Summer 7-17-2017

Spatial and Temporal Intricacies of Natural Resource Use: Studies in Water, Forests, and Hydrocarbons

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BY

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DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Doctor of Philosophy
Economics

The University of New Mexico
Albuquerque, New Mexico

July 2017

DEDICATION

To my parents

Mr. Bed Raj Sharma and Mrs. Damayanti Sharma

and

my parents-in-law

Late Mr. Batu Kendra Pokhrel and Mrs. Urmila Pokhrel

ACKNOWLEDGMENTS

My sincere thanks and heartfelt appreciation goes out to my committee chair Dr. Janie M. Chermak, who has provided me with many hours of instruction, guidance, and mentorship throughout the ups and downs of graduate school. She pulled me down to earth when I flew in the sky of hauteur and pushed me up when I drowned in the pit of despair. I am proud to have you as my mentor.

I also thank my committee members, Prof. Robert Berrens, Dr. Jennifer Thacher, Dr. Richard Bernknopf, and Dr. Vincent Tidwell, for their valuable recommendations and feedback. Your comments have strengthened this work.

I am also grateful to the following university staff: Mary Garcia, Shoshana Handel, Daniela Wilken, Leah Hardesty, Maria Rita Daw, and Tami Henry for their unfailing support and assistance.

I am grateful to my siblings and their family, who provided me with moral and emotional support in my life. I am also grateful to my other family members and friends who have supported me along the way.

I am indebted to my parents Mr. Bed Raj Sharma and Mrs. Damayanti Sharma, and my parents-in-law, the late Mr. Batu Kendra Pokhrel and Mrs. Urmila Pokhrel, to whom this work is dedicated. You always inspired me to be the best version of myself. Thank you for inspiring me in life.

I thank my lovely son, Ayush, for his sweet smile and understanding. You have sacrificed your childhood for my Ph.D. I owe you.

And finally, last but by no means least, I want to express my deepest love and thanks to my loving wife, Rachana Adhikari (Noorie), for her support, taking care of our son, and taking responsibility for all housework during my graduate study period.

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ABSTRACT

This dissertation examines spatial and temporal impacts of natural resource use. The second chapter integrates hydrological and economic systems to examine the impact of drought on these two systems and explores the spatial impact of policies aimed to mitigate the drought impact. The systems dynamics model developed for this chapter simultaneously considers the physical hydrology in the Middle Rio Grande water basin in New Mexico, the engineered water management system, and a behavioral model of residential water demand for three cities: Albuquerque, Rio Rancho, and Santa Fe, New Mexico. The simulation results showed that droughts that occur in later periods, when there are larger populations, have more substantial impacts. Later and longer drought increases per capita water consumption, reduces aquifer volume, and in general reduces river flow. However, increased public awareness can outweigh the stress on water resources due to population growth. Furthermore, increased awareness and decreased population in one city results in to decreased groundwater pumping costs in another city. The third chapter utilizes survey-based contingent evaluation data to investigate public

support among urban Albuquerque, NM households for restoration of a watershed that impacts the urban water supply security, but is spatially removed from the urban area. Econometric results show evidence of both significant public support for forest restoration and the importance of accounting for respondent uncertainty. Econometric estimation results indicate that even if people live in a distant area they are willing to pay for forest restoration. The fourth chapter examines the tradeoff between natural resource development and ecosystem services. The model developed in this chapter is within the system dynamics framework but integrates spatial information too. A hypothetical example is undertaken for the Piceance Basin in Colorado that simultaneously estimates the economic benefits from unconventional natural gas production and the impacts of this land use change on the collocated Mule Deer and fish population and competing direct and consumptive uses of nearby water supplies. Simulation results show that mineral development simultaneously produces private benefit through the sale of produced mineral and social cost through the degraded ecological services. Price uncertainty further aggravates the problem.

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Chapter 1 : Natural Resource Extraction and Spatial Externality

1.1. Introduction

The concepts of spatial interaction and spatial externalities are increasingly important in the theory of environmental and natural resource economics (Anselin 2003). Natural resources and their extraction can exhibit spatial behavior that generates spatial impact when they are extracted.[1] In other words, the choice to use or manage resources can have impacts that are accrued not only locally, but at a wider scale as well. The level of the impacts can change over space and time, hence, there are spatial intracacies, manifested through externalities, that may change policy choice, if considered in the policy formation. A difficulty with this is developing the data necessary to be able to analyze and incorporate these intracacies, which is exacerbated by the interdisciplinary nature of these types of problems. This dissertation focuses on development of modeling such interactions and/or assessing the impact of resource use and management across three rresource use cases.

Another important issue related to natural resource extraction is intersystem impact. Natural systems and human systems are inextricably linked, so that a change in one system brings changes to another system. An analysis of changes in one system in isolation ignores costs and benefits created to another system. For example, if natural

[1] For example, groundwater pumped by a farmer in one location may reduce river volume in another location, affecting the population of aquatic species and the welfare of aquatic-species- loving people.

resource extraction ceases because of pollution and its costs to society, there will be a stagnation in industrial development that results in unemployment. Intra-system analysis of natural resource extraction is the possible solution for this issue. It allows for analyzing costs and benefits accrued to different systems and evaluation of whether proposed natural resource extraction is beneficial from the social point of view.

This section is focused on spatial externalities of wildfire, water resources, and hydrocarbon development.

1.1.1 Wildfire and Spatial Externality

Climate change and other factors have increased wildfire risk, making mitigation an important public policy issue (Adhikari et al. 2016, Butry and Donovan 2008). Wildfire creates different types of spatial externalities. In a fire-prone community, wildfire risk reduction activity of a homeowner has significant spillover effects on the wildfire risk to neighboring houses (Butry and Donovan 2008). However, spillover effects can result in an inefficient level of mitigation. Collective action is suggested as a means of avoiding inefficient mitigation as a result of spillover effects (Butry and Donovan 2008). The authors concluded that collective action leads to efficient levels of mitigation and internalizes the spillover effect.

Wildfire has been identified as one of the major disturbances to the watershed and water quality conditions. Post wildfire water contamination results in high treatment costs on downstream public water supplies (Bladon et al. 2014)--a spatial externality. Wildfire risk reduction through forest health improvement can minimize such costs. Adhikari et al. (2016), using a contingent valuation survey approach, found that forest restoration

activities can be funded through payment for ecosystem services even if a majority of the households are spatially removed from the needed restoration activities.

1.1.2 Water Resource and Spatial Externality

Water resources create several types of severe spatial externality. Brozović et al. (2010) discuss the groundwater pumping externality in which water pumped by an agent in one location increases the pumping cost to another agent in another location. Brozović et al. (2010) showed that the marginal pumping externality without considering spatial aspects of the aquifer is less than that predicted by a spatially explicit model.

A farm produces various types of pollutants, such as agricultural nutrients, soil, and agricultural chemicals that pollute water. The polluted water creates costs to people downstream (Griffin and Bromley 1982). Different types of incentives and regulations can internalize such externality (Griffin and Bromley 1982).

1.1.3 Hydrocarbon Development and Spatial Externality

Hydrocarbon development has become one of the major factors creating land use change in the United States and worldwide. A land use change affects the form and function of landscape interaction, resulting in a change in the interaction of different systems, including ecological and economic systems, thus creating spatial externality. Development activities such as construction of roads, well pads, and wells carried out for oil and gas production have been found to affect natural resources such as air, water, vegetation, fish, and wildlife. These impacts are spatial in nature, creating spatial externality and social cost.

Several studies have showed that hydraulic fracturing is a source of drinking water contamination that affects habitats located remotely from an active gas extraction area (Barbot et al. 2013, Gregory et al. 2011, Osborn et al. 2011, Vidic et al. 2013). Oil and gas production-induced erosion and sedimentation load is another source of spatial externality. Road and other construction activities in gas extraction areas increase land erosion, leading to increased sedimentation load in nearby rivers and lakes (Anderson and Macdonald 1998). Increased sedimentation load affects aquatic species negatively (Hausle 1973).

1.2 Research Methods, Empirical Tools, and Chapter Summary

The concept of spatial economics began with Von Thunen (1826) who first developed a spatial model of the relationships between markets, production, distance. After this publication, several studies have been carried out to examine the spatial aspects of economic issues with the dominance of natural resource use. These studies widely vary in their methods, methodologies, and issues but are common in to discuss the spatial aspect of the problem. For example; Sanchirico and Wilen (2005), Swallow and Wear (1993), and Konoshima et al. (2008) use dynamic optimization model to examine the issue of fisheries, forest, and wildfire respectively. Similarly, Blackman et al. (2008), Albers et al. (2008), and Nepal (2014) use spatial econometric models to examine the spatial issues related with forest, conservation, and wilderness areas.

This study uses simulations to examine the spatial impact of natural resource use. In two of the three chapters, a study area is divided into various zones, gridcells, and locations to find the impact of resource use activities in one zone, gridcells, or locations to another zone, gridcells, and location using system dynamics model. The system

dynamics models are backed by dynamic optimization models. In the third chapter, if people living in a distant municipal area are concerned over the wildfire risk in remotely located forest and willing to pay for minimizing the risk of wildfire.

The goal of the following chapters is to examine the spatial and intersystem impact of natural resource use with a focus on water, forest, and hydrocarbon. Methods and tools are interdisciplinary in nature. An interdisciplinary approach to examining the issue of natural resource use minimizes the conflict among stakeholders that mainly arises due to fundamental differences in philosophy and modeling techniques for different system. The major challenge faced when modeling different system together was the lack of data for the economic system. Similarly, the stochastic nature of the economic system as opposed to the more deterministic nature of the natural system is another important problem in the interdisciplinary modeling approach.

Chapter 2 integrates hydrological and economic models to analyze the impact of drought on two systems (hydrological and economic) as well as their synergic impact, and also explores the spatial impact of groundwater pumping. Global climate change is expected to produce more frequent, high severity, and longer duration drought episodes in the future. This may exacerbate regional and global water scarcity considerably. The multifaceted use of water and its intrinsic link with the climate system brings multifaceted impacts of drought on water resources. Drought-induced water deficiency produces complex social, economic, and environmental impacts. The complexity of the impact lies in the extent to which economic sectors are dependent on water resources.

If causes and associated mitigation strategies are ignored, then managing scarce and stressed water resources for current and future consumption is the major issue in the

context of the drought impact on water resources. Traditionally, water resources have been managed using "command and control" approaches that emphasized providing adequate water resources to meet human needs without considering other systems with backward and forward linkages to human consumption of water. However, a sustainable development approach to water use calls for a balance among economic efficiency, social equity, and environmental sustainability. One way of achieving this balance is to follow an Integrated Water Resource Management (IWRM) approach that bridges natural systems and human systems.

