boundaries of a basin. Because energy cooperatives often include power that is produced from a variety of sources, an increase in hydropower production may offset other power sources that are less environmentally friendly.

There are economic and environmental benefits to increasing hydropower production in the Rio Chama basin. Because LACPUD does not own water stored in El Vado Reservoir, and therefore cannot produce additional power at their discretion, it purchases approximately $400,000 of coal-powered energy as part of an agreement with their power cooperative (Personal and email correspondence with Steve Cummins, Deputy Utilities Manager, LACDPU, October 2012). The coal-powered energy is referred to "spinning" reserve power. This agreement is a large economic burden for the county that could be eliminated or reduced if an implemented environmental flow alternative produced excess power at El Vado, and Los Alamos County was able to have some control over operations at El Vado to produce the power when needed. Reducing dependencies on fossil-fuel sources of energy would also be more environmentally friendly in this system.

As demonstrated in the Rio Chama, SD models that include multiple analysis components, such as hydrologic and economic, are valuable for holistically examining impacts of flow alternatives, both within and outside of a basin.

2.5.4 Future SD modeling research

A logical next step in using SD modeling to assess environmental flows is to explicitly include ecological processes in the modeling framework. Our study assumed the proposed environmental flow alternatives from the stakeholder meeting would benefit key ecological components of the Rio Chama, and then tested the impacts of those alternatives on other water-uses in the basin. A more holistic assessment of the alternatives needs to include an evaluation of the desired ecological goals. This will be a challenge given the large uncertainty associated with many ecological processes and the lack of knowledge regarding key hydrologic-ecological relationships (*Richter et al.*, 2012). Linking hydrologic characteristics and ecological integrity can be such a challenge (both scientifically and due to resource demands), that some new environmental flow methodologies propose the use of presumptive standards to determine appropriate flows (*Richter et al.*, 2012) or aggregate flow recommendations according to similarities in basin characteristics (*Poff et al.*, 2010). Still, when feasible, including ecological processes into the modeling framework will provide a more holistic assessment of flow alternatives.

I envision our SD modeling efforts on the Rio Chama as the first step to incorporating environmental flows in the basin. Results from this study are important for guiding initial decisions regarding the feasibility of each proposed alternative, but additional management details that werent represented in our model, such as detailed water accounting (e.g. water rights and authorizations), would need to be examined before environmental releases become integrated into the systems operation. Although our modeling approach does not lend itself to immediate operational changes, it serves an important role of recognizing and assessing physical and institutional constraints that exist in the system (*Harm Benson et al.*, 2013). When coupled with stochastic simulations, hydrologic uncertainties can be explicitly included in the model. Even though other sources of uncertainty clearly exist in managing any river system (ecological processes, political, socio-economic) (*Clark*, 2002), a stochastic representation of hydrologic variability helps managers hedge their decisions against unknown conditions.

2.6 Conclusion

My work demonstrated how environmental flow alternatives can be assessed using an SD approach. This approach included building a model with a diverse team of experts and stakeholders so that important management considerations were represented. I found that the proposed environmental flow alternatives in the Rio Chama basin would generally decrease reservoir storage, increase reservoir releases during the spring season, and have small impacts to hydropower production and whitewater boating access. Using an SD model to evaluate environmental flow alternatives can compliment collaborative and adaptive management strategies, especially when used within a stochastic framework to represent uncertainty.

Chapter 3

System Dynamics Modeling to Evaluate Riparian Recruitment

3.1 Introduction

Water resource managers, policy makers, scientists, and others fortunate enough to work in the field likely agree on one thing: properly managing our water resources is complicated. Water supplies are sliced into temporal and spatial pieces to fulfill a host of economic, social, and environmental needs. Projections of water availability do not indicate this job will become any easier (*Postel*, 2000). This is especially true in the arid southwestern United States, where many water sources have been over-allocated and are strained as climate change shrinks supplies (*Cayan et al.*, 2010) and population growth increases water demand.

While the development of our water supplies has provided resource stability and societal prosperity, in many cases it has also harmed the ecological systems that humans depend upon (*Bunn and Arthington*, 2002). Recognition that aquatic ecosystems have an inherent right to water has steadily grown during the past few decades (*Naiman et al.*, 2002), and the management of our water resources often includes allocations for the environment. Replicating portions of a rivers natural flow regime (*Poff et al.*, 1997; *Poff*, 2009) is a common approach for providing the hydrological conditions needed by fluvial ecosystems. While undoubtedly important, environmental allocations add another layer of complexity to existing management systems that struggle to balance the myriad of water demands within a basin.

Numerous methodologies have been developed to capture the complexity of water resource systems and implement environmental flows (*Tharme*, 2003; *Petts*, 2009). These methods typically employ deterministic models to predict impacts on hydrologic parameters that are used to assess deviations from natural flow conditions (the Indicators of Hydrologic Alteration methodology (*Richter et al.*, 2006) is a common way to assess alternative impacts on hydrology). As computing power increases, optimization methods (*Yin et al.*, 2012; *Shiau and Wu*, 2013) are being used to identify flow alternatives bound by large numbers of management constraints. These deterministic or command and control models (*Holling and Meffe*, 1996) focus on the efficiency of resource control rather than exploring system-wide responses or the influence of feedback mechanisms of management alternatives.

System dynamics (SD) modeling is an underutilized tool that can provide flexible and system-response analyses of environmental flows (*Mirchi et al.*, 2012). Developed post-World War II to analyze feedback control systems (*Forrester*, 2007), SD models have since been used to examine nonlinear systems related to groundwater-surface water interaction (*Tidwell et al.*, 2004), reservoir operations (*Ahmad and Simonovic*, 2000), ecohydrological connections (*Miller et al.*, 2012), and socio-economic impacts of management alternatives (*Wei et al.*, 2012). Because SD models are able to incorporate causal connections between social, economic, and environmental aspects of a system (*Simonovic*, 2008), they are well suited to study water management, which involves balancing all those aspects within a basin. In addition, the power of SD models to represent uncertainty through probabilistic variables and stochastic simulations make them useful for exploring the impact of uncertainty on environmental studies.

SD models are also excellent tools for incorporating expert and stakeholder feedback, which is an important component of any environmental flow study (*Poff et al.*, 2010). *Tidwell et al.* (2004, 2006) demonstrated the usefulness of SD modeling in interacting with the public and eliciting stakeholder feedback.

Recognizing the unique benefits of an SD approach, I developed an SD model to assess environmental flow alternatives in the Rio Chama, a highly constrained river system located in northern New Mexico, USA. My objective was to develop and demonstrate a stochastic SD modeling framework to evaluate environmental flow alternatives. This objective was accomplished by completing three tasks: 1) gather environmental flow recommendations provided by a diverse group of ecology experts familiar with the Rio Chama system; 2) incorporate one or more of these recommendations within a stochastic SD modeling framework; and 3) assess the practicality of multiple flow alternatives based on improvements to ecological health and impacts to reservoir management.

3.2 Rio Chama environmental flow case study

3.2.1 Basin description

The Rio Chama basin is used as a case study for evaluating environmental flow alternatives within an SD modeling framework. The Rio Chama, located in northern New Mexico, is the largest tributary to the Rio Grande Figure 3.1. The basin drains 8,300 square kilometers and contains three dams; El Vado and Abiquiu Dams (on the main stem) are used primarily for water delivery and flood control purposes, and Heron Dam (on Willow Creek) is used to store trans-basin water from the San JuanChama (SJC) Project. A 50 km section of river between El Vado Dam and Abiquiu Reservoir is the focus of an ongoing environmental flow study and is ideal for modeling purposes because 1) a large hydrologic dataset is available, 2) a significant portion of this reach is located in a National Wilderness Area with only minor withdrawals, simplifying water budget balancing, and 3) the reach is bound by reservoirs, allowing easy control of environmental flow releases and storage.

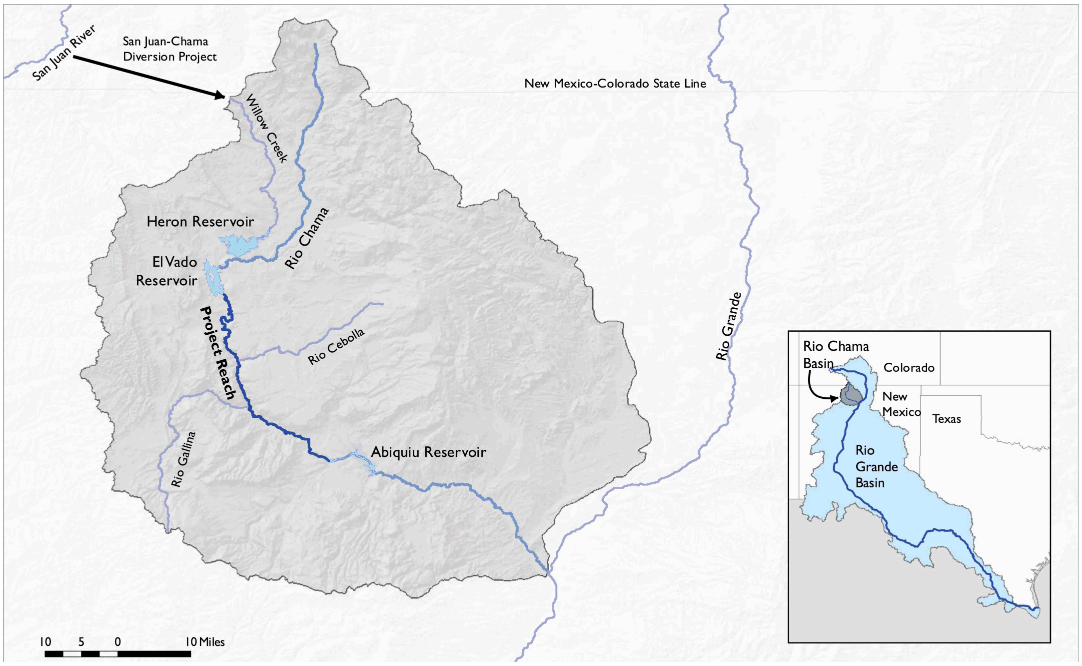

Figure 3.1: Location of the Rio Chama basin. San Juan-Chama Project water is stored in Heron Reservoir or El Vado Reservoir. Environmental flows are released from El Vado Reservoir and stored in Abiquiu Reservoir.

The construction and operation of El Vado (1935), Abiquiu (1954), and Heron (1974) Dams has altered the natural flow regime of the Rio Chama. Because water in the basin is primarily used to satisfy irrigation and municipal needs, flows in the river are controlled by water delivery demands issued from water owners. In addition, the Bureau of Reclamations SJC Project, a trans-basin delivery project which transfers water from the Upper Colorado basin to the Rio Grande basin, has increased base flows during most months of the year. Broad alterations to the natural flow regime include reduced peaks, higher base flows, rapid rise- and fall-rates during the summer season, and greater annual flow volumes.

Although the Rio Chama is managed primarily for downstream water delivery demands and flood control, other recreational and economic water uses are important parts of the system. Small hydropower plants, owned and operated by Los Alamos County Department of Public Utility, are located at El Vado and Abiquiu Dams and have a combined capacity of approximately 25 Megawatts. Releases from El Vado Reservoir provide whitewater boating flows during summer weekends for commercial and private boaters. Further, the Rio Chama is commonly used by commercial and private anglers.

Constraints imposed by the Rio Grande Compact can influence operations of El Vado and Abiquiu Reservoirs and therefore river flows between the two reservoirs. For example, Article VII of the Compact (Rio Grande Compact, 1938) restricts the storage of intra-basin (native) water at El Vado or Abiquiu Reservoir during periods when the Elephant Butte storage volume is below approximately 162,000 hectare-meters (400,000 acre-feet). As a result, only SJC water is stored while native flows pass freely through the basin.

3.2.2 Environmental flow workshop

A collaborative effort to improve the rivers ecology through modified releases from El Vado Reservoir began in 2010. A project team composed of ecological engineers, riparian ecologists, benthic invertebrate ecologists, geomorphologists, and environmental law experts have been collecting geomorphic and ecological data on the river to describe baseline environmental conditions and develop flow alternatives. In addition, a varied group of stakeholders have been encouraged to participate in the environmental flow study, including government agencies, water owners, whitewater boaters, anglers, hydropower owners, ranchers, and other interested citizens. Stakeholder involvement ensures that particular aspects of the basin are properly representing in the SD model.

The project team hosted a workshop in March, 2013 to develop specific environmental flow recommendations. Experts in terrestrial ecology, hydrology, riverine benthic ecology, and geomorphology determined that three flow conditions were important for improving ecological conditions in the Rio Chama (Figure 3.2). First, a peak flow of approximately 170 $m^3\,s^{-1}$ is needed every 10 years to rework channel and overbanks to provide heterogeneous habitat conditions. Second, a discharge of up to 140 $m^3\,s^{-1}$ every three to five years is important for inundating the floodplain and encouraging riparian vegetation recruitment, specifically narrow leaf cottonwood (*Populus angustifolia*) and Rio Grande cottonwood (*Populus fremontii*) species. Third, a bankfull discharge of approximately 60 $m^3\,s^{-1}$ every two years is necessary for flushing sediment and channel maintenance. In addition, the workshop participants recommended that base flows be held steady during the fall and winter seasons to prevent disruption of brown trout spawning.

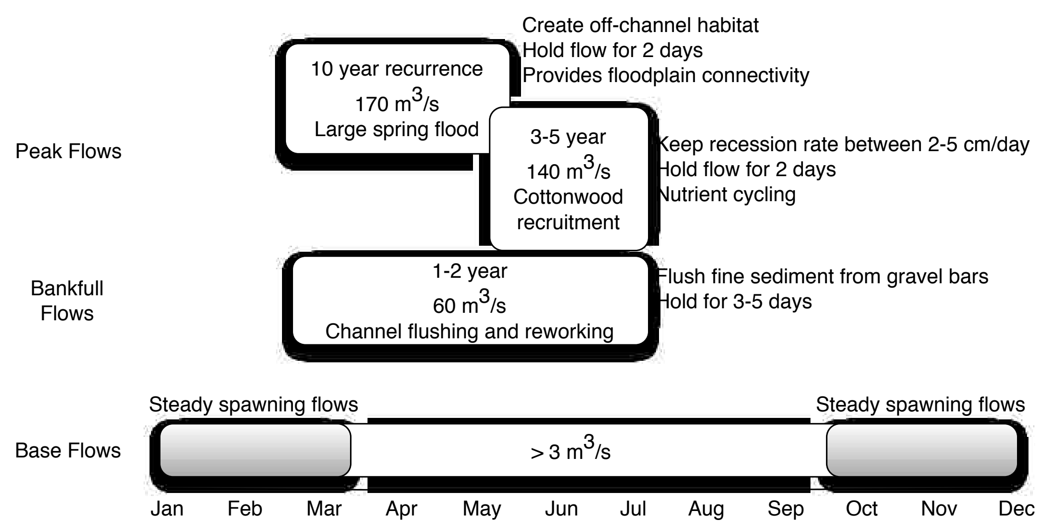

Figure 3.2: Environmental flow recommendations for the Rio Chama based on a collaborative workshop of hydrology, ecology, and geomorphology experts.