This chapter analyzes the impact on the water system of drought and various policies aimed at curbing drought and examines the spatial impact of different policies that are implemented to alter groundwater pumping behavior using a systems dynamics model. This type of model allows us to consider outcomes for complex problems. For example, a systems dynamics model considers the timing and duration of a drought that may severely impact water availability, especially in semi-arid climates like the American Southwest. The systems dynamics model developed for this chapter simultaneously considers the physical hydrology in the Middle Rio Grande water basin in New Mexico, the engineered water management system, and a behavioral model of residential water demand for three cities (Albuquerque, Rio Rancho, and Santa Fe, New Mexico) over a 50-year time horizon. The simulation results showed that droughts that occur in later periods, when there are larger populations, have more substantial impacts. The impact is not only for human consumption but also on the aquifer level and river flow. Later and longer drought increases per capita consumption, reduces aquifer volume, and in general reduces river flow. Oppositely, increased public awareness can outweigh

the stress on water resources due to population growth. Furthermore, increased awareness and decreased population in one city results in decreased groundwater pumping costs in another city. Increased awareness and decreased population induces the city to pump less groundwater, which results in increased aquifer volume and reduced pumping costs for another city. While alternative policies can provide some relief, the type of policy, the severity of that policy, and the timing of the drought are critical. Given some of the forecasts of severe and multiple droughts in the Southwest in coming years, management tools that consider a longer-term time horizon may provide adequate time to develop more robust policies.

The third chapter explores the possibility of contributing to forest restoration aimed at reducing wildfire risk and sustainable water management by people living in a distant municipal area. Catastrophic and high-severity wildfire risk is increasing in the western United States (US) and elsewhere. Wildfire can be a major disturbance to the watershed and water quality conditions. For many communities, reducing the risk of high-severity wildfires through forest restoration is vital for the sustainability of watersheds and securing safe drinking water. However, generating revenue through public support to cover the costs of restoration is a significant challenge. Although examples exist that show how funds can be generated from the public living near forestlands, an unresolved issue is whether households in a relatively distant municipal area would significantly support wildfire risk reduction efforts.

The objective of the third chapter is to analyze survey-based contingent evaluation data to investigate public support among urban Albuquerque, NM households for the restoration of a watershed that impacts urban water supply security, but is

spatially removed from the urban area. Econometric results show evidence of both significant public support for forest restoration—"linking forests to faucets"--and the importance of accounting for respondent uncertainty. Two types of uncertainty, preference uncertainty and delivery uncertainty, have been considered simultaneously for the first time in literature. Preference uncertainty in this chapter refers to uncertainty in preferences for water security as an important collectively provided good; delivery uncertainty refers to the uncertainty regarding the possibility that restoration activities across a forested landscape or watershed might deliver improved water security. Econometric estimation results from a Double Hurdle model indicates that even if people are living in a distant area they are willing to pay for forest restoration, and the estimated willingness is not significantly less than the amount estimated in similar studies for the people living in the proximity of forest.

The fourth chapter develops an analytical tool set to examine the spatiotemporal inter-relationship among energy, mineral development, and ecosystem services. This approach emphasizes the quantitative estimation of the joint societal benefits of resource development and collocated ecosystem services.

The model developed in the fourth chapter is within the system dynamics framework but integrates spatial information, too. It is a spatiotemporal model that provides a new capability to simulate complex domains or systems over space and time and the capacity to be relocated to alternative locations when desired. A hypothetical example is undertaken in the Piceance Basin in Colorado that simultaneously estimates the economic benefits from unconventional natural gas production and the impacts of this land use change on the collocated Mule Deer population and competing direct and

consumptive uses of nearby water supplies. The hypothetical example combines natural gas production from hydraulic fracturing, ecological impacts to Mule Deer, demands on water use and aquatic species, total cost, total revenue, net resource benefits from resource development, and uncertainty regarding natural gas prices.

Chapter 2 : Economics of Drought in Semi-Arid Regions: A Hydro-economic Policy Perspective

2.1 Introduction

Drought-induced water deficiency produces complex social, economic, and environmental impacts (Wilhite and Glantz, 1985). The complexity of impact lies in the dependency of economic sectors on water resources (Wilhite et al., 2007). The U.S. economy lost about $15 billion in the agriculture sector alone during the 1988-89 drought in the central and eastern U.S. (National Weather Service, 2008). The United States economy experienced an estimated damage of $190 billion between 1980 and 2003 due to droughts (Baum 2015). Specific to the Southwest, the cost of the 2012-2015 drought to California's economy was estimated to be $2.74 billion, of which $1.84 billion of the loss was in the agriculture industry (Baum 2015). Further, the expectation is that droughts will become more severe, more frequent, and longer duration.

The impact of drought is propagated through intertwined physical and human factors. Lower levels of precipitation and higher temperatures reduce snow pack and surface water availability. Decreased surface water results in increased dependence on groundwater and decreased levels of power generation. Increased pressure on water resources due to drought is further aggravated by increased drought-induced water demand. Consequently, understanding the relationship between the physical and human worlds and their interactions, is important. To that end, this research develops a spatial system dynamic model that integrates hydrological and economic systems (i) to examine

the impact of drought on water resources and water demand, and (ii) to evaluate the spatial impact of policies aimed at managing water demand.

Drought impacts both groundwater and surface water, which results in a reduced supply of and increased demand for water. During a drought, low precipitation, high temperature, and increased evapotranspiration reduce surface water level. Similarly, decreased recharge rates due to increased temperatures and decreased rainfall, and increased pumping due to drought-induced demand adversely affect groundwater. Because surface water and groundwater are inextricably linked, the impact of drought on one source of water affects the quantity and quality of water from other sources (Tweed 2009).

Leaving aside causes of drought such as climate change and necessary efforts to mitigate such causes, managing scarce and stressed water resources for current and future consumption looms as the major issue when considering drought's impact on water resources. Traditionally, water resources have been managed using a "command and control" approach that emphasized providing adequate water resources to meet human needs without considering other systems with backward and forward linkages to human consumption of water (Holling and Meffe 1996). However, a sustainable development approach to water use calls for a balance between economic efficiency, social equity, and environmental sustainability (Lenton and Muller 2012). One way of achieving this balance is to follow an Integrated Water Resource Management (IWRM) approach that entails bridging natural systems with the human systems (Lenton and Muller 2012). It requires knowledge of the relevant physical sciences, technology, and multiple

institutional, social or political issues confronting water resources planners and managers (Loucks et al. 2005).

Balancing future demand and supply of water resources considering the possibility that these resources will be manipulated by future droughts requires highly competent water management practices. An efficient water management system is supposed to consider natural and human systems and inspire the public's confidence while designing policies. A policy designed based on a convoluted model that's hard for people to comprehend may end up a failure. One way of making a water management policy successful could be to adopt an open and participatory model development process. The open and participatory process minimizes risks of being obscure to the public in terms of the operation, application, and utility of such models and builds familiarity, confidence, and acceptance in models (Louks et al. 1985, Tidwell et al. 2004). However, due to several reasons such as lack of time and financial resources, if the participatory model development process is beyond the scope, then an information-based policy instrument could serve similar purposes. Information-based policy instruments influence people through knowledge transfer, communication, and persuasion (Mackay and Shaxton 2011, Park 2013). Lack of information prohibits potential target agents from making the best decision, whereas a well-informed target agent chooses the preferred alternative policy (Schneider and Ingram 1990, Park 2013). A system dynamics model can achieve the two requirements for an efficient water management practice, i.e. developing a model that incorporates both physical and human systems, and designing policy that employs information-based policy instruments. The system dynamics model provides a real-time and interactive environment for educating

stakeholders, and a scientifically informed basis for exploring alternative water resource utilization scenarios (Roach and Tidwell 2009). The core value of a system dynamics modeling approach is to integrate various systems in a single model. Simulating the model by incorporating all appropriate systems, it is possible to generate the relationships between variables in a system, which can show the feedback between several variables in the intertwined systems when one variable is altered. This can not only provide stakeholders a method to understand a system, but also provides policyholders with improved information with which to develop policy. In this study, the impact of drought on water resources in the Middle Rio Grande (MRG) water basin is analyzed with a system dynamics model. Three systems have been considered: groundwater hydrology, surface water hydrology, and water demand. Demand is modeled incorporating residential and industrial water demand in the three largest cities along MRG water basin: Albuquerque, Santa Fe, and Rio Rancho. The results show that drought itself reduces water resources and increases per capita daily water use, but longer drought and drought in later periods are costlier than earlier and shorter-term droughts. Increasing water rates and public awareness reduces the pressure on water resources due to drought and population growth.

2.2 Study Area

The Middle Rio Grande Basin (MRG) is the focus of this study (Figure 2-1). The basin, which covers over 3,060 square miles, lies in central New Mexico and covers seven counties (part of Santa Fe, Sandoval, Bernalillo, Valencia, Socorro, Torrance, and Cibola counties), and is home to three major cities (Albuquerque, Rio Rancho, and Santa Fe). Elevation of MRG ranges from 4,650 feet to 11,254 feet. Annual average

temperature and precipitation in this basin range from 54.0F - 56.50F and 7.8 inches – 12.7 inches. High temperature and low precipitation contributed MRG basin's desert climate (Bartolino and Cole 2002).

The Rio Grande is the major river in the basin. It flows about 1,900 miles north to south from Colorado to the Gulf of New Mexico (NMWQCC 2004). The MRG basin extends just north of Cochiti reservoir to the Elephant Butte dam in the south. The extent of the basin is shaded in Figure 2-1. Primary sources of surface water in the Middle Rio Grande are runoff and stream flow from the Upper Rio Grande, Rio Salado, Jemez River, Guadalupe River, and Rio San Jose.

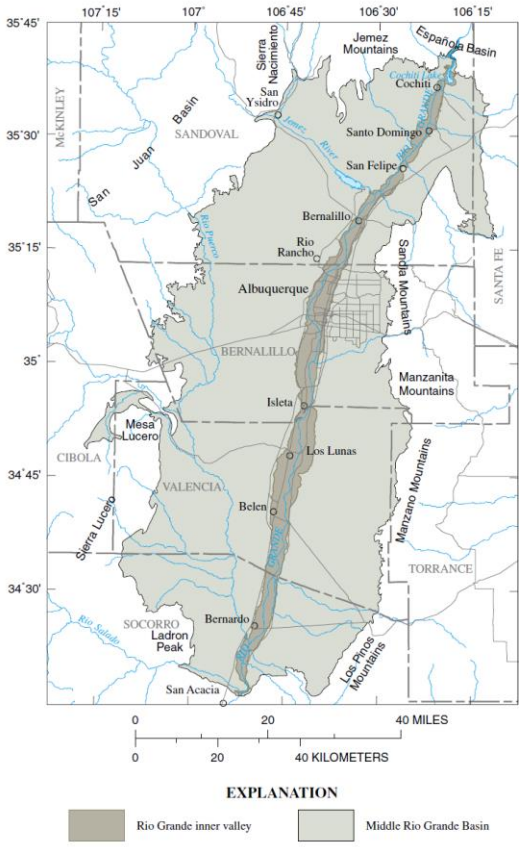


Figure 2-1:Middle Rio Grande (Source: Adapted from NMWQCC (2004))

The Middle Rio Grande basin consists of a deep alluvial aquifer whose boundary roughly coincides with the MRG basin and interacts with the Rio Grande. The aquifer is recharged from the runoff of precipitation and melting snow from the surrounding mountains. Discharge of the aquifer takes place from wells, stream flow, underflow, and evapotranspiration.