3.3 Modeling Methodology

3.3.1 Model structure

From the various flow recommendations stemming from the collaborative workshop, cottonwood recruitment flow was selected as the first recommendation to evaluate using an SD model. This allowed us to evaluate and refine the model structure while also clearly demonstrating the SD modeling approach for assessing environmental flow alternatives. A simplified diagram of the model structure is shown in Figure 3.3. Because the project research is located downstream of El Vado Reservoir, environmental flows are only possible with modified releases from the reservoir.

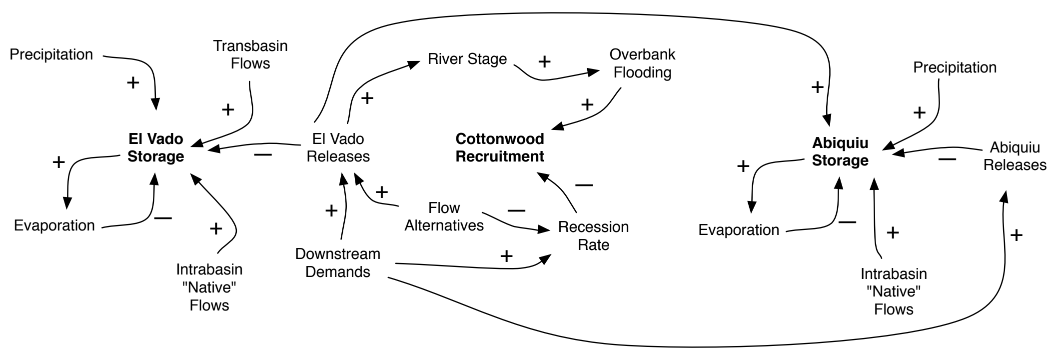

Figure 3.3: Causal loop diagram showing the key variables that influence cottonwood recruitment and reservoir storage in the Rio Chama basin. The arrows represent connections between variables, and signs next to each arrow represent positive or negative reinforcing.

The Rio Chama SD model was constructed using GoldSim (*Goldsim Technical Group*, 2012). Like all SD modeling software, GoldSim solves differential equations to determine changes to material or information stocks based on inflow and outflow rates. However, GoldSim was chosen for this research because of its ability to perform stochastic simulations based on probabilistic variables. This functionality is unique among other SD modeling platforms, which perform deterministic or limited stochastic simulations based on static variables. In addition, the availability of probabilistic elements allowed us to explicitly incorporate variable uncertainty within a Monte Carlo simulation framework (*Kossik*, 2012) and statistically assess impacts from environmental flow alternatives.

Model realizations were conducted using a one-day time step for a 365-day simulation period, and 1000 realizations were used to evaluate each environmental flow alternative.

3.3.2 Data sources and distribution fitting

Historical time series data were used to develop monthly probability distributions for each hydrologic variable (Table 3.1 and Table 3.2). For instance, the precipitation input for El Vado Reservoir was composed of 12 probability distributions (one for each month of the year). The historical data was collected from a variety of sources, including United States Geological Survey stream gage records and the United States Army Corps of Engineers' hydrological database for the Rio Grande basin. Distributions were assigned to each variable based on the results of method-of-moments or maximum likelihood estimation fitting techniques. Fitting calculations were performed in R (*R Core Team*, 2013) using the fitdistrplus (*Delignette-Muller et al.*, 2013) package.

3.3.3 Model calibration and evaluation

The purpose of the SD model used in this research was to examine the broad impacts of environmental flow alternatives on cottonwood recruitment and other water users in the basin. The model was not designed as a forecasting tool, but rather as a tool for understanding system responses and patterns. Therefore, the calibration techniques focused on aggregate system performance instead of forecasting accuracy (a thorough discussion of this topic is provided by *Barlas* (1996) and *Barlas and Carpenter* (1990)).

The model was evaluated at two levels. First, the overall structure and behav-

Table 3.1: Data sources and fitted distributions for El Vado Reservoir's water balance parameters. Cited references in the table are for studies that recommend or use similar distributions for comparable variables.

Data	Source	Time Period	Distribution(s)
		Reservoir Inflows	
Rio Chama	USGS gage 08284100	1935/10/30–present	Gamma (*Bobée and Ashkar*, 1991) or log-normal (*Loucks et al.*, 2005)
SJC Project	USGS gage 08284520	1971/01/01–2008/09/30	Exponential
Precip	USACE records	1975/01/01–2007/12/31	Gamma (*Watterson and Dix*, 2003)
		Reservoir Outflows	
Releases	USGS gage 08285500 or simulated	1935/10/30–present	Gamma or exponential
Evap	USACE records	1975/01/01–2007/12/31	Normal
		Storage	
Reservoir stage	USACE records or simulated	1974/12/31–2007/12/31	Mass balance calculation

ior of the model was calibrated based on simulated storage levels in El Vado and Abiquiu Reservoir. Second, the monthly probability distributions were evaluated by comparing simulated results to historical means.

Simulations were performed using historical time series data to evaluate how well the model calculated storage levels in El Vado and Abiquiu Reservoirs. A compilation of 15 years was randomly selected from the historical dataset available between 1975 and 2007. One-year simulation periods using daily time steps were performed and the final end-of-month storage value in each reservoir was compared to historical conditions. The mean relative error in end-of-month storage for each reservoir was computed based on all 15 calibration years.

Table 3.2: Data sources and fitted distributions for Abiquiu Reservoir's water balance parameters.

Data	Source	Time Period	Distribution(s)
		Reservoir Inflows	
Rio Chama	Simulated El Vado releases	—	—
Local inflow	Difference between gages 08285500 and 08286500	Varies	Scalar
Precip	USACE records	1963/02/05–2011/06/13	Gamma
		Reservoir Outflows	
Releases	USGS gage 08287000	1961/08/01–2012/11/05	Gamma or log-normal
Evap	USACE records	1975/04/01–2011/06/31	Normal
		Storage	
Reservoir stage	USACE records or simulated	1963/02/05–2007/12/31	Mass balance calculation

Monthly adjustment factors for both reservoirs were added to the model based on the calculated mean relative errors. The 13 years of historical data that were not used in the calibration processes were used to validate the model after the adjustment factors were introduced. The mean relative errors in end-of-month storage levels for each reservoir were less 0.5% for El Vado Reservoir and 0.2% for Abiquiu Reservoir during the validation years, which was considered appropriate for this study.

3.3.4 Model variables

After the ability of the model to adequately calculate the basins water budget was validated, probability distributions were assigned to hydrologic model variables. The monthly probability distributions for each variable were then evaluated by computing the relative error of mean values based on model and historical data. The relative errors for mean values were less than 5% for any given month and variable.

3.3.5 Riparian recruitment modeling

The recruitment box model (*Mahoney and Rood*, 1998) was used to assess the conditions necessary for successful cottonwood recruitment and to evaluate environmental flow alternatives. The box model is a simple conceptual model to evaluate the physical conditions necessary for cottonwood fecundity. It attributes seedling survival to floodplain elevation, annual timing of peak flows, and river stage declines that match seedling root growth. *Mahoney and Rood* (1998) show that a hydrologic recession rate of 2.5 cm/day is ideal for recruitment. Recession rates with three-day averages of up to 10 cm/day may still produce successful recruitment, but rates greater than this are too fast to allow adequate root establishment (*Burke et al.*, 2009). The recruitment box model has successfully been applied to improve riparian communities within numerous river systems, including the Truckee River in California (*Rood et al.*, 2003a) and Oldman and St. Mary Rivers in Alberta, Canada (*Rood et al.*, 2005). *Burke et al.* (2009) recently used the box model to connect dam operations in the Kootenai River basin of western North America to the deterioration of cottonwood recruitment potential.

A one-dimensional hydraulic model was developed using HEC-RAS for a segment of the Rio Chama that is amenable to new cottonwood establishment. The HEC-RAS model was used to develop stage-discharge curves for the reach and to determine the discharge at which overbank flooding occurs. The average discharge and floodplain elevation at initial overbank flooding was assumed to be the minimum required to initiate recruitment.

Because cottonwood recruitment occurs during the late-spring and summer (*Patten*, 1998), it was assumed that seed dispersal and recruitment on the Rio Chama will take place between April and June. Table 3.3 shows the combination of conditions that were assumed necessary for cottonwood recruitment to occur in the Rio

Chama. These conditions were incorporated into the SD model to assess the impact of different environmental flow alternatives.

Table 3.3: Hydrologic and timing condition assumed necessary to begin cottonwood requirement in the Rio Chama.

Attribute	Requirements
Timing	Overbank flooding occurs April–June
Flooding elevation	Floodplain inundation begins at 100 $m^3\,s^{-1}$ or at a river stage of 2,016 m. These were assumed the minimum required for recruitment.
River stage recession rate	Three-day average recession rates between 1 and 10 cm/day were assumed to be adequate to initiate cottonwood recruitment.

In addition, the following equation was used to evaluate the success of riparian recruitment given the river stage recession rate:

$$g(h) = 0.94 \exp\left[-0.5\left(\frac{\ln\left(\frac{h}{1.28}\right)}{0.99}\right)^2\right] \tag{3.1}$$

where $g(h)$ scales fecundity from 1 to 0 (successful establishment to failure) based on the rate of stage decline, h (cm/day). This equation was developed by *Lytle and Merritt* (2004) based on experimental data provided by *Mahoney and Rood* (1991). The log-normal function produces a maximum value with a 2 cm/day recession rate (*Lytle and Merritt*, 2004), indicating that recession rates above or below 2 cm/day are less ideal for successful establishment.

3.3.6 Environmental flow alternatives

Three environmental flow alternatives were compared to existing conditions based on their effectiveness at providing the necessary conditions for cottonwood recruitment and their impact on reservoir storage levels (Table 3.4). It was necessary to divide Rio Chama water according to its source due to the complex management structure of the basin. The alternatives used in this study focused on changing the release patterns of native water (originating in the basin) from El Vado Reservoir since it constitutes the largest proportion of water volume in the basin. San Juan-Chama Project water deliveries (transported via a trans-basin pipeline from the Upper Colorado basin) were modeled according to existing management patterns and not modified in the flow alternatives.

Table 3.4: Descriptions of each environmental flow alternative tested within the system dynamics model.

Flow Alternative	Description
Alternative 1	Native water releases from El Vado Reservoir matched native inflows to the reservoir.
Alternative 2	Native water releases from El Vado Reservoir were increased by 20% to promote overbank flooding.
Alternative 3	A 5-year event discharge (130 $m^3 s^{-1}$) was simulated by using a binomial probability distribution to trigger the release during random model realizations. The discharge was decreased by 5% for four days following the peak release.

With the exception of Alternative 3, each environmental flow alternative represented deterministic rules that were constrained by inflow conditions at El Vado Reservoir. This was to ensure that the flow alternatives could realistically be incorporated into current management operations for the system. Alternative 3, however, used a probabilistic method of releasing high flows from El Vado Reservoir.

The first flow alternative (Alternative 1) allowed native water to pass through El Vado Reservoir without being stored. In other words, native Rio Chama water simply passed downstream as if the dam did not exist. San Juan-Chama Project water, however, was still released using monthly distributions based on historical operations. The sum of native and SJC Project water represented the total discharge passed downstream of El Vado.

The second alternative (Alternative 2) increased the release of native water from El Vado by 20% when the inflows into the reservoir are greater than the predicted outflows. In this alternative the SJC Project releases remain the same as predicted by historical records.

The last alternative (Alternative 3) simulated the 5-year flood event by randomly selecting a model realization in which to force a peak flow release from El Vado. If a model realization was triggered as an environmental flow year, a random day between April 1 and June 30 was selected as the start day for the peak flow release. The release from El Vado was 130 $m^3 s^{-1}$ on the first day followed by a flow decrease of 5% during the next four days. This ensured that the recession was less than 10 cm/day.

3.4 Results

3.4.1 Cottonwood recruitment

The efficacy of each environmental flow alternative in promoting cottonwood recruitment was evaluated based on the frequency in which all the recruitment requirements were simultaneously met (Table 3.5) and the value of the fecundity rating metric (Equation 3.1).

Table 3.5: Success ratio for each alternative

Flow Alternative	Mean Success Metric	Relative Deviation in End-of-Year Storage	Success Ratio
Alternative 1	0.36	0.15	2.4
Alternative 2	0.45	0.75	0.6
Alternative 3	0.42	0.037	11.4

The appropriate recession rate, timing, and stage elevation requirements must be present at the same time in order to facilitate recruitment. The timing and frequency of these unified requirements provide an indication of which flow alternatives provide the most favorable recruitment conditions. The frequency with which all recruitment conditions were met varied between alternatives, but followed a similar pattern for each. Frequencies reached a peak during the month of May (Julian days 121–151) and were considerably less during April and June. Because the releases from El Vado are determined by monthly probability distributions, results show obvious changes that occur at the start of each month (Figure 3.5). Thus, it is not surprising that the greatest frequencies for recruitment conditions occur in May when mean discharges from El Vado Reservoir are also greatest.

The likelihood of coinciding recruitment conditions is greatest in Alternative 2, which provides a probability of approximately 7% for any given day in May. Alternative 1 provides a 2.5% probability of occurrence in May. Because Alternative 3 sporadically releases a peak discharge from El Vado Reservoir rather than continuously controlling reservoir releases, it only slightly increases the probability of recruitment conditions compared to existing settings.

Because a higher frequency of recruitment conditions may not necessarily indicate increased success, the recruitment quality of each flow alternative was inferred using Equation 3.1. The equation provided by *Lytle and Merritt* (2004) yields a metric for evaluating recruitment success based on the recession rate of the river. The median (solid line) and mean (dashed line) success metrics are shown in Figure 3.4. As expected, the lowest values occur under existing conditions. The alternatives have nearly identical median values (Alternative 1 = 0.43; Alternative 2 = 0.45; Alternative 3 = 0.43). However, Alternative 2 provides the greatest mean value (0.45) followed by Alternative 3 (0.42). The mean values for existing conditions and Alternative 1 were similar (0.37, 0.36). The gap between median and mean values for Alternative 1 is caused by the low recruitment success during April (represented by the white breaks in Figure 3.4).