The MRG valley is rapidly urbanizing. According to the US census data, the population of Rio Rancho increased by 69.1% from the year 2000 to 2010[2]. Despite the rapid urbanization, nearly three-quarters of total water withdrawal (ground and surface water) is associated with agriculture (Wilson et al. 2003).

2.3. Theoretical Model Consideration

Management of water resources is complicated by its interlinkages with the hydrologic, ecological, and human systems (Burnett et al. 2015). These linkages produce spillover effect or externality leading to an outcome that is not socially optimal. Burnett et al. (2015) classify these externalities into four categories: flow externality (e.g. acid rain from coal), stock-to-flow externality (e.g. resource-amenity value), stock externality (greenhouse gases), and stock-to-stock externality (watershed quality affecting downstream sedimentation). Out of these four externalities, the first two have only a temporary impact, and the last two have a dynamic impact. This study, adapting the dynamic optimization model in Burnett et al. (2015), Pfeiffer and Lin (2012), and Janmaat (2005), considers two issues: the impact of drought on groundwater, and the consequences of groundwater pumping in one location on the stock of aquifer in another area that ultimately results in a pumping cost externality.

[2] http://www.city-data.com/city/Rio-Rancho-New-Mexico.html

The marginal opportunity cost of groundwater pumping has three components: marginal extraction cost (c), marginal user cost (MUC), and marginal externality cost (MEC). Marginal extraction cost (MEC) refers to the cost incurred to the downstream consumer due to the extraction of one unit of water resources. Such costs can be of different types. For example, Provencher and Burt (1993) and Pfeiffer and Lin (2012) explain pumping cost externality in which groundwater pumped by one agent causes increased pumping cost for another agent. Hellegers et al. (2001) discuss externality created by groundwater extraction in the form of desiccation of neighboring reserves and degradation of groundwater quality.

Consider I numbers of cities located above an aquifer basin. The source of water for each city is either surface water, groundwater, or both. All cities are identical in the sense that they have the same marginal cost of groundwater extraction, $c(Q_{GWt})$, such that $c'(Q_{GWt}) \geq 0$ where Q_{GWt} is the total groundwater stock at the time t, and same benefit of water consumption function $\int_0^{u_{it}} p(z_{it}, Q_{SWit})dz = B(u_{it}, Q_{SWit})$ where u_t is the groundwater consumption, and Q_{SWt} is the surface water consumption.

Adapting Pfeiffer and Lin (2012), and Janmaat (2005), the equation of motion describing the change in groundwater stock over time, $\dot{Q}_{GWit}$, is given as:

$$\dot{Q}_{GWit} = -u_{it} + R_{it}(u_{it}, Q_{SWit}, d_{it}) - E_{it}(d_{it}) + \sum_{j \in I} \theta_{ji} Q_{GWj} \tag{2.1}$$

The equation (1.1) implies that the groundwater stock depends on the amount city i is pumping, u_i, the amount of recharge to patch i, $R_{it}(u_{it}, Q_{SWit}, d_{it})$ where

$\delta R_{it}/\delta u_{it}$, $\delta R_{it}/\delta Q_{SWit} \geq 0$ and $\delta R_{it}/\delta d_{it} \leq 0$. It also depends on drought impact on the stock $E_{it}(d_{it})$. The term $E_{it}(d_{it})$ represents a drought damage function on groundwater. Such damages occur, e.g. due to groundwater evapotranspiration that increases during a drought period (Yeh and Famiglietti 2009). Furthermore, $\dot{Q}_{GWit}$ also depends on the net amount of water that flows into a patch i of the aquifer that is underneath the city i, $\sum_{j \in I} \theta_{ji} Q_{GWj}$ where θ_{ij} is the fraction of water stock in a patch i that flows out to patch j. The fraction θ_{ij} is governed by Darcy's law and the magnitude of this fraction for a patch decreases as the stock of water in that patch increases, i.e. $\frac{\delta \theta_{ji}}{\delta Q_{GWi}} < 0$.

Consider a social planner whose objective is to maximize net social benefit defined as the benefit obtained by water consumption less cost accrued due to water consumption. Each city has property rights to the patch of the aquifer underneath the city. The objective function faced by one of the cities is:

$$\underset{u_t \geq 0}{Max} \quad V = \int_0^{\infty} e^{-rt} \left[B(u_{it}, Q_{SWit}) - c(Q_{GWit}) u_{it} \right] dt \tag{2.2}$$

Subject to

$$\dot{Q}_{GWit} = -u_{it} + R_{it}(u_{it}, Q_{SWit}, d_{it}) - d_{it}(Q_{GWit}) + \sum_{j \in I} \theta_{ji} Q_{GWj} \tag{2.3}$$

$$\lim_{t \to \infty} \lambda_{it} u_{it} = 0, \lim_{t \to \infty} \lambda_{it} Q_{SWit} = 0$$

The current value Hamiltonian of this maximization problem is:

$$H^c = B(u_{it}, Q_{SWit}) - c(Q_{GWit})u_{it} + \mu_{it}\left(-u_{it} + R_{it}(u_{it}, Q_{SWit}, d_{it}) - E_{it}(d_{it}) + \sum_{j\in I}\theta_{ji}Q_{GWj}\right) \quad (2.4)$$

Necessary conditions for an interior optimum include:

$$\frac{\delta H^c}{\delta u_{it}} = \frac{\delta B(u_{it}, Q_{SWit})}{\delta u_{it}} - c'(Q_{GWt}) + \mu_{it}\left(\frac{\delta R_{it}(u_{it}, Q_{SWit}, d_{it})}{\delta u_{it}} - 1\right) = 0 \quad (2.5)$$

$$r\mu_{it} - \dot{\mu}_{it} = \frac{\delta H^c}{\delta x_{it}} = -\frac{\delta c(Q_{GWit})}{\delta Q_{GWit}}u_{it} + \mu_{it}\left(\sum_{j\in I}\frac{\delta\theta_{ji}}{\delta Q_{GWit}}Q_{GWj}\right) \quad (2.6)$$

$$\dot{Q}_{GWit} = -u_{it} + R_{it}(u_{it}, Q_{SWit}, d_{it}) - d_{it}(Q_{GWit}) + \sum_{j\in I}\theta_{ji}Q_{GWj} \quad (2.7)$$

The analytic solution to the above problem is difficult to achieve. Since the purpose of this section is to show the spatial impact of groundwater extraction and impact of drought on groundwater, it is not necessary to have an analytic result. The derivation proceeds assuming a stable state exists. In the steady state, setting $\dot{\mu}_{it} = 0$, equation (2.6) yields

$$\mu_{it} = \frac{\delta c(Q_{GWit})}{\delta Q_{GWit}\left(\sum_{j\in I}\frac{\delta\theta_{ji}}{\delta Q_{GWit}}Q_{GWj} - r\right)}u_{it} \quad (2.8)$$

Substitution of μ_{it} in (2.5) yields

$$\frac{\delta B(u_{it}, Q_{SWit})}{\delta u_{it}} = c'(Q_{GWt}) + \frac{1}{\left(\sum_{j\in I}\frac{\delta\theta_{ji}}{\delta Q_{GWit}}Q_{GWj} - r\right)}\frac{\delta c(Q_{GWit})}{\delta Q_{GWit}}u_{it}\left(1 - \frac{\delta R_{it}(u_{it}, Q_{SWit})}{\delta u_{it}}\right) \quad (2.9)$$

Equation (2.9) says that the benefit of consuming water is maximized to the point where the marginal benefit of it is equal to marginal cost plus the present value of the

shadow value of water. Spatial impact of groundwater pumping is captured by the term $\sum_{j \in I} \frac{\delta \theta_{ji}}{\delta Q_{GWit}} Q_{GWj}$. The shadow value of groundwater for city *i* is dependent not only on the stock of water in the underneath aquifer, Q_{GWit}, but also on Q_{GWjt}. Suppose the city *j* pumps more water at time *t* resulting in less Q_{GWj}. Since θ_{ji} is stock dependent such that $\frac{\delta \theta_{ji}}{\delta Q_{GWit}} < 0$, and $\frac{\delta c(Q_{GWit})}{\delta Q_{GWit}} u_{it} \left(1 - \frac{\delta R_{it}(u_{it}, Q_{SWit})}{\delta u_{it}}\right) > 0$, a decline in Q_{GWj} brings down the magnitude of the right-hand side of the equation (2.9), resulting in a lower level of marginal benefit, $\frac{\delta B(u_{it}, Q_{SWit})}{\delta u_{it}}$, to be in equilibrium. This implies that an increase in pumping activity in one city affects the welfare of another city negatively (a negative spatial externality).

Another critical question is whether the social cost incurred due to groundwater pumping can be compensated by consuming surface water. The benefit function in the above optimization problem includes river water (Q_{SWt}). An increase in Q_{SWt} implies a proportionate decrease in groundwater pumping to produce a higher level of social benefit. However, the net impact of substituting groundwater with surface water can be determined only if a cost function of supplying surface water is incorporated in the model.

Finally, turning to the impact of drought, the drought has no direct impact on equilibrium conditions, as it does not appear in the three necessary conditions. However, based on the groundwater recharge and drought damage function, it reduces groundwater stock, which ultimately produces a lower level of equilibrium. Another way the drought

impact could be analyzed is to make it a determining factor of groundwater recharge that is adversely affected by drought severity (Scanlon et al. 2012). If that is the case, then a drought will reduce the value of $\frac{\delta R_{it}}{\delta u_{it}}$ in equation (2.5), resulting in an increase in the value of the marginal unit of groundwater stock and decreasing present period pumping.

2.4. System Dynamics Model

From the methodological point of view, optimization and simulation are two prominent methods that are being used for designing and implementing hydro-economic models, models that incorporate both hydrological and human components to analyze water-related issues. While an optimization model is suitable to answer the question "What is best?", The simulation model is used to respond to the "What if?" question (Harou et al. 2009). Although both approaches have their pros and cons, the optimization approach needs an objective function that's hard to construct. MCost of the optimization models seek to maximize social benefit function, whose exact structure is almost impossible to recognize. This is because a social benefit function is an aggregation of individual preferences and it is not possible to construct social preferences from arbitrary individual preferences (Arrow 1950). Furthermore, multiple nonlinearities, combinatorial relationship, and uncertainties make it challenging to implement an optimization model (Glover et al. 1999). Simulation models, on the other hand, are particularly suitable if a situation is too complicated and uncertainties are associated with it (Glover et al. 1999), and if there is a broad range of opinions regarding sustainability.

Using dynamic simulation models to address the complex nature of problems in water resource management has a long tradition (Rogers and Fiering 1986, Winz et al.

2009). System Dynamics Modeling (SDM), Discrete Event Simulation (DES), and Agent Based Modeling (ABM) are three methods of dynamic simulation models (Marshall et al. 2015). While DES and ABM are most suited for process-centered problems and individual-level problems, respectively, SDM is suitable if a problem requires systemwide perspective (Marshall et al. 2015). SDM is commonly used when the aim is to integrate various systems influencing water resource management for solving inter- and intra-sectoral long-term problems (Winz et al. 2009).

System dynamics is a system-level modeling methodology that is formulated with the premise that the structure of a system governs system behavior (Sterman 2000, Tidwell et al. 2004). An SDM starts with a conceptual model. A conceptual model is constructed using causal loop diagrams--diagrams that help us to visualize how different variables in the system are interrelated--that enable us to understand the high-level dynamics that have effects on all interacting systems (Brookshire et al. 2016). A conceptual model is followed by a numerical model constructed using stock and flows that allow us to visualize the working of the systems and to investigate the impact of various shocks on the system through simulation (Winz et al. 2009).

The SDM developed for this study is based on the theoretical model formulated in the previous section. As in the theoretical model, the SDM has four systems interacting together – surfacewater, groundwater, water demand, and drought. The difference is that, while the theoretical model aggregates all these systems individually and represents each system by one variable, the SDM disaggregates these variables into several other variables. For example; water demand in the theoretical model is represented by a single variable, u; in the SDM, it is disaggregated into residential (indoor, outdoor), industrial,

and commercial demand. Similarly, both SDM and theoretical models are spatial and dynamic. Now the obvious question is why SDM, which is expensive compared to optimization models in terms of time and other resources needed to formulate, are used if the theoretical model gives the best result.

An analytical solution of a problem is the first best solution. However, finding an analytical solution is a difficult task and the difficulty increases with complexity. A meaningful analytical solution requires explicit functional forms. This requirement of a theoretical model and its solution makes it intractable. However, pieces of a model are tractable. When a system of equation is too complex for analytical solution, then the functioning of the system can be analyzed using simulation. This is because this study employs the SD modeling approach instead of finding an optimal solution based on the theoretical model. Different scenario outcomes represent the first-order necessary condition and there is always a chance that the one outcome can be the optimum outcome.

Figure 2-2 shows the conceptual model for this study. The conceptual model represented by the causal loop diagram depicts primary variables interacting with each other to affect water demand and supply in the study area. Arrowheads with a plus (+) or minus (-) sign represent the direction of causality. For example, an arrowhead originating from the variable drought connecting to the variable demand with a positive sign indicates that increasing the severity of drought causes a rise in demand for water. The bold-faced variables in Figure 2-2 represent the center of the three sub-models: surface water model, groundwater model, and economic model. Combining these three sub-

models gives the whole system to be discussed in this study. Each sub-model is discussed separately in the following sections.

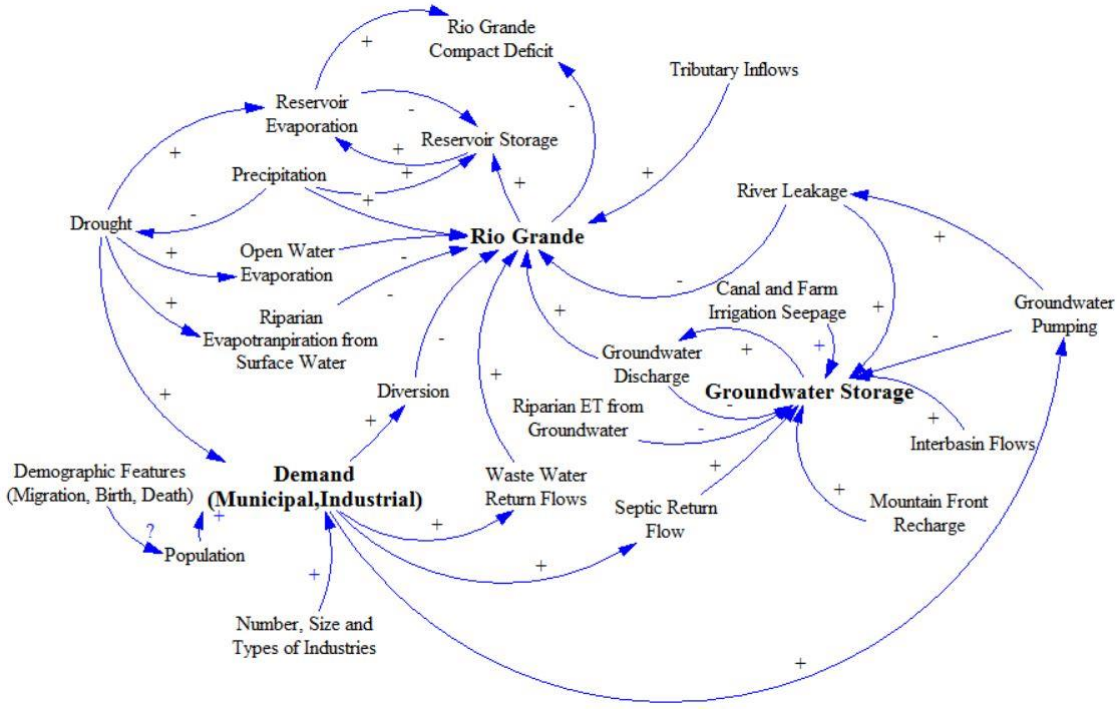


Figure 2-2: Conceptual Framework

2.4.1 Hydrological Model

The hydrological model for this study is borrowed from Roach and Tidwell (2006a), Roach and Tidwell (2006b), and Tidwell et al. (2004) and extended these models by adding the drought variable. These two studies have developed a system dynamics model of surface water and groundwater dynamics for the entire Rio Grande system in New Mexico that extends from near Lobatos, Colorado to Caballo Reservoir. This study uses only the Middle Rio Grande section of those two models for its purpose. The MRG section includes Valencia, Bernalillo, and Sandoval County in terms of political boundaries and the Albuquerque groundwater basin regarding the hydrological boundary that includes the Rio Grande spanning from Cochiti Reservoir in the north to

San Acacia in the south. However, in this section, the above two models are summarized as a convenient way to comprehend the system dynamics model developed for this study.

2.4.1.1 Surface Water Model

Roach and Tidwell (2006a) developed a physically based monthly time step model of surface water dynamics. The surface water model is an aggregation of the sub-models for the Rio Grande and its two major tributaries: the Rio Chama and Jemez Rivers, 32 gaze locations, 17 reaches, and seven reservoirs. These physical extents of the model and reach locations are shown in Figure 2-3.

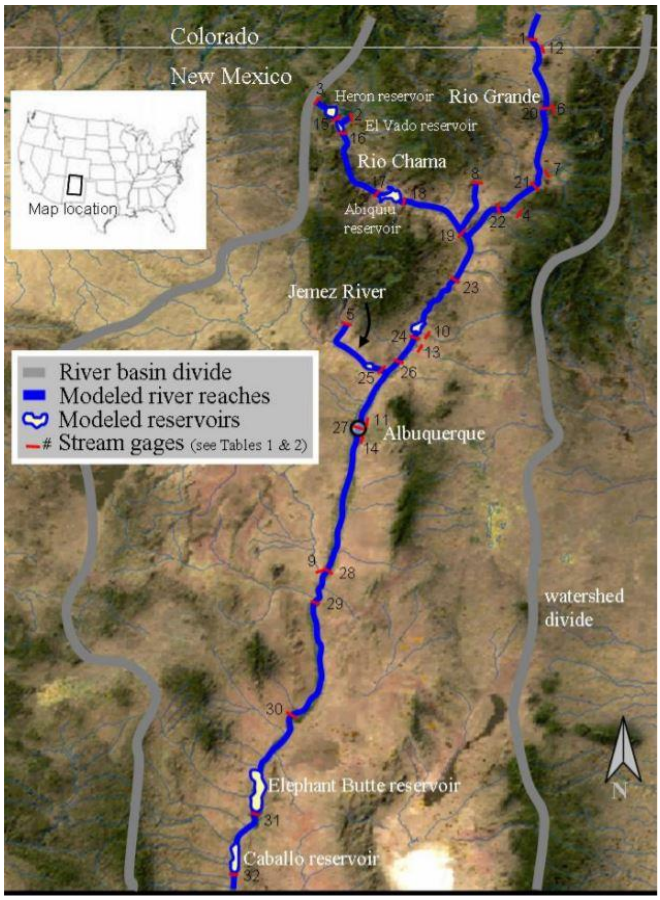


Figure 2-3: Physical Extent of Hydrological Model and Reach Locations
Source: Roach and Tidwell (2006a)

The conceptual model of the surface water is shown in Figure 2-4. The central part of the model is the Rio Grande. While the Rio Grande gains water from surface water inflows and returns flows, groundwater seepage, and direct precipitation, the loss of the river water is through surface water diversion, leakage to the groundwater system, and open water evaporation. River routing, reservoir operations, open water evaporation, riparian evapotranspiration, river diversion, return flows, and groundwater interaction conditional on the magnitude of agricultural, municipal, industrial, and environmental demand are the components of the surface water balance in the model. Inflows and outflows of the surface water system are discussed below.

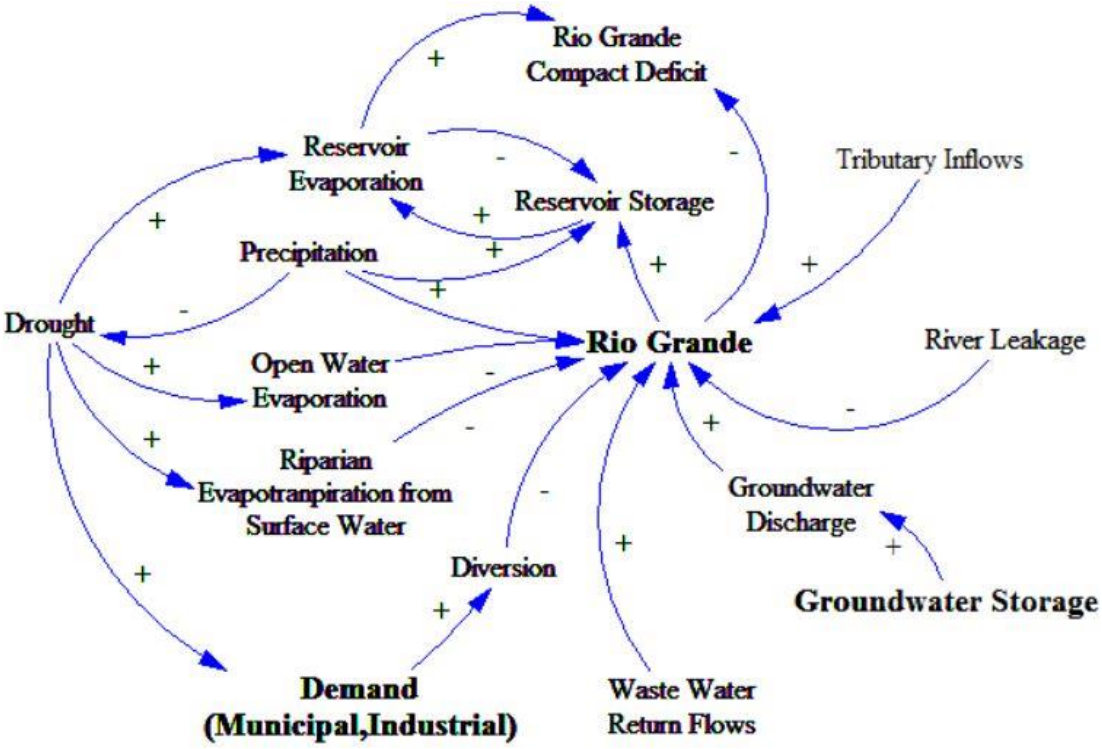


Figure 2-4: Conceptual Framework for Surface Water Model

Inflows: The major component of the surface water inflow in the MRG is the mainstem Rio Grande. Rio Grande inflow has been modeled at Otowi gage (indicated by 23 in Figure 2-3), where annual average flow for the period 1975-1999 was 1,200,600 AF per