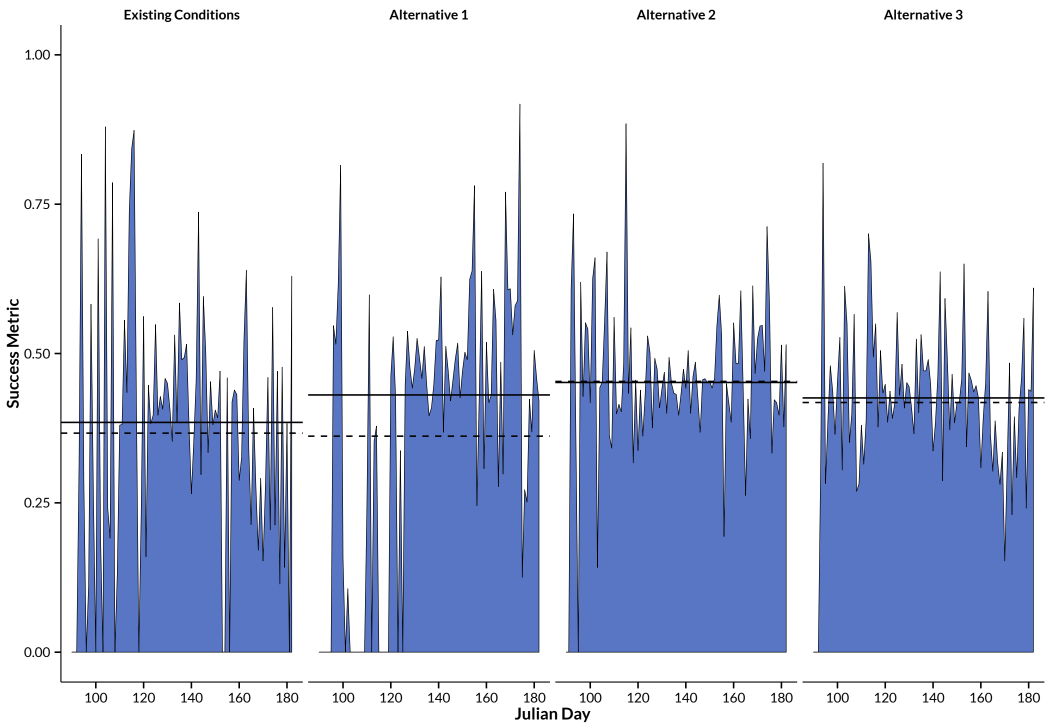

Figure 3.4: Success metric (ranging from 0 to 1) for each flow alternative during the months April–June. The solid and dashed horizontal lines are the median and mean values, respectively, for each alternative.

The cottonwood recruitment quality for each alternative is noticeably more varied when separated according to month (Figure 3.5). Alternatives 2 and 3 perform well during April, while Alternative 1 performs poorly, even when compared to existing operations. The alternatives provide conditions of similar quality during May, which marginally surpass those of existing conditions. Alternative 1 produces the best recruitment conditions during June, followed by Alternatives 2 and 3. Depending on the timing of cottonwood phenology within the Rio Chama basin, managers may want to consider the effectiveness of each alternative for the given month when selecting the appropriate flow alternative.

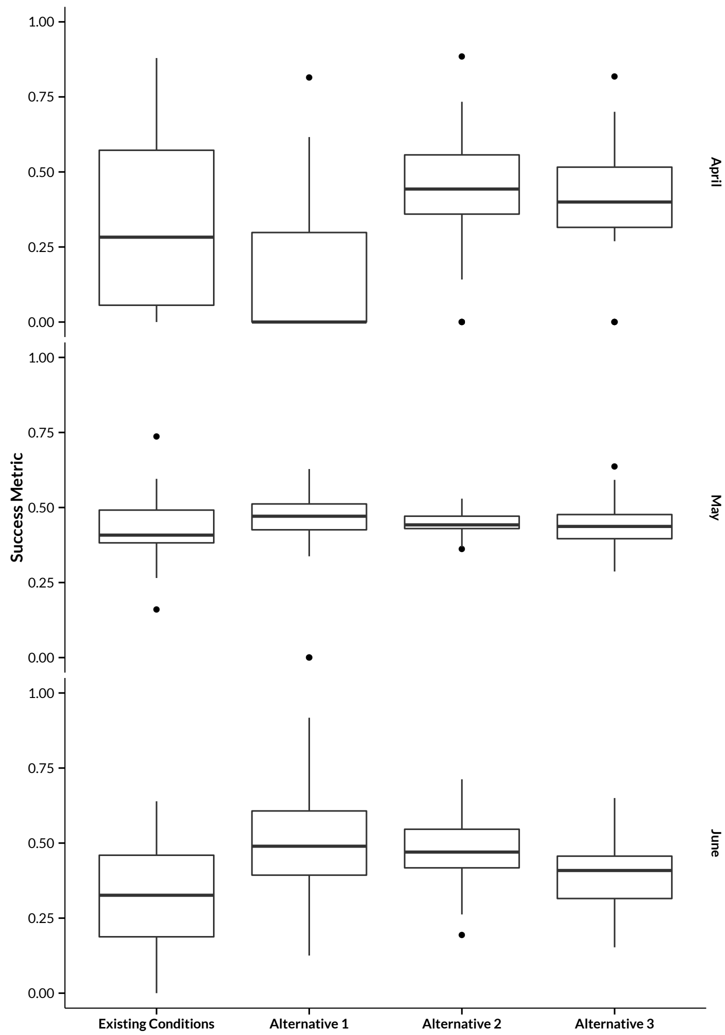

Figure 3.5: Boxplots of the success metric (equation 1) for each alternative broken into monthly segments.

A more detailed assessment of the recession rate and overbank flooding criteria reveals the impact of each on the recruitment success for every alternative. The histograms in Figure 3.6 and Figure 3.7 show the model results for both criterion facetted by alternative and month. As displayed in Figure 3.6, each alternative, regardless of the simulation month, produces recession rates that center around 4 cm/day. This value is greater than the ideal rate of 2 cm/day that results in high recruitment success according to *Lytle and Merritt* (2004). The lack of variation in recession rate indicates this criterion is likely not a major driver in differences of recruitment success between alternatives (Figure 3.4 and Figure 3.5). Also, it is worth noting that because Alternative 1, which matches native inflows and outflows of El Vado Reservoir, produces a recession rate near 4 cm/day, this may be close to historical flow conditions in the basin.

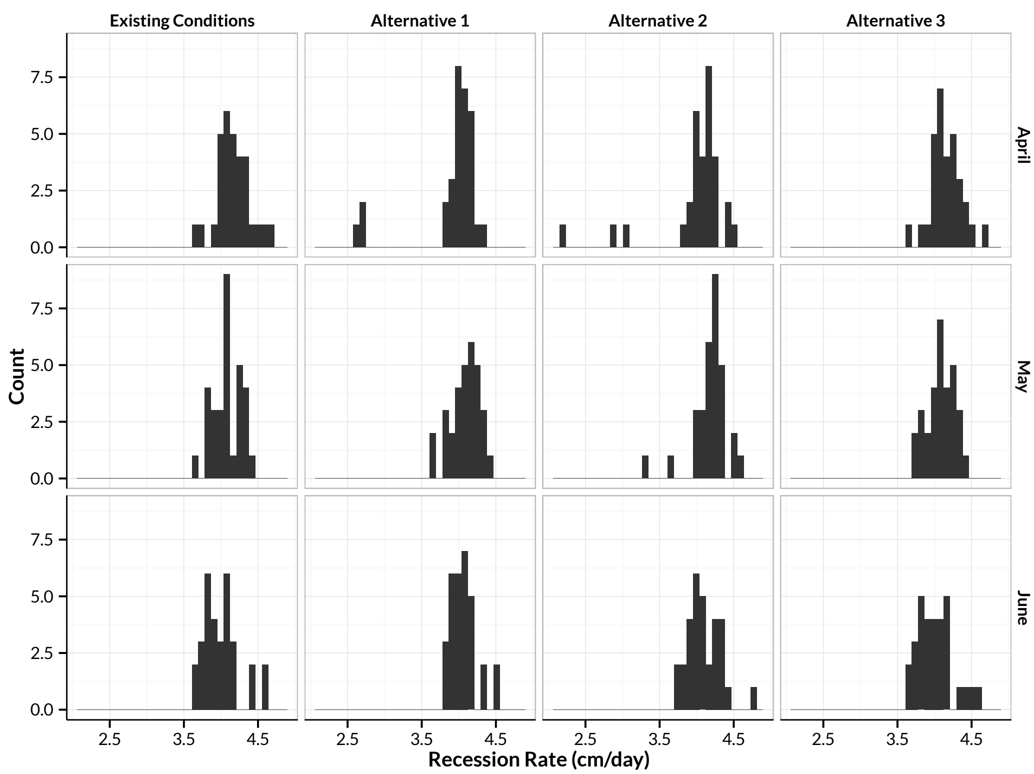

Figure 3.6: Histograms for mean daily river stage recession rate facetted by alternative and month.

Contrasted against the recession rate histograms, the overbank flooding histograms indicate more variability, especially on a monthly basis (Figure 3.7). All the alternatives have low flooding probabilities during April, most notably Alternative 1. This explains why the success metric for Alternative 1 (Figure 3.5) is nearly zero for April even though the alternative produces recession rates within the acceptable range for recruitment. All the alternatives increase flooding probabilities in May; combined with adequate recession rates this creates similar success metrics among alternatives during the same month. During June the likelihood of overbank flooding drops according to all the alternatives.

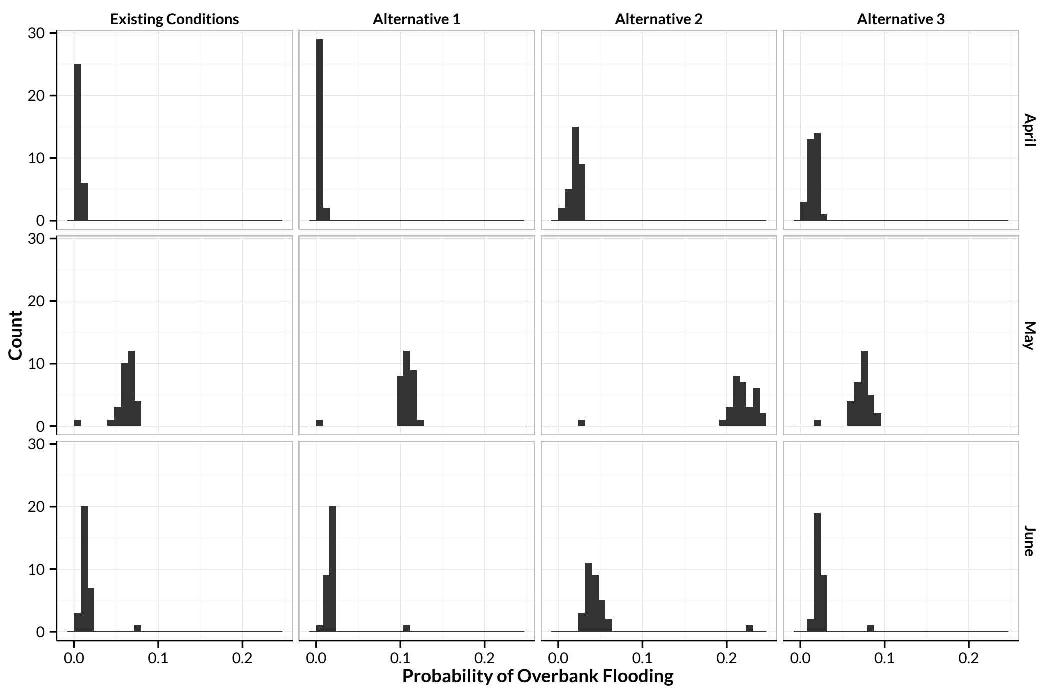

Figure 3.7: Histograms for mean daily overbank flooding probabilities facetted by alternative and month.

3.4.2 Reservoir storage

The practicability of each flow alternative is contingent on its impact on storage levels in El Vado and Abiquiu reservoirs. If an alternative causes large deviations in storage compared to existing conditions, the adoption of new flow recommendations by basin managers will be less likely. From the perspective of the reservoir managers, the ideal flow alternative is one that is most beneficial to the downstream ecology but the least interruptive to the operational status quo.

When compared to typical reservoir levels maintained under existing conditions, Alternatives 1 and 2 create substantial declines in storage at El Vado Reservoir after one year. There was a 15% decrease in median end-of-year storage volume associated with Alternative 1. In addition, the storage of runoff water during the spring season, which is important for irrigation releases later in the year, was not possible under Alternative 1.

Storage levels sharply decreased during the spring season and continued to decrease throughout the rest of the year under Alternative 2. The median end-of-year storage volume was 75% less than existing conditions under this alternative, essentially draining the reservoir in order to provide environmental flows. Alternative 3 demonstrated the mildest impact to storage volumes in El Vado, with only a 3.7% decrease in median end-of-year levels. In addition, the pattern of storage displayed under existing conditionscapturing spring runoff followed by gradually releasing water through the summerremained consistent under Alternative 3.

Because Abiquiu Reservoir is located downstream of the project reach, storage volumes were directly impacted by releases from El Vado Reservoir. Not surprisingly, the declines in El Vado storage volumes caused by Alternatives 1 and 2 led to increases in median end-of-year volumes within Abiquiu—7.4% and 75%, respectively. Whereas Alternative 1 caused an initial sharp increase in volume during the spring season followed by a steady decline during the following months, Alternative 2 maintained the same initial storage volume throughout the entire year. Alternative 3 created a slight bump in end-of-year storage volume compared to existing conditions (2.7%), and matched the existing pattern of storage throughout the year.

3.4.3 Comparative ratio

It is clear that alternatives that are most beneficial to the riparian community may have the strongest impact on reservoir storage. Large volumes of water released from El Vado Reservoir increase the likelihood of overbank flooding but also decrease water availability. A success ratio, similar to a traditional benefit/cost ratio, can be applied to the alternatives so I can better compare the impacts of each. The ratios between the average success metric (Equation 3.1) and percent deviation in El Vado storage for each alternative are shown in Table 3.5. Based on success ratio calculations, Alternative 3 provides the most recruitment benefit given its impact on storage, followed by Alternative 1 and Alternative 2. The success ratios can be used by managers and stakeholders to rank and evaluate the relative merits/impacts of each alternative.

3.5 Discussion

As climate change, population growth, shrinking water supplies, and new environmental demands increase the complexity of water management, we need better tools for evaluating system-wide impacts of new management strategies. My research demonstrates that system dynamics modeling can provide a more holistic approach for comparing flow alternatives based on their impact to environmental processes as well as other important basin considerations.