year (AF/yr) (Roach and Tidwell 2006a). The contribution of tributaries that include Rio Jemez, Santa Fe River, Galisteo Creek, North Floodway Channel near Alameda, South Diversion Channel near Albuquerque, and Tijeras Arroyo is about 77,000 AF/yr[3]. Waste water flow from the cities of Bernalillo, Rio Rancho, Albuquerque, Los Lunas, and Belen added about 61,000 AF water per year, on average, to the Rio Grande during 1996-1999.

Another important inflow to the MRG surface water is the diversion from the San Juan Chama Project (SJCP). Since 1971, 110,000 AF/yr of water from the San Juan river basin has been diverted to the Rio Grande River basin via the Chama River, a tributary of the Rio Grande. Of the total diverted water, the city of Albuquerque (CoA) and Middle Rio Grande Conservancy District (MRGCD) receive 43.8% and 19%, respectively. Remaining water is received by other small contractors, including the city of Santa Fe, and the city of Los Alamos.

Stormwater could be another source of inflow in the surface water model. However, even though the peak storm flow in the City of Albuquerque may exceed 4,000 ft^3/s for very brief period of time (Langman and Anderholm 2004), average annual storm water inflow is only about 4,800 AF/yr (Dahm et al 2002), which is less than 0.4 percent of the annual average water flow in the main stem Rio Grande. Furthermore, other cities in the study area are much smaller than the CoA, and undeveloped areas in and near CoA produce negligible storm water runoff (Kosco et al. 2014). Due to the negligible impact on Rio Grande flow and the tedious modeling task, storm water inflow to the Rio Grande

[3] Rio Jemez (5,4834 AF/yr), Santa Fe River (8,680 AF/yr), Galisteo Creek (4,150 AF/yr), North Floodway Channel near Alameda (7,868 AF/yr), South Diversion Channel near Albuquerque (560 AF/yr), and Tijeras Arroyo (527 AF/yr).

is omitted from the model. Furthermore, it is also assumed that there is a negligible impact of precipitation in the river water. Finally, groundwater discharge to surface water in the MRG for 1994 has been estimated to be 4,400 AF/yr into rivers, canals, and reservoir and 219,000 AF/yr of discharge into drains (Kernodle, McAda, and Thorn 1995). However, this variable has been used to calibrate the model instead of using historical data. This issue will be discussed later in the calibration section.

Outflows: Modeled surface water outflows are reservoir evaporation, open water evaporation, riparian evapotranspiration, diversion, and Rio Grande compact balance. The reservoir evaporation is modeled for the MRG in Abiquiu, Cochiti, and Elephant Butte reservoir. While pan evaporation was measured for Abiquiu and Cochiti for April through October, it was measured during all months for Elephant Butte, where the evaporation pan does not freeze. Reservoir evaporation in Abiquiu, Cochiti, and Elephant Butte reservoir is roughly 5,000 AF/yr-20,000 AF/yr, 5,000 AF/yr, and 50,000 AF/yr-250,000 AF/yr, respectively. Similarly, open water evaporation from the Rio Grande and associated sand bars averages 28,000 AF/yr.

Riparian evapotranspiration is another source of surface water loss in the MRG. Riparian acreage, spanning from Cochiti to San Acacia, used in the model is 41,540 acres that grow mainly cottonwood, willow, Russian olive, salt cedar, New Mexico privet, elm, shrubs and grasses. On average, water loss due to riparian evapotranspiration has been estimated to be 84,000 AF/yr.

The Middle Rio Grande encompasses 277,760 acres, with 123,000 acres of irrigable land, of which roughly 60,000 acres are irrigated (Gahn 2013). Forage crops like alfalfa and pasture hay are grown on about 80% of irrigated land (Tidwell et al. 2004).

The Rio Grande supplies a major portion of irrigation water through a 1,230-km network of canals, laterals, and ditches maintained by the Middle Rio Grande Conservancy District (MRGCD). South of Cochiti to San Acacia, on average, 561,000 AF/year of water are diverted from the Rio Grande for irrigation purposes. On average, consumptive use of water is 131,336 AF/yr and the evapotranspiration rate, aggregated over all crops, is about 28 inch/yr (Tidwell et al. 2004). Besides the direct consumption by crop, other irrigation losses are irrigation seepage, conveyance seepage, consumptive losses from the conveyance system that reach a magnitude 2.4 AF/yr, 91,000 AF/yr, and 9,700 AF/yr, respectively.

New Mexico, Colorado, and Texas signed the Rio Grande Compact (RGC) in 1938. The amount of water that New Mexico is entitled to deplete depends on the annual flow of water measured at Otowi gage. According to the compact, New Mexico is allowed to deplete 43% of the water when the annual flow of the Rio Grande at the Otowi gage is very low. This percentage goes down to 13% when the annual flow of the Rio Grande at the Otowi gage is very high. In an average year, 1.1 million AF of Rio Grande water flows past the Otowi gage. This entitles New Mexico to consume 393,000 AF of water. The compact apportions the water for upper, middle, and lower reaches of the Rio Grande in New Mexico. The Middle Rio Grande planning region falls in the middle reach. Middle reach can deplete a maximum 405,000 AF/yr water plus the inflow to the Rio Grande between the Otowi gage and Elephant Butte Dam. Per the RGC, New Mexico's deliveries are measured as the releases from the Elephant Butte Dam plus the change in storage in Elephant Butte reservoir. Evaporative loss from the Elephant Butte reservoir is thus credited to the middle region.

Municipal use is another source of outflow in the Middle Rio Grande. Among the three modeled cities, Albuquerque, Santa Fe, and Rio Rancho, the first two cities use both surface water and groundwater for meeting the demand. The City of Albuquerque diverted 48,702 AF water from the Rio Grande for its drinking water project and an additional 2,638 AF of surface water from the Rio Grande for the Non-Potable Surface Water Reclamation Project (Stansifer 2016). Similarly, the city of Santa Fe diverts 8,730 AF water annually from the Rio Grande via Buckman diversion.

***Numerical Model for Surface Water[4]*:** This study borrows the numerical model from Roach and Tidwell (2006a), which adopted the spatial system dynamics approach to model surface water dynamics in the middle Rio Grande. The model divides the river system into 17 conceptual spatial units referred to as reaches and includes seven reservoirs in the model. Three mass balance equations--mass balance in reach, reservoir, and conveyance system--are the fundamental equations of the surface water model. The mass balance equation for a reach (j) is given as:

$$Q^j_{msout} = Q^j_{msin} + Q^j_{sw} + Q^j_{gwsw} - Q^j_{evap} \tag{2.10}$$

Where,

Q^j_{msout} = mainstream flow out of the bottom of reach j

Q^j_{sw} = net sum of all surface water inflows into and diversions out of reach.

[4] The detail of the numerical model for surface water and groundwater used in this study can be found in Roach and Tidwell (2006a) and Roach and Tidwell (2006b). Annex C of this paper presents an extended summary of these models.

Q^j_{msin} = mainstream flow into the reach *j*

Q^j_{gwsw} = net sum of all interactions between the river and groundwater system in the reach, and is positive for a groundwater gaining, and negative for a groundwater losing reach.

Q^j_{evap} = Open water evaporative losses

Similarly, the mass balance equation for the reservoir is calculated using the equation (2.11).

$$\Delta S^r = Q^r_{sw} + Q^r_{precip} - Q^r_{gw} - Q^r_{evap} - Q^r_{release} \quad (2.11)$$

Where

ΔS^r = change in storage for a given time step at reservoir *r*

Q^r_{sw} = gaged and ungagged surface water inflows

Q^r_{precip} = precipitation that falls directly on the reservoir surface

Q^r_{gw} = groundwater leakage from the reservoir

Q^r_{evap} = evaporation from the reservoir

$Q^r_{release}$ = release from the reservoir including spills

Mass balance in the conveyance system assuming negligible direct evaporation losses from conveyance features is modeled as in equation (2.12)

$$Q^j_{swdiversion} + Q^i_{convtf} = Q^j_{cropET} + Q^j_{convgw} + Q^j_{swreturn} + Q^j_{convtf} \quad (2.12)$$

Where,

$Q^{j}_{swdiversion}$ = diversion from the reach *j*

Q^{i}_{convtf} = flow from the conveyance system immediately upstream

Q^{j}_{convET} = Evapotranspiration from crop

Q^{j}_{convgw} = Conveyance water-groundwater exchange. It is positive if the conveyance system gains water from groundwater system and vice versa.

$Q^{j}_{swreturn}$ = Surface water flows out of the conveyance system to the river

Q^{j}_{convtf} = Surface water flows out of the conveyance system to the downstream conveyance system

Each reach gains water from gaged and ungagged surface water inflows, and return inflows, and loose water through surface water diversion. Evaporation, precipitation, and interaction between surface water and groundwater are other three components of the surface water model that are estimated using standard equations as explained in Annex C.

4.1.2 Groundwater Model

The groundwater model for this study is borrowed from Tidwell et al. (2004), Roach and Tidwell (2006a), and Roach and Tidwell (2009). Figure 2-5 depicts the conceptual model of the groundwater dynamics. At the center of the groundwater model is the groundwater storage or aquifer. The aquifer of the Albuquerque basin is an unconfined aquifer that gains water from interbasin flows, mountain front recharge, river

leakages, canal and farm irrigation seepage, and septic return flow. The sources of groundwater outflows are demand-induced groundwater pumping and groundwater discharge to the Rio Grande.

The groundwater inflows include 31,000 AF/yr from interbasin inflows, 12,000 AF/yr from mountain front recharge, 4,000 AF/yr from septic return, 90,000 AF/yr from canal seepage, and 35,000 AF/yr from crop-irrigation seepage (McAda and Barroll 2002). Similarly, groundwater outflows include 84,000 AF/yr from riparian evapotranspiration, 150,000 AF/yr from pumping, and 341,000 AF/yr from interior and riverside drains.