The predominant goal of my SD model was to provide a framework for comparing flow alternatives rather than accurately forecasting a specific ecological response to each alternative. I recognize that my approach omits other factors that influence riparian recruitment, such as geomorphic disturbance (*Richter and Richter*, 2000). When the model is used foremost as a tool for understanding relationships between basin components, it facilitates a natural transition into an adaptive management approach. Managers and stakeholders can use comparative metrics, such as the success ratio presented in this research, to justify or dispel objections related to perceived institutional or physical capacity issues, and can move forward with new operational strategies within an adaptive management framework (*Harm Benson et al.*, 2013). This is the strategy being used in the Rio Chama basin where it is difficult to break free from the management status quo.

The management implications of environmental flow alternatives are unique to every basin. The flow alternatives examined in this study face a number of challenges in the Rio Chama basin. As indicated by the model results, recruitment potential increases as more water is released from El Vado Reservoir to promote overbank flooding. Although this extra water can theoretically be stored in Abiquiu Reservoir without impacting water owners further downstream in the basin, political and physical factors make it difficult. Because Abiquiu Dam was constructed by the US Army Corps of Engineers (USACE) as a flood control project, the USACE only has the authority to store native water within the designated flood pool of the reservoir when downstream property damage is likely to occur from flooding. Therefore, even if reservoir space is available to store additional water released for environmental purposes, the USACE may be unable capture the water. Storage in Abiquiu Reservoir is further restricted by private property easements along the reservoir. Agreements made when the dam was built allow flooding of easements only during flood control operations, not to accommodate environmental flows.

Beyond the political complications of storing environmental flows in Abiquiu Reservoir, additional evaporative losses in Abiquiu also create a physical disadvantage. Any water that could be stored in El Vado Reservoir but is instead released for environmental purposes will experience greater evaporative losses when stored in Abiquiu due to the lower elevation of the reservoir. This is a drawback for any water owner that agrees to allocate a portion of their yearly volume for environmental flows.

Although not explicitly presented in this paper, other water uses within the

Rio Chama basin have been included in the SD model. Hydropower production at El Vado Dam can be evaluated for each alternative, as well as the impacts on whitewater rafting opportunities downstream of the dam. Both of these activities are economically important for the area and will be further considered as this project moves forward.

One of the strengths of SD modeling is its ability to facilitate stakeholder cooperation in water management projects. The model I presented in this study has been used to engage and encourage stakeholder involvement in the Rio Chama basin as water managers consider implementing environmental flow alternatives in the system. A collaborative workshop was held in November, 2013, to demonstrate the models capabilities and receive stakeholder feedback.

The SD modeling approach demonstrated in this paper can be applied in other basins around the world. Because the SD methodology is flexible, it can be used to represent the unique management challenges present in every river system. As managers strive to balance economic, ecological, and social needs in their basin, SD modeling provides an excellent way to evaluate the connections between basin components and the relative impacts of various flow alternatives.

Chapter 4

Spatial Bayesian Network Modeling of Riparian Recruitment

4.1 Introduction

The sustainable management of our water resources needs to include consideration of management impacts to aquatic and riparian ecological processes (*Arthington et al.*, 2010). It is clear that water diversions (*Shiau and Wu*, 2004), reservoir operations (*Moore et al.*, 2012), energy production (*Babel et al.*, 2012), and other management activities can alter the natural hydrologic characteristics of a river. Changes to the natural flow regime of a system can cause negative impacts to aquatic and riparian ecological processes (*Poff et al.*, 1997).

Bayesian networks (BNs) are increasingly being used to evaluate environmental consequences of water management (*Shenton et al.*, 2013, 2011; *Leigh et al.*, 2012; *Stewart-Koster et al.*, 2010; *Chan et al.*, 2012; *Gawne et al.*, 2011). Because BNs are able to explicitly include system uncertainty through probabilistic representations of interactions (*Uusitalo*, 2007), utilize various sources of information (including expert opinion) (*Uusitalo*, 2007), and represent ecological processes within a mechanistic framework (*Catford et al.*, 2013), they are ideal for assessing responses of complex ecological systems to human activities. In addition, the graphical interface and simple schematics of many BN models make them useful in participatory management planning (*Castelletti and Soncini-Sessa*, 2007).

A noted limitation of the BN modeling approach has been its inability to consider spatial factors within a system (*Shenton et al.*, 2011; *Hart and Pollino*, 2009). Static BNs are unable to consider spatial changes in variable values across a system due to their acyclic framework and consequent inability to model feedback loops (*Hart and Pollino*, 2009). As a result, single BN models are typically applied to evaluate large geographic regions (e.g. (*Leigh et al.*, 2012; *Ticehurst et al.*, 2007)) without consideration of small-scale spatial variables that may influence environmental processes. Some work has been done to implement BNs across spatial domains (*Smith et al.*, 2011; *Rains et al.*, 2004) but at resolutions that are too coarse for many ecological applications.

My research objective was to assess the spatial impacts of water diversions on key ecological processes within a river. To meet this objective I coupled two-dimensional hydrodynamic and BN modeling frameworks in order to explicitly account for effects of small-scale spatial variability on ecological systems. Specifically, I focused on the implications of water diversion scenarios on cottonwood and willow species recruitment potential on the Gila River, New Mexico, USA. Hydrologic and topographic variables were described by two-dimensional modeling of select sites on the Gila River. A BN model for riparian vegetation recruitment was implemented on a grid cell-by-cell basis using the descriptions of the variables and topographic mesh (approximately 1 m^2 resolution) produced with the two-dimensional model.

This work demonstrates the unique benefits of combining fine-scale hydrodynamic and BN models when evaluating ecological responses to water management alternatives. These benefits include a detailed consideration of topographic and hydrologic variability on the riparian recruitment process, visual representation of model results that facilitate the identification of worst impacted areas, and more informed implications of water management scenarios.

4.2 Study Area and Diversion Scenarios

4.2.1 Upper Gila Basin Characteristics

The Gila River drains approximately 212,380 km^2 of southwestern New Mexico and southern Arizona. Originating in the Mogollon Mountains along the Continental Divide in New Mexico and emptying into the Yuma River, the basin encompasses a wide variety of climate regions ranging from arid to sub-humid (*Hawley et al.*, 2000). The upper Gila basin, the location of my study sites (Figure 4.1), comprises nearly 34,000 km^2, half of which is located in New Mexico.

The hydrology of the upper basin is determined primarily from mountain snow melt and monsoon thunderstorms which occur from July to September (*Hawley et al.*, 2000). Snow accumulation in the high elevation of the upper basin headwaters provide the predictably highest mean discharge during March (Figure 4.2). The lowest flows occur between late June and early July, followed by a period of higher flows and variability through September caused by the North American Monsoon (*Gutzler*, 2000). October through February produces large hydrologic variability due to large infrequent winter storm events.

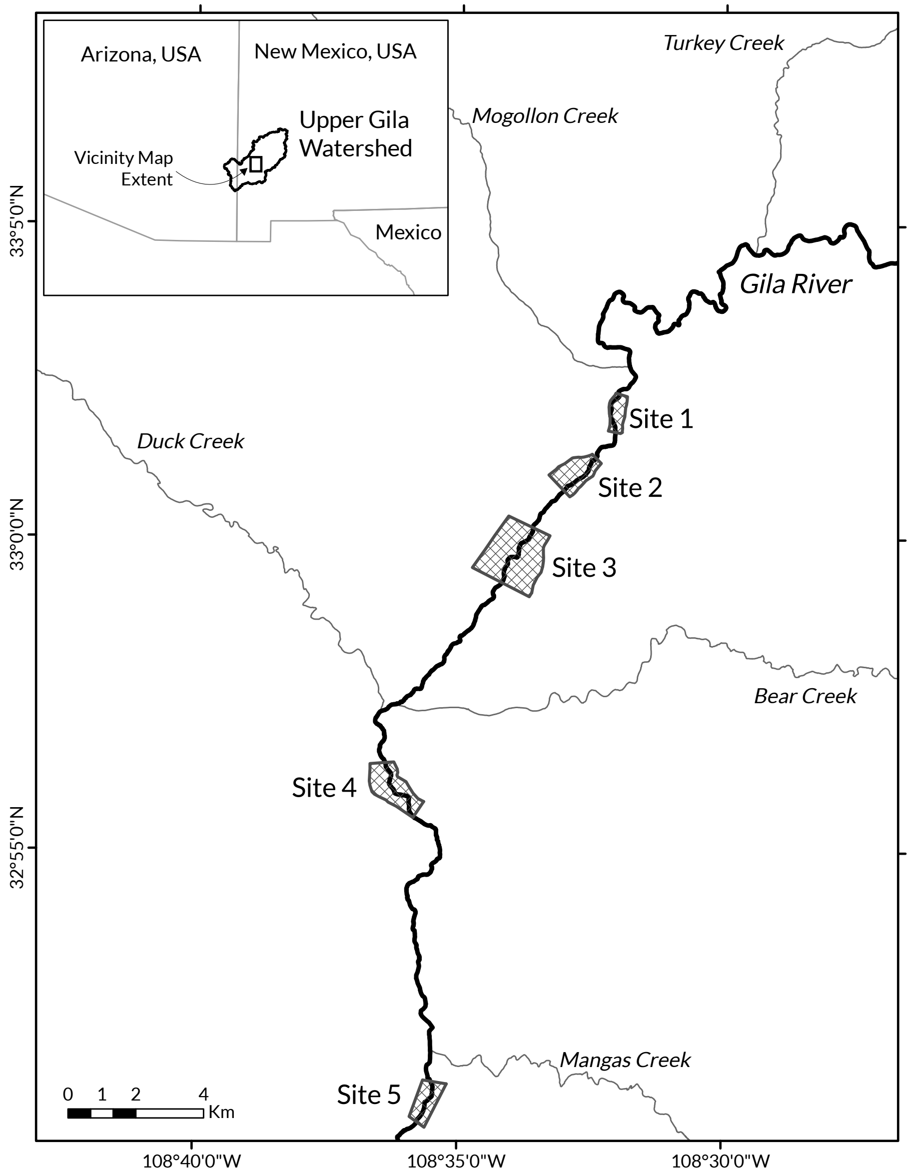

Figure 4.1: Vicinity map of the upper Gila basin and locations of the five research sites used in this study.

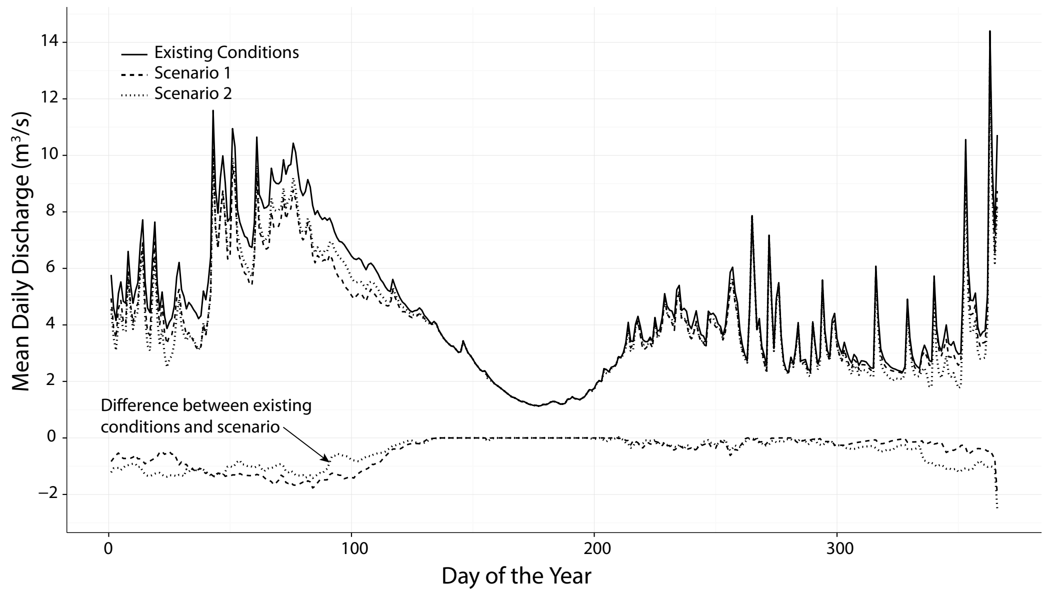

Figure 4.2: Mean daily discharge for existing conditions and the diversion scenarios between August 30, 1935 and August 6, 2013. Data for existing conditions originated from USGS gage 09430500 (Gila River at Gila). Also illustrated are the mean daily differences in discharge between existing conditions and each scenario.

4.2.2 Diversion Scenarios

The majority of the Gila River watershed is located in Arizona and is an important component of the Central Arizona Project, which provides irrigation and consumptive water throughout the state. The upper Gila watershed, half of which is located in New Mexico, is comparatively undeveloped except for local agricultural withdrawals. However, recent judicial decisions have entitled New Mexico to develop 1,730 hectare-meter (14,000 acre-feet) per year of water from the upper Gila watershed as part of the Arizona Water Settlement Act of 2004. Although New Mexico has not determined how the water will be developed, one possible outcome is a diversion project that captures water from the Gila River and transports it to other water users in the region.

My work focuses on the impacts of two diversion scenarios that are under consideration by the state of New Mexico (Table 4.1). Under scenario 1, water is diverted from the river until the 1,730 hectare-meter limit is reached for the year. However, when the river discharge is less than 4.25 $m^3 s^{-1}$ (150 $ft^3 s^{-1}$), withdrawals cease until a future date when the flow rate is greater than 4.25 $m^3 s^{-1}$. Scenario 2 follows the same diversion requirements as scenario 1 but does not have a minimum flow requirement that restricts withdrawals; water is allowed to be diverted regardless of the river discharge. The specific quantities and timing of withdrawals under each scenario depend on complex terms described in the New Mexico Consumptive Use and Forbearance Agreement (online at `http://www.ose.state.nm.us/PDF/ISC/BasinsPrograms/GilaSanFrancisco/Final-CUFA-Oct27-2005.pdf`). The time series for each scenario were developed by The Nature Conservancy (TNC) in 2013 as part of a larger collaborate effort to evaluate the environmental impacts of the flow diversions. TNC developed the scenario hydrology by estimating daily diversion volumes as stipulated by CUFA and modifying the historical flow records from 1937–2012. I compared the impacts of each scenario to the historic daily hydrology based on USGS records from 1937–2012 from gage 09430500 (online at `http://nwis.waterdata.usgs.gov`).