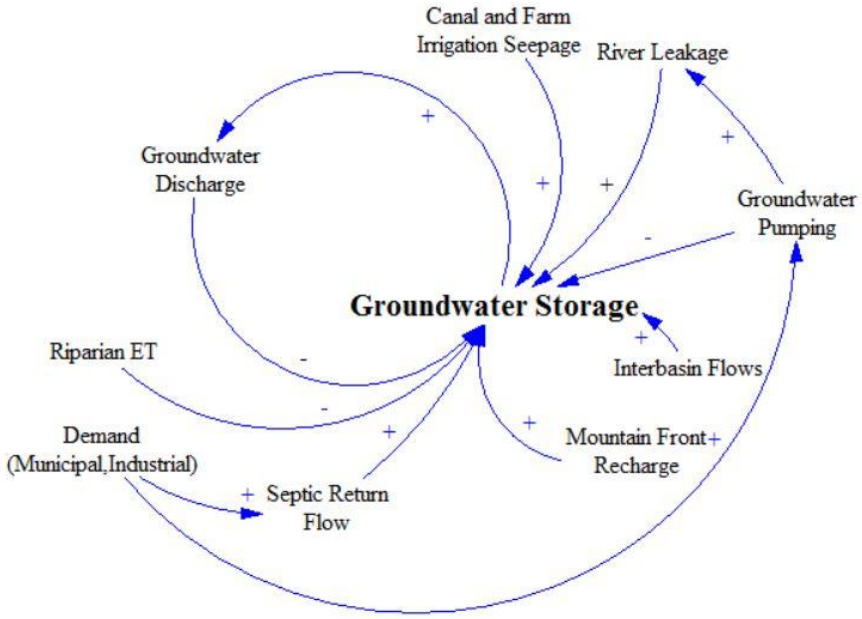


Figure 2-5:Conceptual Framework for Groundwater Model

The groundwater inflows include 31,000 acre-feet/yr from interbasin inflows, 12,000 acre-feet/yr from mountain front recharge, 4,000 acre-feet/yr from septic return, 90,000 acre-feet/yr from canal seepage, and 35,000 acre-feet/yr from crop-irrigation seepage (McAda and Barroll 2002). Similarly, groundwater outflows include 84,000 acre-feet/yr from riparian evapotranspiration, 150,000 acre-feet/yr from pumping, and 341,000 acre-feet/yr from interior and riverside drains.

***Numerical Model for Groundwater*:** Tidwell et al. (2004), Roach and Tidwell (2006a), and Roach and Tidwell (2009) adopted the compartmental spatial system dynamics (CSSD) approach to model groundwater dynamics. In this approach, the Albuquerque basin aquifer is divided into 51 zones (Figure 2-6) and analysis is carried out for each zone (or compartment) simultaneously using the spatial system dynamics (SSD) method.

The basic equation for the groundwater model is the change in storage of water in any zone over a period, which is equal to the sum of net inflows into the zone from other zone and boundary flows to the zone. Boundary flow includes ET, well extraction and injection, recharge, stream leakage, and drain capture. Aquifer storage in a zone is calculated as a function of head, specific yield, and bottom elevation of the zone. Similarly, the groundwater model also estimates river-aquifer and reservoir-aquifer interactions, groundwater flow to the agricultural drains, and ET through shallow aquifer. Equations used to estimate the value of these variables can be found in Appendix C and in Roach and Tidwell (2006b).

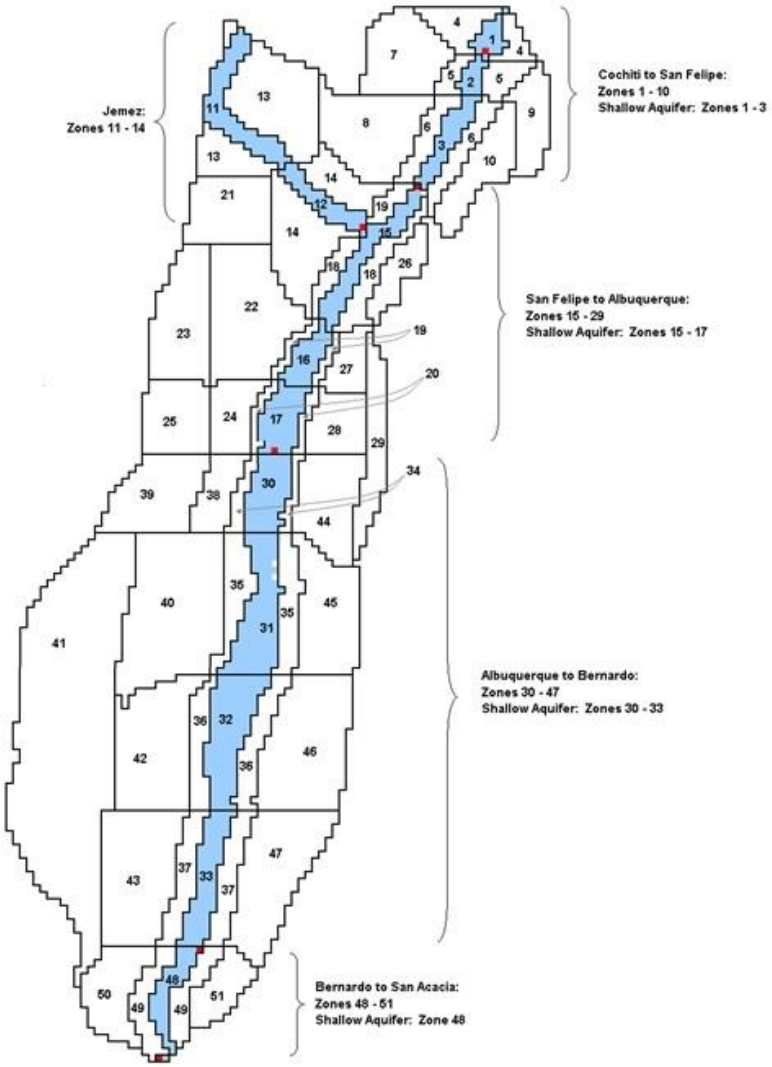


Figure 2-6: Albuquerque Basin Aquifer Compartments
Source: Roach and Tidwell (2006b)

2.4.2 Economic Model

The contribution of this paper is to develop an economic model in a system dynamics framework and dock it with the hydrological model developed by Roach and Tidwell (2006a, 2006b) with an extension by adding a drought variable. It is necessary to integrate an economic model with a hydrological model because an analysis in isolation may result in a substandard policy prescription. It has been pointed out that the true picture of climate change impact can be obtained through considering interactions

between climate change and variability, surface and groundwater hydrology, water engineering, and human systems (Vörösmarty et al. 2000).

The economic model simulates the impact of spatial and dynamic water demand on surface and ground water of the Middle Rio Grande basin. Three cities considered for the economic model are Albuquerque, Santa Fe, and Rio Rancho. Although these cities are adjacent to each other, they are very different in terms of population and sources for water supply. All three cities see increasing water scarcity in the future, but are considering different ways of coping. For example; while Rio Rancho is experimenting with injection of reclaimed water into the aquifer, Albuquerque is focusing on several plans, including reliance on surface water with groundwater being a drought reserve.

The conceptual framework for economic model is shown in the Figure 2-7.

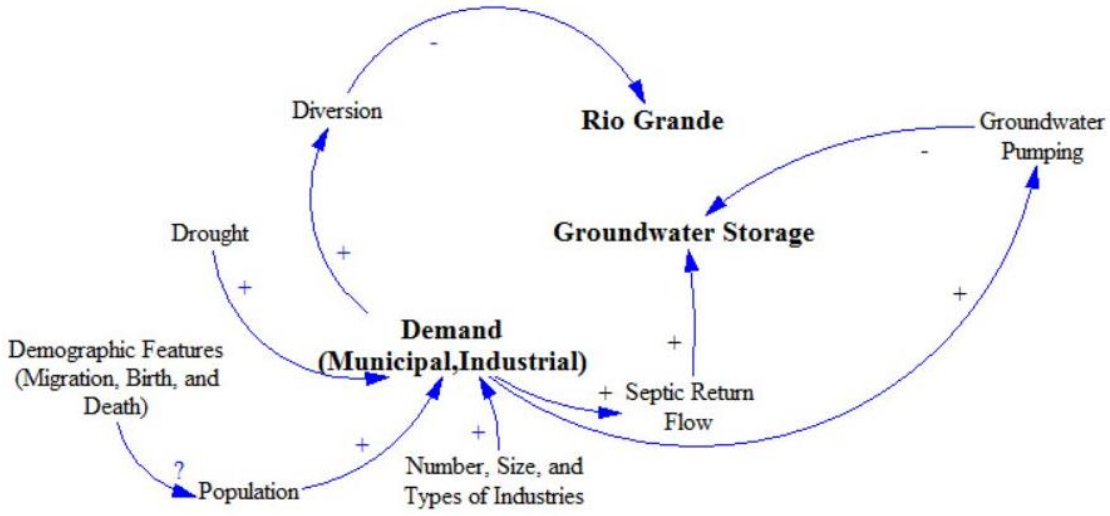


Figure 2-7: Conceptual Framework for Economic Model

The central part of the economic model is the demand for water from the residential, business, and industrial sectors. While Albuquerque and Santa Fe utilize both sources of water and groundwater, Rio Rancho is dependent on groundwater only to meet

the demand. In 2015, the City of Albuquerque supplied 82,181 AF of water (Yuhas 2016). Of the total supplied water, 55% was diverted from the Rio Grande and the remainder was pumped from its 50 operating wells. Total waste water in Albuquerque for the same year was 55,552 AF--about two-thirds of the total supplied water. The breakdown of the total supplied water for Albuquerque is shown in Figure 2-8.