Table 4.1: Descriptions of each diversion scenario evaluated in the study

Scenario	Description
Existing Conditions	Historical hydrology between August 30, 1935 and August 6, 2013 according to USGS gage 09430500
Scenario 1	Modified historical hydrology with no diversions when discharge is less than 4.25 $m^3 s^{-1}$
Scenario 2	Modified historical hydrology with no minimum flow requirements

4.3 Modeling Framework

I used a combination of two-dimensional hydrodynamic and BN modeling to assess the impact of each scenario on cottonwood and willow recruitment within each research site. The hydrodynamic models were used to determine the discharge at which locations within the research sites are initially inundated, as well as develop stage-discharge curves for each site. The inundation discharges and stage-discharge curves were used in conjunction with the hydrologic time series of each scenario to instantiate the BN with flooding and recession rate evidence. Figure 4.3 shows the framework of this modeling approach.

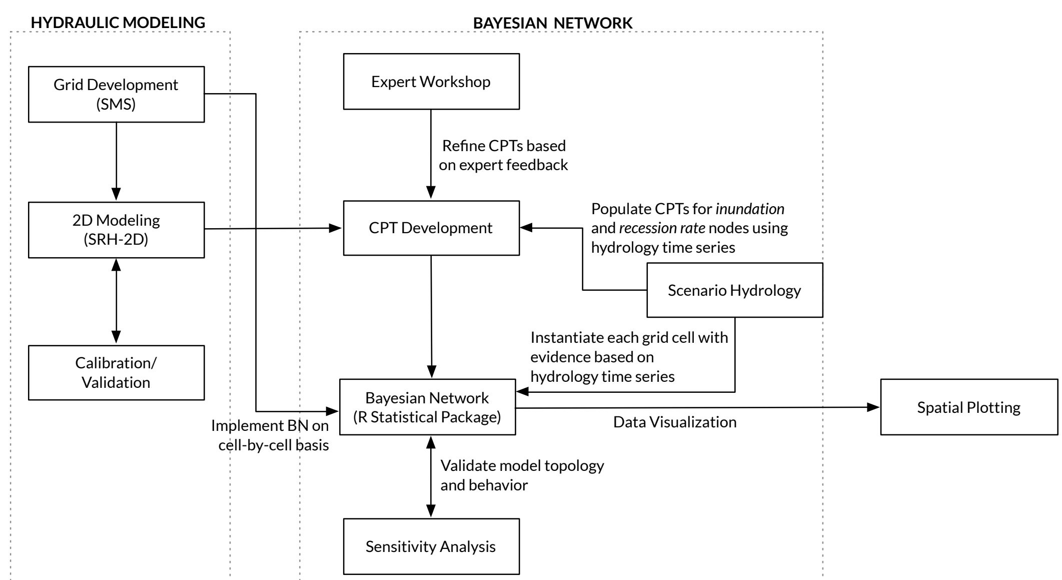

Figure 4.3: Schematic of modeling framework. Results from two-dimensional hydraulic modeling were used to instantiate the Bayesian network for each grid cell within each research site.

4.3.1 Two-dimensional Hydrodynamic Model

Spatial hydrodynamic models were developed for each site using the Sedimentation and River Hydraulics–Two Dimensional Model (SRH–2D) (*Lia*, 2008). SRH–2D is a numeric model capable of solving the fully dynamic Saint-Venant equations for two-dimensional and unsteady flow. Detailed descriptions of the topography, surface roughness, and boundary conditions were necessary to construct each model. A topographic mesh with a 1 m resolution was constructed for each site using the Surface-water Modeling Solution (SMS) software package, version 11.0 (*Aquaveo, LLC*, 2013) and Lidar data collected in April 2009 by the New Mexico Interstate Stream Commission. The mesh contained a combination of rectangular elements to describe the main channel and triangular elements to represent the floodplain and areas of complex terrain. Roughness values for each grid cell were assigned a Manning's n-value based on field observations and aerial imagery. Upstream and downstream boundary conditions were established using results from a one-dimensional hydraulic model of an approximate 32 km river reach that included all five research sites. The one-dimensional model was built with the Hydrologic Engineering Center–River Analysis System (HEC-RAS), version 4.1 (*US Army Corps of Engineers*, 2010).

Simulations were performed for twelve flow rates at each site, resulting in sixty unique simulations. Each simulation required approximately 20 hours of processing time to complete.

4.3.2 Bayesian Network Model

Bayesian Principles

BNs are graphical models that use directed arcs to connect nodes that represent system variables. The arcs indicate direct dependencies between variables, and the strength of the dependencies between variables is described by conditional probabilities (*Korb and Nicholson*, 2011). Because the connecting arcs can only pass information in one direction, BNs can also be referred to as directed acyclic graphs. Nodes in a BN can represent discrete or continuous properties of a variable. In the case where node values are discrete, they must be mutually exclusive (represent only one discrete state at a time) and exhaustive (represents the full range of possible values) (*Korb and Nicholson*, 2011). A child node has an arc connecting it to one or more parent nodes higher in the network.

Information is propagated between variables in the network according to Bayes' rule (*Gelman et al.*, 2004):

$$p(\theta|y) = \frac{p(\theta)p(y|\theta)}{p(y)} \tag{4.1}$$

where $p(\theta|y)$ is the posterior probability (the probability of θ after information about y), $p(y|\theta)$ is the likelihood function, $p(\theta)$ is the prior probability, and $p(y)$ is the sum of all joint distributions for θ and y. For discrete variables, Bayes' rule can be represented by conditional probability tables (CPTs) (*Korb and Nicholson*, 2011).

My process for developing a BN for riparian vegetation recruitment followed the recommendations of *Marcot et al.* (2006) when applicable. I first developed a conceptual model of the recruitment process based on scientific literature with particular emphasis placed on cottonwood recruitment in arid river systems. Next, I converted my conceptual model to a BN and populated the CPTs using literature. After the construction of the BN I sought feedback from riparian ecologists in order to refine the model structure and CPT values. Unfortunately, case study data does not exist for my research sites, so I validated the model topology and behavior using sensitivity analyses. Finally, I fully implemented the BN to assess the impact of each management scenario on recruitment potential.

Conceptual Framework

My conceptual understanding of the recruitment process was primarily based on the "recruitment box" model described by *Mahoney and Rood* (1998), which has successfully been used to predict recruitment in numerous systems (*Rood et al.*, 2005). The recruitment box model asserts that a combination of hydrodynamic conditions are necessary for the successful recruitment of cottonwood seedlings (*Populus* species), most notably the timing of floodplain inundation, river stage recession rate, and availability of groundwater. According to *Mahoney and Rood* (1998) ideal recruitment conditions occur when overbank flooding takes place shortly after seed dispersal, typically late spring to early summer. Seedling roots must maintain contact with moisture after germination, limiting the recession rate of the hydrograph after a flooding event and requiring adequate contact with shallow groundwater. The concurrence of these criteria are episodic even under natural conditions, leading to stands of equal-aged trees (*Braatne et al.*, 2007). Willow seedlings (*Salix* species) have similar phenology requirements (*Shafroth et al.*, 1998; *Amlin and Rood*, 2002). I determined the preferred range of conditions for various recruitment drivers based on scientific literature, especially studies pertinent to arid environments (Table 4.2).

Table 4.2: Preferred conditions for dominant drivers of cottonwood recruitment

Driver	Preferred Conditions	Reference
Inundation timing	April–May; recruitment can occur into early summer if seeds are available during the inundation event	*Shafroth et al.* (1998); *Patten* (1998); *Stella et al.* (2006)
Recession rate	0–3 cm/day; rates up to 6 cm/day can provide adequate contact with water depending on soil conditions. I chose to use a 14-day recession rate although the literature is not clear on the most appropriate time period	*Amlin and Rood* (2002); *Mahoney and Rood* (1998); *Stella et al.* (2010); *Braatne et al.* (2007)
Groundwater depth	50–200 cm below ground surface; lower elevations are at risk for scour, higher elevations at risk for dessication	*Scott et al.* (1997); *Stromberg et al.* (1996); *Mahoney and Rood* (1998)

Network Topology

I used the conceptual framework to construct a BN model that linked the dominant drivers of the riparian recruitment process (Figure 4.4). Each driver represented a node in the network, and each node was split into discrete states based on my conceptual understanding of the recruitment process. The number of discrete states for each node were chosen so the full range of possible values for the node could be captured while limiting the computational requirements of the network. The *hydrologic conditions* node represented the combined hydrologic influence of the *inundation* and *recession rate* nodes. The *recruitment potential* node represented the ecological endpoint of the model, and used *groundwater depth* and *hydrologic conditions* as parent nodes.

Prior probabilities for the nodes were described by CPTs that specified the probability of a particular state given all the possible combinations of states for a parent node. The CPTs for the *inundation* and *recession rate* nodes were populated using the hydrologic time series for each scenario. The *inundation* node was split into bins ranging from 28 $m^3 s^{-1}$ to 113 $m^3 s^{-1}$ (1000 to 4000 $ft^3 s^{-1}$) in 14 $m^3 s^{-1}$ increments. The bins were required to account for differences in flood frequencies at different elevations within each site. I calculated the conditional probabilities (dependent on the *timing* node) of each discrete state within the *recession rate* node, as well as for each discrete state for each bin of the *inundation* node.

Scientific literature and expert consultation were used to determine the prior probabilities of the remaining nodes. A workshop of riparian ecological experts in January, 2014 was used to refine the CPTs. A complete set of CPTS for the BN can be found in the supplemental material.

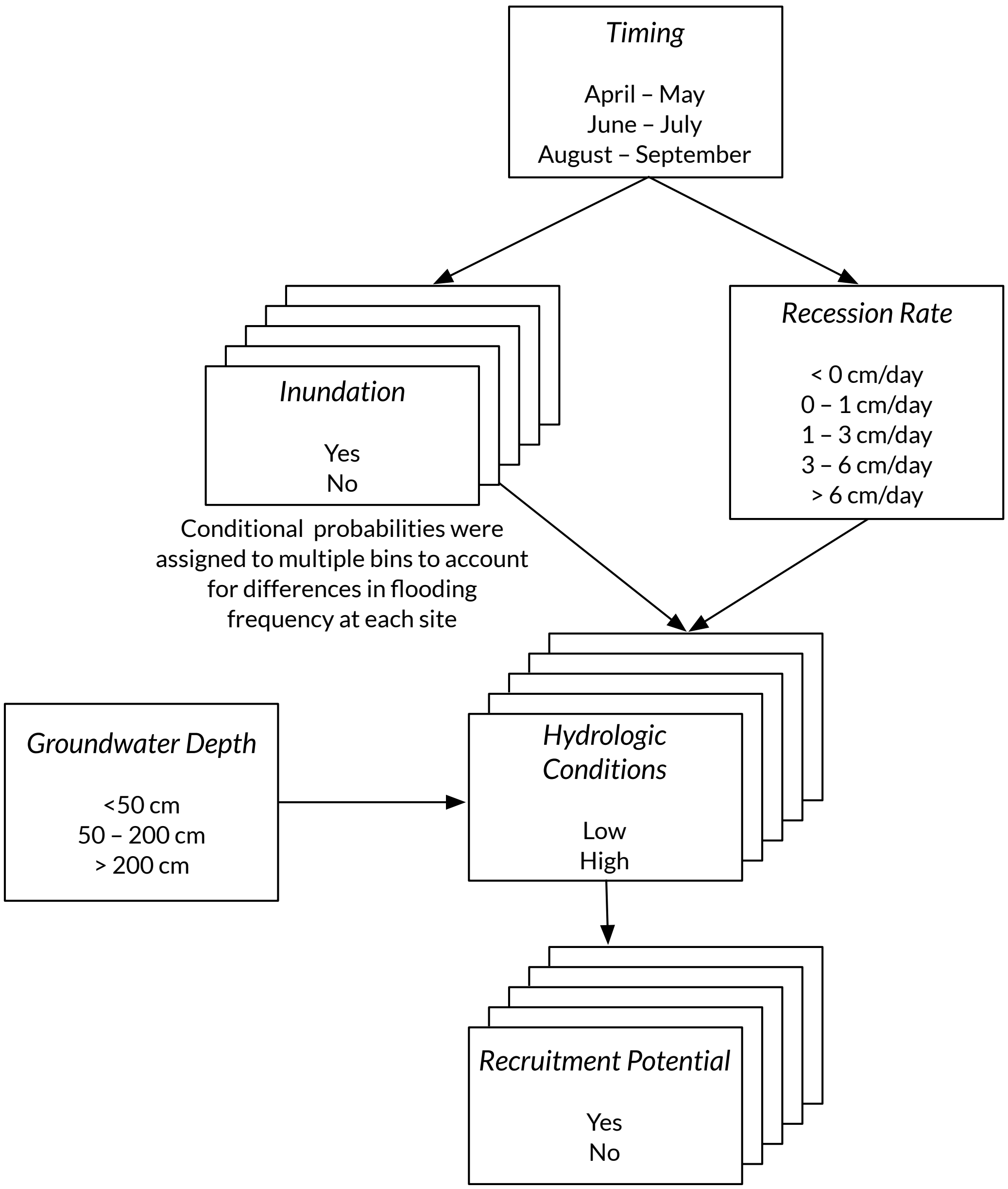

Figure 4.4: Bayesian network of important hydrologic drivers for riparian recruitment. The discrete state of each node is listed below the node name.

Network Implementation

The BN was written and implemented using the bnlearn package (*Nagarajan et al.*, 2013) and the R software package (*R Core Team*, 2013). Posterior probabilities for *recruitment potential* were calculated on a cell-by-cell basis using on the computational mesh developed for the hydrodynamic model. The *timing*, *inundation*, and *recession rate* nodes were instantiated for each grid cell using the discharge time series of each scenario. Approximate solutions for posterior probabilities were calculated using stochastic sampling and the likelihood weighing algorithm described by *Korb and Nicholson* (2011). Approximately 25,000 samples were used to calculate posterior probabilities at each grid cell.

I performed an entropy reduction analysis to quantify the influence of each node on the posterior probability for recruitment potential and confirm my conceptual framework of the recruitment process. Entropy reduction analyses, commonly used to evaluate BN structures (*Pollino et al.*, 2007), measure how much the uncertainty within a network is reduced after gaining information regarding the state of a particular node (*Korb and Nicholson*, 2011). The entropy of a variable can be calculated as (*Korb and Nicholson*, 2011):

$$H(Q) = -\sum_{q} P(q)\log_2 P(q) \tag{4.2}$$

where $H(Q)$ is the entropy of variable Q (using base–2 logs).

Using the definition of mutual information (*Korb and Nicholson*, 2011), the entropy reduction was calculated as follows (*Marcot*, 2012):

$$I = H(Q) - H(Q \mid F) = \sum_{q}\sum_{f} \frac{P(q,f)\log_2\left[P(q,f)\right]}{P(q)P(f)} \tag{4.3}$$

where I is the entropy reduction, $H(Q)$ is the entropy of variable Q without any additional information and $H(Q|F$ is the entropy of variable Q after introducing new information about variable F.