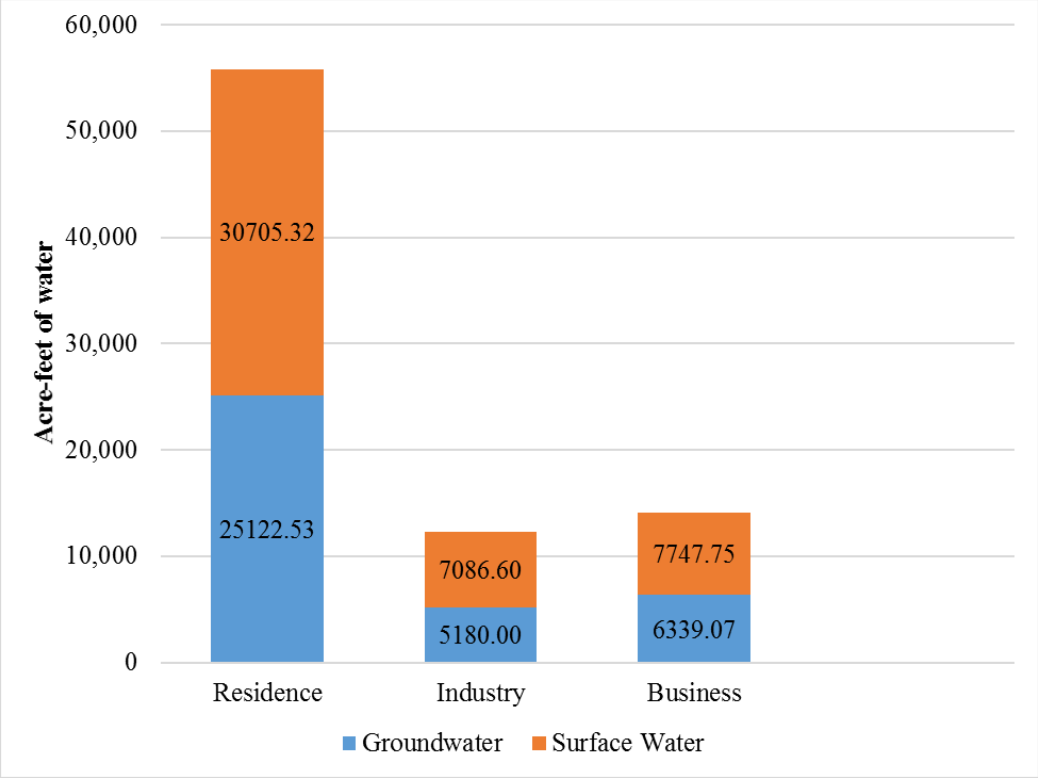


Figure 2-8: Water Supply for Different Sectors in Albuquerque, 2015 *(in Acre-feet)*[5]

The City of Rio Rancho (CoRR) depends solely on the groundwater. CoRR supplies water through its 15 operating wells distributed over the service area. Rio Rancho produced 3.9 billion gallons of water in 2006 (Water Prospecting and Resource

[5] Industry includes both industry and institution. Intuitional use of surface water and groundwater is 6,807 acre-feet and 4,950 acre-feet respectively.

Consulting, 2007). Out of the total production, about two-thirds (67%) is consumed by the residential sector and multifamily households, followed by the commercial sector (18.8%), city and hydrant (9.2%), and the industrial sector (4.9%). One of the largest consumers of water in the city of Rio Rancho is Intel Corportaiton. Intel uses about 4 million gallons of water per day and returns 85 percent to the Rio Grande. However, the majority of Intel's water usage is from its own wells.

Santa Fe uses both ground and surface water to meet the demand. However, about 85% of total need is fulfilled from surface water of the Santa Fe river and Buckman diversion. In 2015, the City of Santa Fe supplied 8,167 AF water through its four sources: the Santa Fe River (3,509 AF), the Rio Grande (3,403 AF), the city well field (626 AF), and Buckman well field (629 AF) (City of Santa Fe 2015). Out of the total billed water in Santa Fe, the single-family residential sector used 56%, the multifamily sector used 11%, and the commercial sector used 23% (City of Santa Fe 2015). The City of Santa Fe operated 20 wells to produce groundwater and treated 5,844 AF of waste water (72% of the total water supplied). In 2015, 18% of the treated wastewater was reused and the remaining 82% flowed into the lower Santa Fe River (City of Santa Fe 2015).

It is obvious that population increase results into increased water use. However, this phenomenon seems to be opposite for the above three cities. From 1990 to 2010, the populations of Albuqerque, Santa Fe, and Rio Rancho increased by 21.64%, 9.23%, and 69.07%, respectively. In the same time, the water consumption per capita per day declined by 27.3%, 24.1%, and 22.7%, respectively. Although the per capita consumpion of water has declined, the total volume of water consumption increased in Rio Rancho due to a larger rate of population growth than the rate of declining per capita

consumption. The decline in the per capita water consumption in these three cities is attributed to water conservation measures adopted by the authorties concerned.

Table 2-1: Population and Water Consumption in Three Cities

Cities	Population		Percentage change in population	Per capita per day water consumption in gallons (GPCD)		Percentage change in GPCD
	2000	2010		2000	2010	
Albuquerque	448,607	545,695	21.6	216	157	27.3
Santa Fe	62,203	67,947	9.2	137	104	24.1
Rio Rancho	51,765	87,521	69.1	188.36	145.64	22.7

Source: Reed (2016), City of Santa Fe (2016), City of Rio Rancho (2014), U. S. Census Bureau (2000), U. S. Census Bureau (2010)

***Numerical Economic Model*:** The economic model is centered on demand for water in the study area. Demand for water is composed of demand from the residential and industrial sectors. Demand for water from business, industry, and institutions is modeled together under industrial demand. Residential water demand is determined by economic, demographic, and different perception variables for a household. The marginal impact of these variables on water demand was estimated using a regression equation that will be discussed below.

Figure 2-9 shows the factors determining the residential water demand. Residential water demand is first estimated for a household. The estimated household demand is multiplied by the total number of households in the city (total population divided by average household size of the city) to obtain total residential water demand for a city. The sum of the residential water demands of the three cities modeled gives the total residential water demand for the study area.

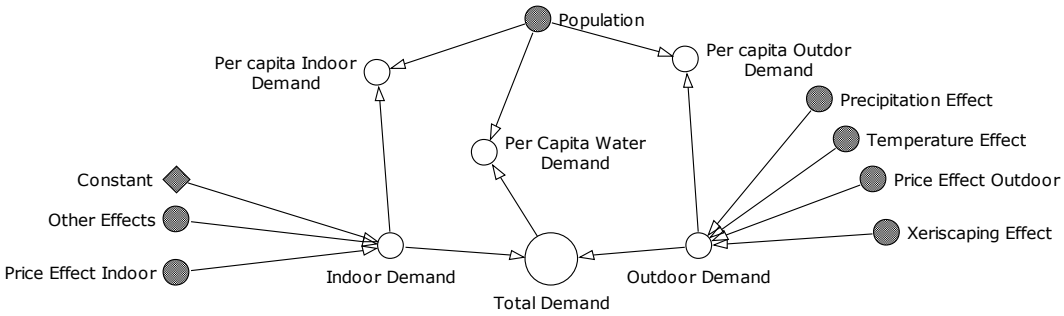


Figure 2-9:Powersim Model of the Residential Water Demand

Industrial water demand, on the other hand, is determined by the number and type of industries, incudes businesses and institutions, and the number of people employed in those industries. Classification of industry in this study is based on NAICS classification. Initial distribution of total employment in each industry is based on the Bureau of Labor Statistics data for the study area. After that, the employment in each sector grows every year by a chosen growth rate of the sector. Industry-specific water use per worker multiplied by the number of those employed thus gives the industrial water demand. Furthermore, if the total working-age population in a year exceeds the total estimated employment, then there is outmigration and vice versa. In migration, out migration, and labor supply are modeled by a population model that provides input for both industrial water demand and residential water demand. The schematic diagram of the population model implemented in the Powersim studio is shown in the Figure 2-10.

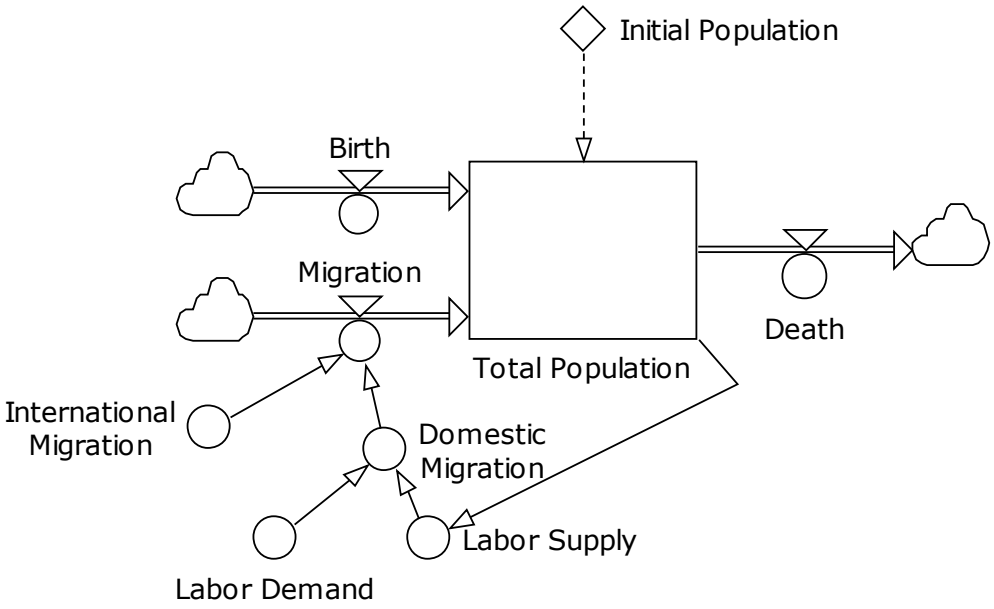


Figure 2-10:Schematic Diagram of Population Model in the Powersim Studio

Based on the outline of the water demand model discussed above, total water demand can be represented by the following equation in which residential water demand has been decomposed into indoor demand and outdoor demand.

$$W_t^D = W_t^{ID} + W_t^{OD} + W_t^{ICD} \tag{2.13}$$

Where,

$W_t^D =$ Total water demand at time *t* in three cities

$W_t^{ID} =$ Indoor water demand at time *t* in three cities

$W_t^{OD} =$ Outdoor water demand at time *t* in three cities

$W_t^{ICD} =$ Institutional, business, industrial water demand at time *t* in three cities

2.4.2.1 Residential Water Demand Model

Residential water demand (sum of W_t^{ID} and W_t^{OD}) function is estimated using random effect panel regression model. The data for the regression were generated from an experiment conducted at the University of New Mexico. There were 205 participants in the experiment[6]. The experiment was able to generate a data set that was equivalent to panel data. Wooldridge test for autocorrelation (Wooldridge 2010) and Breusch-Pagan lagrangian multiplier test (Breusch and Pagan 1980) with *p*-value equal to zero for both tests suggested using random effect model. The estimated outdoor demand indoor demand equation and the experiment were conducted using Albuqurque consumers as subjects. Equations (2.14) and (2.15) are the estimated indoor and outdoor demand function.

$$W^{OD} = 0.943 - 0.384\, price\_reg + 1.395\, odchng\_reg + 4.621\, oduse\_reg + \hat{\boldsymbol{\beta}}_1 \mathbf{X} \qquad (2.14)$$

$$W^{ID} = 0.943 - 0.176\, price\_reg - 0.195\, indchng\_reg - 2.309\, induse\_reg + \hat{\boldsymbol{\beta}}_2 \mathbf{X} \qquad (2.15)$$

Where,

$price\_reg$ = price per water unit (748 gallon) used in the regression. *pricereg* data is obtained from the experiment.