The results from the entropy analysis (Table 4.3) were consistent with my understanding of the conceptual model. The occurrence of surface inundation has the largest impact on recruitment, followed by the recession rate. The *hydrologic conditions* node had the strongest influence on recruitment because it was linked to both inundation and recession rate. Although I did not have field data to validate the model, the entropy analysis demonstrated that the network's topology and behavior agreed with my expectations.

Table 4.3: Results of an entropy analysis to determine the sensitivity of recruitment potential on nodes higher in the network. Higher entropy reduction values indicate a greater influence the recruitment potential node.

Node	Entropy Reduction
Hydrologic conditions	0.006777
Inundation	0.006072
Recession rate	0.000631
Timing	0.000358
Groundwater depth	0.000167

During the development of the model I discovered that the number of instantiations for some cells was reduced under each scenario. Often the eliminated instantiations resulted in high posterior probabilities for recruitment potential because they represented lower quality events (e.g. greater recession rates that are less likely to result in recruitment. A reduction in recruitment events will clearly have a negative impact on the recruitment process, however, so I used a utility function that reduced the posterior probabilities of recruitment potential for cells at which the number of events were decreased. I used a linear function that reduced the posterior probability at each cell by the percent change in instantiations when compared to existing conditions.

4.4 Results

The coupling of two-dimensional hydrodynamic models and BN models allowed us to examine the impacts of each scenario on recruitment potential across different scales. By aggregating the results from each grid cell I can assess the influence of scenarios on posterior probabilities of recruitment potential at reach-wide scales. In addition, due to the fine resolution of the mesh used to implement the BN, I can examine spatial distributions of recruitment potential and identify specific landforms within a site that may be particularly impacted by diversions.

Aggregated Impacts

The median posterior probability of recruitment potential under existing conditions ranged from approximately 0.3 to 0.7 (Figure 4.5). The mean posterior probability values were generally larger than the median indicating the distribution of probabilities is skewed toward higher values. The highest probabilities occurred at site 2; the remaining sites showed similar probabilities.

Both diversion scenarios decreased the recruitment potential at all sites (Figure 4.5). Scenario 1 caused the largest declines in recruitment potential (Figure 4.6). Posterior probabilities were reduced by up to 9.5% under scenario 1 and 4.5% under scenario 2.

Distributions of posterior probability differences between existing conditions and the scenarios further reveal the impacts on each site (Figure 4.7). Most cells experienced a decrease in probability between 0% and 10% under both scenarios. The distribution of cells under scenario 2 is more skewed toward a 0% decrease and rarely includes cells with greater than 20% decreases in recruitment potential. Interestingly both scenarios produce some cells with an increase in recruitment potential. Even though the overall impacts of both scenarios are an overwhelmingly decrease in recruitment potential, it is possible that some areas within each site will see a bump in recruitment depending on the interaction between the hydrology and the particular topographic features in those areas.

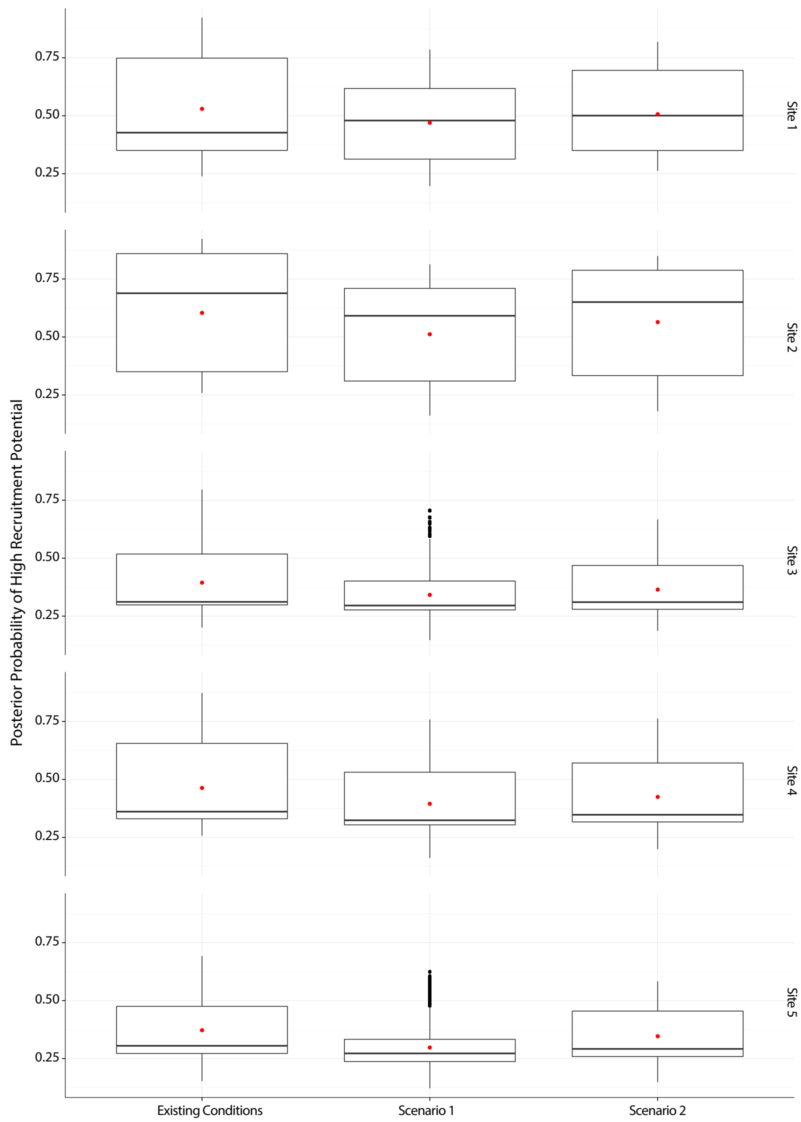

Figure 4.5: Box plots of posterior probabilities of recruitment potential for each site under the different scenarios. The bottom of the boxes represent the 25th percentile and the top of the boxes represent the 75th percentile. The line through the box represents the median value and the colored dot indicates the mean. Error bars above and below the boxes represent the 90th and 10th percentiles, respectively.

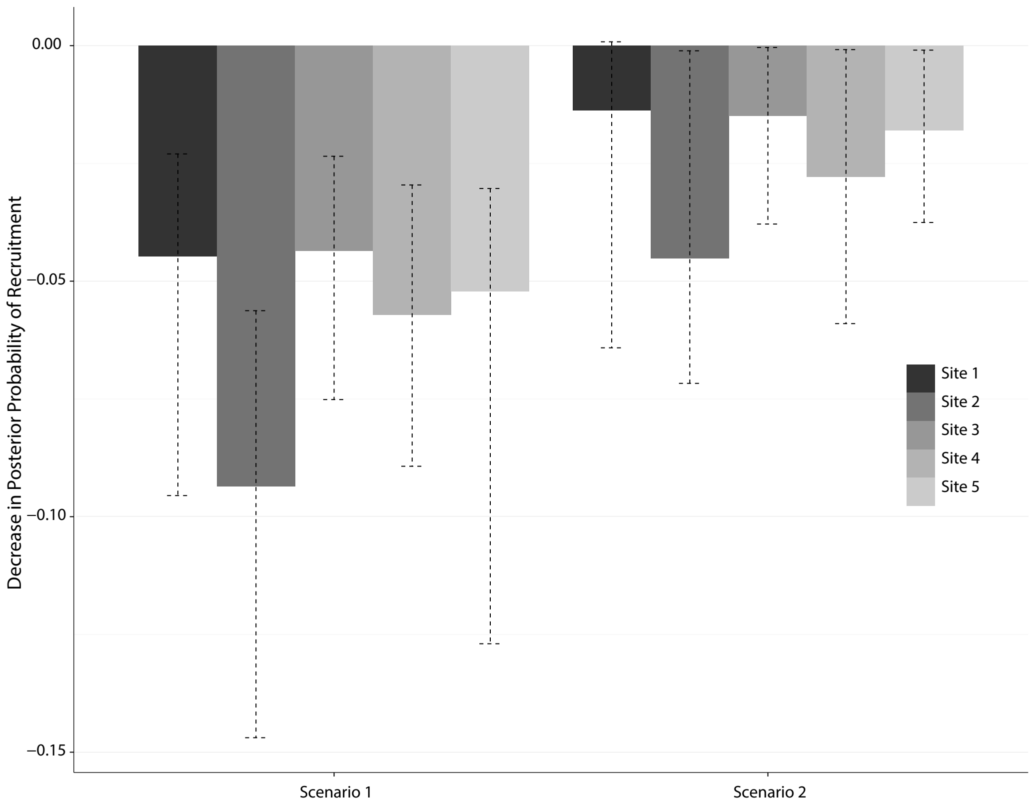

Figure 4.6: Decreases in posterior probabilities of recruitment potential. The bars represent median values, and the lines represent 25th and 75th percentiles.

The scenarios altered the hydrologic characteristics necessary for riparian recruitment differently depending on the time period. As shown in Table 4.4, the number of BN instantiations decreased for both scenarios during the April-May and August-September time periods. Scenario 1 caused overall greater decreases in the number of recruitment events when compared to scenario 2. However, the April-May time period contained fewer overall instantiations; the majority of recruitment events occurred during the August-September time period. The scenarios did not cause any change in the mean number of instantiations during June-July.

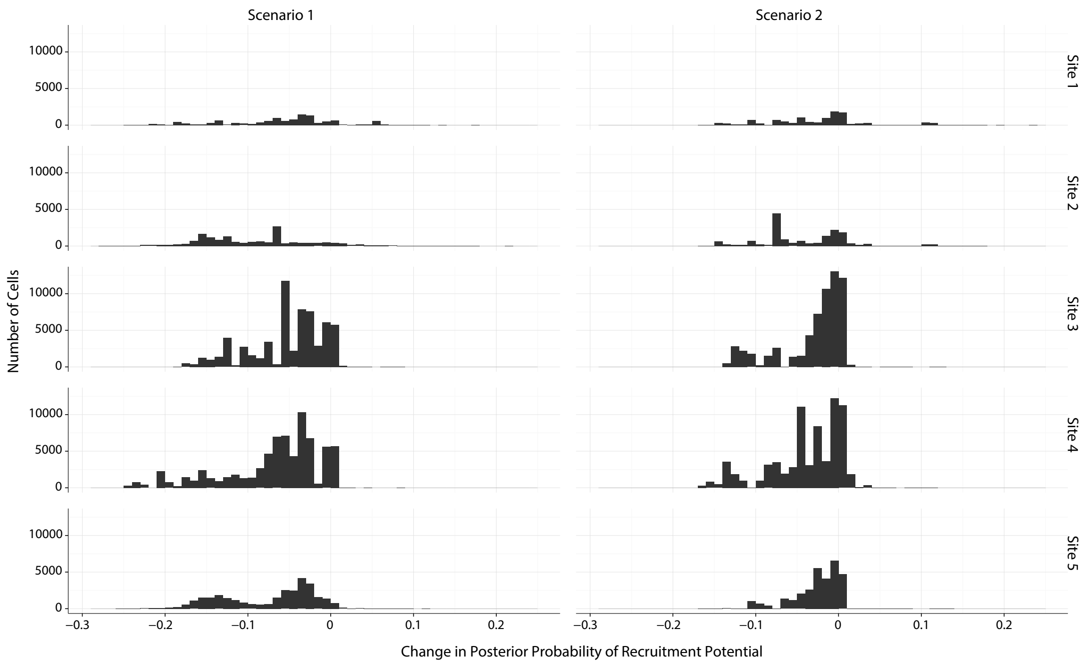

Figure 4.7: Histogram of the difference posterior probabilities of recruitment potential for all grid cells used to implement the BN model.

Table 4.4: Mean decrease in the number of instantiations for each scenario. Numbers in parenthesis indicate the mean number of instantiations. Values are averaged across all grid cells and all sites.

	April–May	June–July	August–September
Scenario 1	25.8% (1.28)	0% (0.16)	10.3% (10.9)
Scenario 2	2.29% (1.69)	0% (0.16)	9.1% (11.1)

Spatial Impacts

My implementation of the BN model on a cell-by-cell basis allowed us to spatially examine the impacts of each scenario. Figure 4.8 demonstrates this by showing spatially distributed results for sites 3 and 4. Although it is clear that scenario 1 produces a greater decrease in recruitment potential than scenario 2 at both sites, the spatial representation of the results reveals areas most impacted by each scenario. Recruitment potential in abandoned side-channels, backwater areas, and in the floodplain near the main channel are particularly decreased by the diversion alternatives.

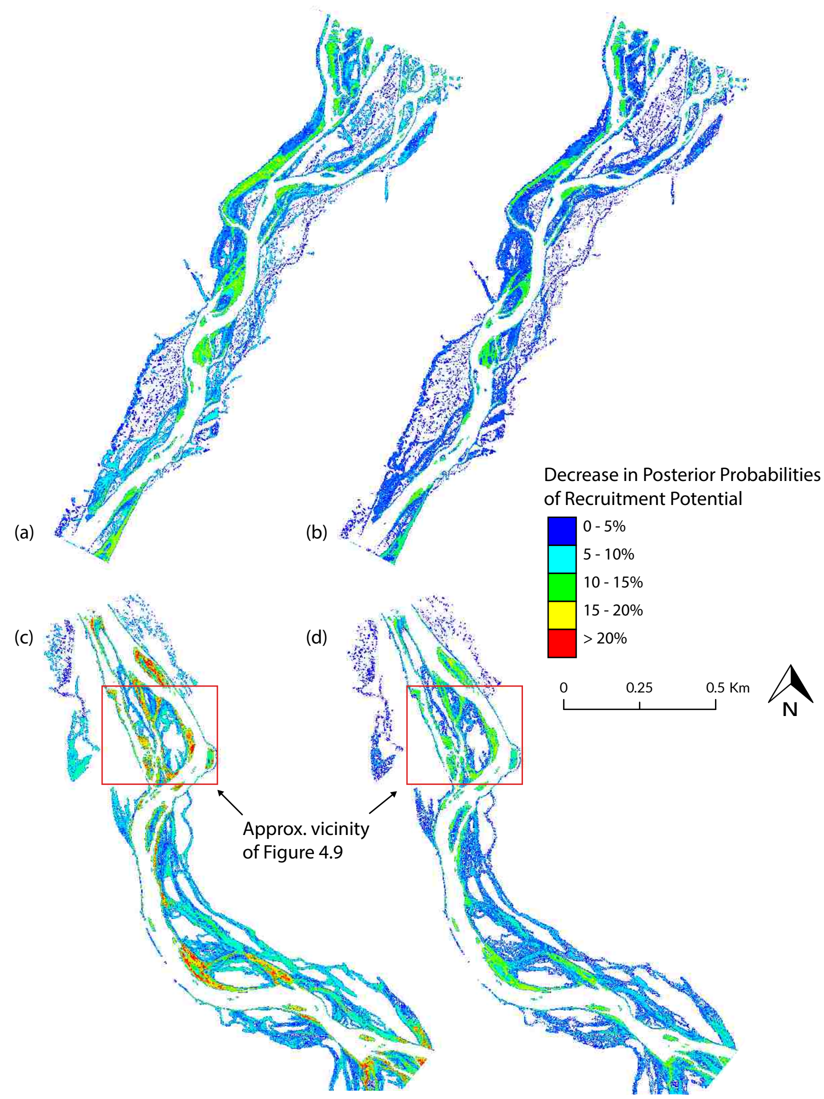

Figure 4.8: Spatial distribution of changes in recruitment potential for a) site 3, scenario 1; b) site 3, scenario 2; c) site 4, scenario 1; and d) site 4, scenario 2. The main channel is the wide white swath in the middle of each plot. The recruitment potential is clearly more impacted by scenario 1 at both sites.

A closer examination of the spatial distribution at site 4 shows the advantage of combining fine-resolution hydrodynamic models with BNs. Side channels and sand bars where recruitment potential has been reduced are clearly evident (Figure 4.9), and the differential impacts of each scenario are pronounced.

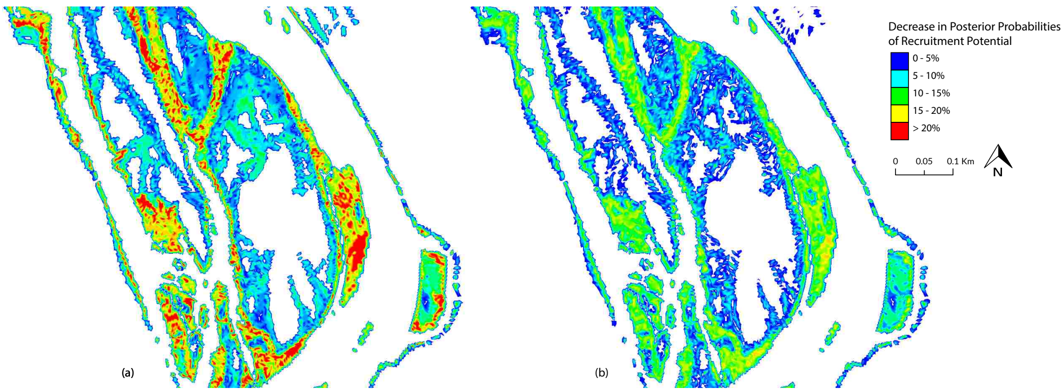

Figure 4.9: Detailed spatial distributions of recruitment potential for a) site 4, scenario 1; and b) site 4, scenario 2. The main channel is the wide white swath on the right side of each plot.

4.5 Discussion

4.5.1 Benefits of Modeling Approach

My work to evaluate the impacts of hydrologic alterations on cottonwood/willow recruitment addresses a hitherto limitation of BN modeling—incorporating spatial variability within a BN framework (*Hart and Pollino*, 2009; *Shenton et al.*, 2011). By using a combination of two-dimensional hydrodynamic and BN modeling I were able to spatially assess the consequences of diversion alternatives on riparian vegetation recruitment. This approach has numerous advantages for examining water management impacts on recruitment processes.

By using a BN framework my imprecise and incomplete understanding of the recruitment process was explicitly captured in the model, as well as uncertainties related to stochastic conditions that influence recruitment. Successful riparian recruitment depends on complex interactions between hydrology patterns, site conditions, seed availability, groundwater availability, and community competition. Describing this process using correlative models is extremely difficult, especially given our incomplete knowledge of the process. My approach takes advantage of the strength of BNs to incorporate uncertainty and other sources of knowledge, such as expert opinion (*Varis*, 1995). As more information becomes available about the system, such as a more accurate understanding of seed dispersal timing, conditional dependences within the network can be updated (*Pollino et al.*, 2007). In addition, *Catford et al.* (2013) argues that causal models, such as the BN used in my study, are preferable over correlative models when evaluating changes to environmental processes because they incorporate ecological mechanisms and cause-effect relationships that are likely to stay valid under changing conditions.

Previous efforts to assess impacts of streamflow alterations on riparian species were unable to capture spatial impacts (e.g. population dynamic models such as *Lytle and Merritt* (2004) and community models such as *Auble et al.* (2005)). Because my approach provides a spatial distribution of management impacts it is useful for understanding possible the hydrogeomorphic impacts, as well. *Wilcox and Shafroth* (2013) showed that vegetation-hydrogeomorphic feedbacks vary spatially, and that spatial variations in vegetation and geomorphic characteristics are important for understanding channel-forming processes. Changes in flow patterns, as proposed by the scenarios in the Gila River, can shift population dynamics and community structures toward non-native species, which can lead to channel narrowing and reduced scour (*Birken and Cooper*, 2006). By understanding which landforms are most susceptible to recruitment reductions, the geomorphic responses and vegetation-hydrogeomorphic implications of each scenario can be better assessed.

Within management discussion forums, a spatial representation of model results allows for a visual examination of diversion impacts. I have found this helpful for water managers and stakeholders in the Gila River basin as they consider the repercussions of each diversion scenario on riparian communities. Mapping areas that are most impacted by the scenarios facilitates dialogue and helps managers and stakeholders understand possible management impacts.

I recognize various limitation to my approach, as well. Although a benefit of my method is the inclusion of expert opinion when field or experimental data are unavailable, this is also a caveat of using a causal modeling framework such as a BN. Without field data I am restricted to validating the model's representation the riparian process using other techniques, such as information reduction analysis (*Pollino et al.*, 2007). However, as data become available through continued research efforts on the Gila River, the BN can be updated to reflect actual conditions on the ground.

In addition, my approach did not explicitly include geomorphic disturbance as a recruitment driver. Flooding events scour land surfaces and deposit fresh sediment for seedling establishment (*Scott et al.*, 1997). Flooding also promotes channel migrations and meander cutoffs, creating secondary channels and other fluvial landforms that are ideal for riparian vegetation colonization (*Richter and Richter*, 2000). My model included the *groundwater depth* node as proxy indicator of scour impacts due to flooding. The discrete states associated with the *groundwater depth* node ($<$ 50 cm, 50–200 cm, $>$ 200 cm) correspond to topographic heights above summer baseflows in which successfully established seedlings are likely to be found located. According to (*Mahoney and Rood*, 1998), seedlings located 50–200 cm above summer baseflow are the most likely to survive recruitment; seedlings located at lower elevations tend to be scoured by high flows and seedlings located at higher elevations are unable to maintain contact with groundwater.

An improvement of my approach could be the use of dynamic modeling. Dynamic BN modeling allows for updating conditional probabilities associated with a node as network conditions change over time (*Nagarajan et al.*, 2013). A dynamic BN approach for assessing impacts to recruitment would be useful for considering the roles of geomorphic disturbance and vegetation-hydrogeomporphic feedback loops, which are difficult or unfeasible with my static BN technique.

4.5.2 Riparian Vegetation Implications

Cottonwood recruitment is naturally episodic (*Mahoney and Rood*, 1998). A reduction in recruitment potential caused by both diversion scenarios, as indicated by my results, will further limit recruitment opportunities of cottonwoods and willows in the Upper Gila, possibly leading to population declines and die-offs (*Rood et al.*, 2003b).

Implementation of the diversion scenarios may lead to increased risk of invasive riparian species, especially *Tamarix* species (*Tamarix ramosissima* and hybrids). Estimated to be the third most abundant woody plant in the western United States (*Friedman et al.*, 2005), *Tamarix* is a non-native species introduced from Asia in the late 1800s to control erosion (*Stromberg et al.*, 2007). The Gila River in the upper basin currently does not contain a significant population of *Tamarix*. However, streamflow alterations have been shown to promote *Tamarix* invasion (*Stromberg et al.*, 2007). Changes in flow characteristics produced by the diversion scenarios, particularly reductions in flow inundation, may allow invasive species to establish along riparian areas. Both scenarios reduce recruitment events more significantly during the late spring/early summer than during other times of the recruitment period. Because *Tamarix* seed dispersal occurs throughout the entire summer (*Glenn and Nagler*, 2005), as opposed to native cottonwood and willow seed releases during the late spring, the reduction in spring events may limit native recruitment in favor of non-native species with seeds available later in the summer.

A increase in *Tamarix* populations could have geomorphic and hydrologic consequences on the river. *Birken and Cooper* (2006) found that channel landforms quickly stabilized following the introduction of *Tamarix* in the lower Green River, Colorado. In-channel sandbars and islands were especially susceptible to *Tamarix* colonization following multiple low-flow years. Geomorphic hardening of channel landforms would lead to decreases in sediment transport and channel migration. Channel narrowing has also been shown to coincide with *Tamarix* establishment (*Birken and Cooper*, 2006; *Everitt*, 1998), although the direct influence of *Tamarix* on channelization is still debated (*Reynolds et al.*, 2014). In addition, *Tamarix* colonization often produced greater evaporation-transpiration (ET) water losses due to expansion of riparian areas (*Hultine and Bush*, 2011), especially for lower order streams (the Gila River is a 5th order system occurring to (*Blinn and Poff*, 2005)). Greater ET loses reduces the amount of water available for other ecohydrologic processes in the river.

4.6 Conclusion

I combined two-dimensional hydrodynamic and BN modeling frameworks to assess the impacts of water diversions on riparian vegetation recruitment on the Gila River, New Mexico. This unique approach allowed us to evaluate the consequences of two diversion scenarios on recruitment potential at a fine spatial scale, which not only helps differentiate impacts at individual fluvial landforms, such as side channels and sand bars, but facilitates discussions of management implications. I found a stark difference in impacts between the two proposed diversion scenarios; scenario 1, which restricts diversions when river flows are less than 4.25 $m^3\,s^{-1}$ (150 $ft^3\,s^{-1}$) resulted in higher reductions in recruitment potential compared to scenario 2. However, both scenarios reduced the overall likelihood of recruitment on the Gila River, making the system more vulnerable to non-native vegetating establishment. My results demonstrate that even small hydrologic alterations in rivers can have negative ecological implications.

Chapter 5

Conclusion

Conventional water resource management tools are have difficulties accounting for many of the challenges facing water management. Most tools are deterministic, which makes them inadequate for assessing natural and climate change-induced variability. In addition, they seldom can evaluate the tradeoffs of management decisions for a wide variety of system components, such as hydropower, recreation, and environmental needs. In fact, environmental needs rarely are an explicit part of today's water management tools.

My research addresses these limitations using two approaches. First, I used stochastic system dynamics modeling to assess the impact of water management alternatives on ecological processes and other components of a basin. Second, I used Bayesian network modeling to spatially evaluate the consequences of management alternatives on ecological health. Both of these approaches are novel because they incorporate uncertainty analyses within a holistic water management framework, or combine spatial variability with Bayesian techniques.

5.1 Objective Summaries

Specifically, I have completed the following three objectives in this research:

1. Evaluate the impacts of environmental flow alternatives on other water users within a complex managed basin using stochastic system dynamics modeling
2. Assess the benefits of environmental flow alternatives on select ecological processes using stochastic system dynamics modeling
3. Demonstrate the unique benefits of combining fine-scale hydrodynamic and Bayesian network models when assessing ecological responses to water management alternatives

Each objective is described in stand-alone chapters of this dissertation. A description of each chapter and its results are summarized below.

5.1.1 Chapter 1

System dynamics (SD) modeling can be an effective method for exploring water resource problem and management alternatives. However, few studies have demonstrated an effective application of an SD approach to investigating water resource issues, especially while incorporating system uncertainty. Thus, this objective demonstrated the use of SD modeling to evaluate the impacts of environmental flow recommendations on other water users within a managed basin. I developed an SD model to assess environmental flow alternatives in the Rio Chama basin, New Mexico, with input from stakeholders, agency managers, and environmental and legal experts. Based on the advice from a collaborative workshop, three flow recommendations were tested within a stochastic framework. A fourth alternative, which attempted to mimic natural flow patterns of the system, was also tested. Impacts of the alternatives on multiple water uses in the Rio Chama basin were assessed, including water supply, reservoir releases, hydropower production and revenue, and whitewater boating.

Results from this study are important for guiding initial decisions regarding the feasibility of each proposed alternative, but additional management details that werent represented in my model, such as detailed water accounting (e.g. water rights and authorizations), would need to be examined before environmental releases become integrated into the systems operation. Although my modeling approach does not lend itself to immediate operational changes, it serves an important role of recognizing and assessing physical and institutional constraints that exist in the system. When coupled with stochastic simulations, hydrologic uncertainties can be explicitly included in the model. Even though other sources of uncertainty clearly exist in managing any river system (ecological processes, political, socio-economic), a stochastic representation of hydrologic variability helps managers hedge their decisions against unknown future conditions.

5.1.2 Chapter 2

Numerous methodologies have been developed to capture the complexity of water resource systems and implement environmental flows. These methods typically employ deterministic models to predict impacts on hydrologic parameters that are used to assess deviations from natural flow conditions (the Indicators of Hydrologic Alteration methodology is a common way to assess alternative impacts on hydrology). As computing power increases, optimization methods are being used to identify flow alternatives bound by large numbers of management constraints. These deterministic or command and control models focus on the efficiency of resource control rather than exploring system-wide responses or the influence of feedback mechanisms of management alternatives.

Recognizing the unique benefits of an SD approach (as described in Objective 1), I continued the development of an SD model to assess environmental flow alternatives in the Rio Chama, New Mexico. Specifically, this objective examined the impact of alternatives on riparian vegetation recruitment. This objective was accomplished by completing three tasks: 1) gather environmental flow recommendations provided by a diverse group of ecology experts familiar with the Rio Chama system; 2) incorporate one or more of these recommendations within a stochastic SD modeling framework; and 3) assess the practicality of multiple flow alternatives based on improvements to ecological health.

Results from this objective demonstrate the inclusion of specific ecologic processes within a holistic modeling framework. I recognize that my approach omits other factors that influence riparian recruitment, such as geomorphic disturbance. When the model is used foremost as a tool for understanding relationships between basin components, it facilitates a natural transition into an adaptive management approach. Managers and stakeholders can use comparative metrics, such as the success ratio presented in this research, to justify or dispel objections related to perceived institutional or physical capacity issues, and can move forward with new operational strategies within an adaptive management framework. This is the strategy being used in the Rio Chama basin where it is difficult to break free from the management status quo.

5.1.3 Chapter 3

Compared to the previous two objectives, this objective took a different approach to evaluating management impacts on ecological integrity. I coupled two-dimensional hydrodynamic and Bayesian network (BN) modeling frameworks in order to explicitly account for effects of small-scale spatial variability on ecological systems. Specifically, I focused on the implications of water diversion scenarios on cottonwood and willow species recruitment potential on the Gila River, New Mexico. Hydrologic and topographic variables were described by two-dimensional modeling of select sites on the Gila River. A BN model for riparian vegetation recruitment was implemented on a grid cell-by-cell basis using the descriptions of the variables and topographic mesh (approximately 1 m by 1 m resolution) produced with the two-dimensional model.

This work demonstrates the unique benefits of combining fine-scale hydrodynamic and BN models when evaluating ecological responses to water management alternatives. These benefits include a detailed consideration of topographic and hydrologic variability on the riparian recruitment process, visual representation of model results that facility the identification of worst impacted areas, and more informed implications of water management scenarios.

5.2 Future Research

There are numerous areas of research that should be further explored regarding management of water resource systems for ecological integrity. A deeper understanding of hydrology-ecology interactions, better recognition of uncertainty sources associated with management alternatives, and implications of regime shifts on water management and ecological processes are topics that require additional research.

5.2.1 Hydrology-ecology interactions

Aquatic and riparian processes respond to a variety of hydrologic drivers, which are often confounded. In order to make meaningful management decisions regarding impacts to a river's environment, we need to improve our understanding of how ecological processes respond to different drivers (*Poff and Zimmerman*, 2010). This requires data collection efforts in a range of undisturbed to modified rivers across a variety of river and stream scales. In addition, new statistical techniques that take advantage of large biological, land use, and hydroclimate datasets can help reveal important relationships between human actions and hydroscape modifications. Machine learning approaches, such as random forest modeling, may be able predict baseline or natural flow conditions in systems where data of unaltered conditions are not available (for example, see *Hill et al.* (2013)).

5.2.2 Uncertainty Sources

Incorporating uncertainty into water management decision tools often complicates the decision-making process. Instead of a single deterministic answer these tools produce a range of possible outcomes that managers need to consider. Although this may seem like a disadvantage, incorporating uncertainty allows managers to make more informed decisions (*Refsgaard et al.*, 2007).

Still, additional research is needed to help water managers make the best decisions in the face of uncertainty. Tools that incorporate uncertainty help us recognize areas or system components that contain the most variability or vague information. Research efforts should be focused on improving our understanding of those components so that the overall uncertainty within a system is reduced. This will be useful for, not only helping us gain more knowledge about a system, but giving managers more confidence in their decisions.

5.2.3 Regime shifts

Changes in climate and landscape regimes are already having huge impacts on water quantity and quality within some basins. For instance, drought and wildfires are having profound consequences to the hydrologic characteristics and water quality of streams in northern New Mexico (*Peters et al.*, 2004).

Understanding how these regime shirts will impact our water resources is one of the largest challenges facing water management. It is important that future research examines the consequences of regime shifts, and provides flexible methods for water managers to respond to changes in hydrologic conditions. Because these shifts often occur suddenly, research needs to pro-actively explore the possible impacts so that policy makers can plan response strategies. An adaptive governance framework will be key to sustainability managing our water resources into the future (*Folke et al.*, 2005).

I believe that to solve the future challenges facing water resource management, interdisciplinary research will be required. I am committed to participating in interdisciplinary research throughout my career.

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Appendices

Appendix A

Environmental Flows Background

Introduction

Rapid human population growth, increased management of water resources, and the expansion of urban areas into natural environments are straining riverine systems around the world. Historically, humans have managed these riverine systems to provide a dependable supply of water for consumptive use. However, in the past half-century studies have shown natural flows to be important for maintaining geomorphologic processes (Doyle et al., 2007), aquatic biodiversity (Bunn and Arthington, 2002; Hynes, 1970), riparian plant communities (Nilsson and Svedmark, 2002), and other important riverine ecological processes (Poff and Zimmerman, 2010), leading to the development of techniques for determining environmental flow requirements. Tools for providing environmental flows are now readily available for scientists and engineers to utilize during river restoration planning and have been applied in systems around the world.

The objectives of this appendix are to 1) examine the historical evolution of environmental flows as it pertains to restoration efforts, 2) describe the most important components of environmental flow development and their scientific basis, and 3) provide a contemporary case study of an environmental flow methodology applied to the Rio Chama, New Mexico. Important components of environmental flows, particularly as they related to the natural flow regime of a river, will be highlighted with particular emphasis on those easily applicable to restoration projects. An examination of restoration efforts currently underway on the Rio Chama, a major tributary to the Rio Grande in northern New Mexico, will provide contextual support for how one specific environmental flow technique—the Indicators of Hydrologic Alteration (IHA) methodology—can be applied to a river system. A final discussion will postulate the direction of environmental flow science for the next few decades as climate change and declining water availability restricts restoration flexibility.

Brief History of Environmental Flow Development

Until the later half of the twentieth century, water management strategy focused almost exclusively on providing adequate water for human needs. This focus began to shift in the 1960s as worldwide concern for protecting biodiversity and sustaining environmental systems permeated water resource policy. Research on the physical processes of running water and the riverine ecology became intricately linked (Hynes, 1970). The first substantial environmental flow (sometimes referred to as instream flow or e-flow) standards were developed in the late 1970s as pressure for minimum flow requirements needed for water permits under the Clean Water Act threatened fisheries (Petts, 2009). Abstraction limits were set to ensure enough water was present throughout specific periods of the year for fish survival, but even these standards were based on professional judgement rather than scientific evidence (Fraser, 1972). Orsborn and Allman (1976) presented the need for a more holistic consideration of flows for fish, recognizing the importance of flow variability in a river system. Hence, the modern idea of environmental flows was bornthe idea that river environments are dynamic systems in which aquatic species have evolved, and ensuring the natural variability of the system is vital to protecting river ecosystems (Poff, 2009; Poff et al., 1997; Postel and Richter, 2003).

The Instream Flow Incremental Methodology (IFIM) was widely adopted in the 1980s. The IFM approach allowed researchers to quantify river habitat as a function of discharge (Stalnaker et al., 1995). According to Bovee (1982), an original developer of the IFIM processes, the primary "decision variable generated by IFIM is total habitat area for fish or food organisms." A popular component of IFIM is Physical Habitat Simulation (PHABSIM), in which specific habitat attributes are linked to life stages of various aquatic species (commonly fish) (Annear et al., 2004). The discussion on physical habitat in stream restoration describes the IFIM and PHABSIM methodologies in more detail.

Environmental flow methodologies proliferated in the 1980s and 1990s. The most notable contributions to the field were the Indicators of Hydrologic Alteration (IHA) methodology (Richter et al., 1996), Range of Variability (RVA) methodology (Richter et al., 1997), and the concept of the 'natural flow regime' (Poff et al., 1997). The IHA method compares the hydrology of a reference "pre-development" scenario to a "post-development" scenario and calculates 32 hydrologic alteration parameters based on important flow variability indictors. The indicators represent common metrics such as median monthly flow, temporally-averaged minimum and maximum flows, hydrograph fall and rise rates, and low or high pulse discharges. The RVA method uses IHA outputs and compares the frequency of occurrence of the same parameters. The RVA method allows researchers to determine how often a specific parameter in the "post-development" scenario falls within the same statistical quantile as the "pre-development" data. Both the RVA and IHA methodologies can be modeled using the Indicators of Hydrologic Alteration Software developed by The Nature Conservancy (The Nature Conservancy, 2009a). The natural flow regime concept is the foundation for the IHA, RVA, and other methodologies developed since. Poff et al. (1997) explains that the natural flow of a river varies on different timescales and can be characterized using the following groupings: magnitude, frequency, duration, predictability, and rate of change. Each of these groupings are important to consider when restoring or protecting a river environment.

King et al. (2003) presented the Downstream Response to Imposed Flow Transformation (DRIFT) methodology as a holistic approach for advising environmental flow development. The underlying philosophy of DRIFT was that major abiotic and biotic components need to be accounted for when successfully managing a river ecosystem, and, therefore, the full spectrum of flows, and their temporal and spatial variability, need to be managed as well.

The Ecological Limits of Hydrologic Alteration (ELOHA) approach is a popular contemporary environmental flow methodology. The ELOHA framework is designed to allow regional-scale development of environmental flows, and is composed of four main steps: 1) compiling or developing hydrologic base data, 2) classifying and grouping similar river basins, 3) calculating flow alterations for post-development conditions, and 4) developing flow- ecological connections (Poff et al., 2010). Adaptive management is also an important component of managing and improving environmental flow recommendations.

The importance of environmental flows is now well established, but the institutional adoption of environmental flow standards is lagging behind the science. Furthermore, there is a wide gap between the recognition of natural flow needs and data needed to support flow-ecology linkages (Poff et al., 2010). Future advancements of environmental flow methodologies will rely on strengthening our understanding of flow-ecology interactions and incorporating adaptive management into environmental flow implementation.

What to Consider Before Development of Environmental Flows

It is easy to jump into the technical aspects of setting environmental flows without first considering other important components of an environmental flow study. Before any modeling efforts occur, considerations such as the study approach, study scale, and resource availability should be determined. These considerations will keep an environmental flow study within budget and on-track to a successful completion.

Objective vs. Scenario-based Approaches

Recognizing the driver of an environmental flow study is important to do before setting goals for a project. A project with a specific ecological goal, such as to flush more sediment from a river, will produce different results than one without a central driver. Acreman and Dunbar (2004) define two different approaches for setting environmental flows. An objective-based approach uses specific ecological, economic, or social goals to drive the determination of environmental flows. For example, managers might want to inundate a pre-defined area of floodplain each year for flood-recession agriculture. Developing flow recommendations that allow the correct area of farmland to be flooded would be the primary focus of such a study. This approach has well-defined objectives in contrast to the scenario-based approach, which studies multiple tradeoffs between various alternatives. A scenario-based approach balances human and environmental flow needs by examining a range of alternatives. Setting flow standards for developed basins often requires a scenario-based approach to juggle the needs of water delivery, hydropower, recreation, and the river environment.

Scale of Study

Rivers function at various spatial and temporal scales. Environmental flow studies should consider at which scale restoration efforts should be focused before beginning a project. Spatial scales include micro-, meso-, and macro-habitats nested within landscape features, such as reaches, segments, and watersheds (Annear et al., 2004). The discussion of physical habitat describes the attributes of each habitat scale. Understanding the ecological controlling factors at each scale is important for a sucessfull project. River segment or watershed scales might be appropriate for influencing sediment transport within a system, whereas a reach scale may be useful when determining flows to improve benthic macroinvertebrate community health.

Changes in river processes over different temporal scales are also important to consider during environmental flow studies. Different components of a river system respond at varying rates (Petts, 1987). The length of temporal scales is generally inversly proportional to the size of the spatial scale; watershed changes may take decades to occur (see the discussion on fluvial geomorphology) while microhabitats shift daily (Annear et al., 2004).

The Importance of the Natural Flow Regime

Modern techniques for developing environmental flows, such as ELOHA, recognize the importance of the natural flow regime to sustain a rivers ecological health. There is agreement among scientists that the natural flow variability of a system should be maintained or replicated to protect the biodiversity and ecological services of a river system (Arthington et al., 2006). The important hydrologic components in a system include magnitude, frequency, timing, duration, rate of change, and predictability of flow events (Poff et al., 1997). The natural flow regime is important for many aspects of aquatic ecological health including water quality, energy sources, physical habitat, and biotic interactions. Not only do these facets of the natural flow regime sustain different ecological niches in a system, but each species in a riverine system evolved based on the characteristics of the naturally occurring flow regime. How each component of the natural flow regime can affect riverine ecology, and why it is important to consider flow variability in river restoration, is examined.

The timing of specific flow events, such as spring runoff or monsoon storms, is important for aquatic and riparian ecology. When the natural timing of riverine flows is disrupted (such timing shifts in peak flows due to hydropower production), common aquatic responses include a disruption of fish spawning cues, decreases in reproduction and recruitment, and a change in diversity and community assemblages. Riparian communities can also be altered due to changes in timing. Examples include reduced riparian recruitment, reduced plant growth, and an invasion of exotic plant species (Poff and Zimmerman, 2010).

Flow magnitudes are also important for maintaining aquatic and riparian communities. The loss of extreme high or low flows, often caused by the introduction of dams, can alter species assemblages, increase the abundance of non-native species, and cause the upland species to encroach the riparian corridor. An increase in high flow magnitudes, can literally wash away species not accustomed to such high flows and reduce species richness (Poff and Zimmerman, 2010).

A change in frequency of peak flows has been shown to negatively influence reproduction rates, decrease habitat for young fishes, and shift community compositions (Poff and Zimmerman, 2010).

A decrease in flow duration can cause floodplains to be inundated for a shorter time period than usual. Many fish species depend on floodplain inundation for access to energy sources, and some riparian communities rely on inundation for new plant recruitment. A decrease in the the duration of inundation can cause reduced area of riparian cover, change in fish assemblages, and an increase in non-native species (Poff and Zimmerman, 2010).

Finally, the rate of change of riverine flows can decree the germination survival of riparian communities, reduce benthic macro-invertebrate diversity, and disrupt the abundance of energy sources available to fish communities (Poff and Zimmerman, 2010).

When designing a restoration project, it is important to understand how the natural flow regime has been altered and the corresponding ecological effects of this alteration. Restoration efforts that do not account for changes in the flow regime may not be successful. For instance, it may not be possible to establish native riparian vegetation if the plant physiology does not respond to the altered hydrologic conditions. Similarly, bank stabilization efforts may fail if the magnitude of peak flows has increased in the system. Tools, such as the Indicators of Hydrological Alteration (IHA) software, can be used to compare various components of the flow regime and determine the largest hydrologic changes within a system. Restoration teams can use IHA data to pinpoint the greatest hydrologic changes in a system and formulate restoration goals accordingly.

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Appendix B

System Dynamics Model and Data

The system dynamics model developed for Chapter 2 and Chapter 3 of this dissertation can be found electronically at `http://www.unm.edu/~rmorriso/sdm/`.

Links are provided to download the model used for these chapters, input data and data processing scripts.

Appendix C

Bayesian Network Model and Data

Documentation for the Bayesian network model developed for Chapter 4 of this dissertation can be found electronically at `http://www.unm.edu/~rmorriso/bayesian/`.

The input data and model results can be found in the same repository.