$odchng\_reg$ = Outdoor change (i.e., it takes value 1 if there is change in outdoor water use volume in next round of experiment)

[6] Residential demand is based on basic results of a water demand experiment carried out at UNM. More information and results can be found in Chermak et al. (2017).

$indchng\_reg$ = Indoor change (i.e., it takes value 1 if there is change in indoor water use volume in next round of experiment)

$oduse\_reg$ = Takes value 1 if the household has outdoor water use activities like swimming etc.

$induse\_reg$ = Takes value 1 if the household has indoor water use activities.

X = Vector of other variables used in the regression. Other variables include *income, race, gender, political belief, religion, location in the Albuquerque area, water attitude, xeriscape, and risk.*

A list of variables used in the regression and their descriptive statistics is given in Table A1. Here, it is important to note that the marginal impact of these variables on water demand was generated through an experiment run for the Albuquerque resident household. In the simulation, however, these marginal impact values (coefficient of the variables in the regression equation) are assumed to be applicable for the city equally. It is further assumed that these values are representative for Santa Fe and Rio Rancho too.

Validity of the estimated marginal impact was checked by comparing price elasticity for indoor and outdoor demand for water with similar studies. Price elasticity for outdoor and indoor demand at mean in this study was estimated to be 0.26 and 0.12 respectively. These elasticity estimates fall within the range of elasticities estimated for various cities in the United States for different times (Dalhuisen et al. 2003, Espey and Shaw 1997).

Definition, measurement, and values of each effect on indoor water demand are discussed below. The variables that determine indoor water demand are categorized into economic, demographic, perception, and technology variables.

A. Economic Variables: Economic variables considered in the indoor water demand model are price, income, and education.

Price Effect

Price effect represents the impact of water rate on indoor water demand. Coefficient of price in the regression equation is 0.18, implying that an increase in price by 1 unit reduces water demand by 0.18 unit. The price effect is thus:

$$PE = -0.18P_w \tag{2.16}$$

Where,

$PE =$ Price effect on water demand

$P_w =$ Water rate

The three modeled cities adopt different water rate structures. The City of Albuquerque imposes a fixed monthly charge that varies by meter size plus commodity charge and other charges (*see* Table A6). For modeling purposes, the water rate for Albuquerque is assumed to be $0.57 per unit of water (1 unit of water = 748 gallons) until 1998 and $0.635 per unit of water after 1998. The modeled water rate for Albuquerque represents the water rate for the 1980s and 1990s. Current water rate structures for Rio Rancho and Santa Fe are presented in Table A7. For modeling purposes, the water rate of $2.04 per unit of water and $3.88 per unit of water until 1998

and $2.105 per unit of water and $3.945 per unit of water after 1998 were used for Rio Rancho and Santa Fe, respectively.

Income Effect

Income effect in the model captures the impact of the growth in the cities on the water resources. Other things remaining same, in most of the case, there is a positive relationship between income and quantity of water demanded (Agthe and Billings 1980, Dalhuisen et al. 2003). The estimated regression equation for this study gives the coefficient of income as 0.0012. Using this coefficient, the income effect is modeled as:

$$IE_i = 0.0012 Inc_i \tag{2.17}$$

Where,

$IE_i =$ Income effect in city i

$Inc_i =$ Total income of the city i

Total income of a city is calculated as a product of employment and wage. As will be discussed later, employment and wages are disaggregated by The North American Industry Classification System (NAICS) division of industries.

$$Inc_i = \sum_s wage_{is} emp_{is} \tag{2.18}$$

Where,

$wage_{is} =$ Wage rate in city i and industrial sector s

$emp_{is} =$ Total number of employed individuals in city i and industrial sector s

Education Effect

Impact of education on water demand is well established. *Ceteris paribus,* a higher level of education leads to higher level of water demand. The estimated regression included several education dummy variables. But only the coefficient (1.94) of dummy for bachelor's or master's degree was statistically significant. The model thus incorporates this coefficient only to construct the education effect.

$$EDUE_i = 1.94 EDUP_i \tag{2.19}$$

Where,

$EDUE_i$ = Education effect in city *i*

$EDUP_i$ = Proportion of population with a bachelor's or master's degree in city *i.*

The values for $EDUP_i$ are 32.2%, 43.4%, and 27.2% for Albuquerque, Santa Fe, and Rio Rancho, respectively.

B. Perception Variables: Perception variables considered in the indoor water demand model are political belief, religious belief, and water attitude.

Political Belief Effect

There is evidence that the political beliefs of a consumer affect demand for water (Chermak and Krause 2001). Therefore, political belief effect is included in the model. The coefficient of the political belief variable in the estimated regression equation is -3.5. Thus, the political belief effect function is:

$$PBE = -3.5 PB \tag{2.20}$$

Where,

$PBE =$ Political belief effect

$PB =$ Political belief

The PB variable in the model is controlled through a slider bar. However, the result in this paper is based on $PB = 0.2$ throughout the simulation period. Here 0.2 represents that 20% of the study area population are Democrats.

Water Attitude Effect

There are statistical evidences for the link between people's attitudes toward the environment and water consumption, and end use water consumption (Adhikari et al. 2016, Willis et al. 2011, Lam 2006). Adhikari et al. (2016) found in Albuquerque, NM, that people who think water issues are a serious problem in the city are ready to pay more for water conservation efforts. Willis et al. (2011) found in Aurora, CO that residents with very positive environmental and water conservation attitudes consumed significantly less water. Water attitude in this study is incorporated using equation (2.21).

$$WAE_i = -0.6WA_i \tag{2.21}$$

Where,

$WAE_i =$ Water attitude effect in city i

$WA_i =$ Water attitude. If there is no change in water attitude, then it takes value 1. Positive attitude toward water conservation results in higher WA_i value.

In the equation (2.21) the coefficient -0.6 is obtained from the estimated regression equation explained earlier. In the model, the value of WA_i can be controlled using a slider bar. However, for this study the value is 1.

Atheist Effect

Whether religious belief shapes environmental-related behavior or not is a question for debate. There are arguments for and against this proposition (Black 1996). The variable *atheist* was included in the experimental regression and has a negative and significant coefficient of -1.83. This indicates that an atheist household consumes 1.83 units less water compared to theists. The coefficient of the variable *atheist* is used to construct the atheist effect.

$$AE_i = -1.83AP_i \tag{2.22}$$

Where,

$AE_i =$ Atheist effect in city *i*

$AP_i =$ Proportion of atheist population in city *i*

Surveys show that the proportion of the atheist population in the US is 0.016 (The Pew Forum 2008). The same value (0.016) has been used as the value of AP_i in the model.

C. Demographic Variables: Demographic variables considered in the indoor water demand model are ethnicity and age.

Latino Effect

Studies show that Latinos are having a profound effect on water consumption (Gayk 2004). A survey in the Tucson area showed that Hispanics are four times as likely

to drink bottled water as tap or filtered water (Williams et al. 2001). The regression equation used for this study also included the variable *Latino* that takes value 1 if the respondent is Latino and 0 otherwise. The coefficient of this variable is -3.9. Using this coefficient, the Latino effect is constructed as:

$$LE_i = -3.9 Latp_i \tag{2.23}$$

Where,

$LE =$ Latino effect in city *i*

$Latp_i =$ Percentage of Latinos in the population in city *i*

Latino percentage can be controlled with a slider bar for each city. The values of $Latp_i$ used for this study are 46.7%, 48.7%, and 36.7% for Albuquerque, Santa Fe, and Rio Rancho respectively.

Age Effect

Literatures reveal that the age of consumers have conflicting effects on water consumption. For example, Lyman (1992) found that older residents use more water. On the other hand, Clark and Finley (2007), and Gilg and Barr (2006) showed that older residents are more likely to conserve water. The coefficient of the variable *age* in the regression used for this study is significant with value 0.14, implying that an increase in age by one year leads to an increase in the consumption of water by 0.14 unit. Age effect in the model is thus incorporated as:

$$AGE_i = \left(0.56 + 0.7 AGEC_k\right) P_{ikt} \tag{2.24}$$

Where,

$AGE =$ Age effect in city i

$AGEC_k =$ Category of age cohort k. It takes value 0 for first cohort, 1 for second cohort and so on. Age cohorts are explained in the population model.

$P_{ikt} =$ Total population in cohort k of city i at time t.

The first term in the right-hand side of equation (2.24) is 0.56 due to the 4-year age range in the first cohort. The age range in the successive cohort is 5 years. It is, therefore, $AGEC_k$ is multiplied by 0.7 $\left(0.14 \times 5 = 0.7\right)$

D. Technology Variables: Technology variables correspond to whether a household uses low-flow devices or not.

Low-Flow Device Effect

Using low-flow devices reduces indoor water use. Coefficient of low-flow device (-2.31) is highly significant in the regression equation estimated. However, a particular family may not have all low-flow devices available in the market. A survey conducted in New Mexico revealed that about 90% households in the state have at least one low-flow device in their home (Hurd and Smith 2005). To incorporate the various low-flow devices separately instead of aggregating them together, three types of low-flow devices (low-flow toilet, low-flow washing machine, and low-flow dishwasher) are included in the model, assuming that 30% of total households have each device.

Price et al. (2014) estimated that low-flow toilets, low-flow washing machines, and low-flow dishwashers reduce water consumption by 37.98 gallons/day/household (1.5436 WU/month), 30.43 gallons/day/household (1.237 WU/month), and 17.84

gallons/day/household (0.7104 WU/month), respectively. Using this information, the low flow device effect is modeled as:

$$LFDE_i = LFTE_i + LFWE_i + LFDE_i \quad (2.25)$$

$$LFTE_i = -0.3 \times 1.5436 HH_i = -0.4631 HH_i \quad (2.26)$$

$$LFWE_i = -0.3 \times 1.237 HH_i = -0.371 HH_i \quad (2.27)$$

$$LFDE_i = -0.3 \times 0.7104 HH_i = -0.2131 HH_i \quad (2.28)$$

Where,

$LFDE_i =$ Low-flow device effect in city *i*

$LFTE_i =$ Low-flow toilet effect in city *i*

$LFWE_i =$ Low-flow washing machine effect in city *i*

$LFDE_i =$ Low-flow dishwasher effect in city *i*

$HH_i =$ Total household in city *i*

Constant Term

A constant term is included in the regression equation estimated. However, the constant term for per capita water use is calibrated to each of three cities. The calibrated value of the constant terms for Albuquerque, Santa Fe, and Rio Rancho are: 3.443, 5.123, and 7.613 respectively.

Outdoor demand is a sum of precipitation, temperature, price, and xeriscaping effect.

$$W_t^{OD} = TEMPE_i + PRECIPE_i + OPE_i \quad (2.29)$$

Where,

$TEMPE_i =$ Temperature effect in city i

$PRECIP_i =$ Precipitation effect in city i

$OPE_i =$ Outdoor price effect in city i

Temperature and Precipitation Effect

The estimated demand equations don't have to have temperature and precipitation variables. In order to incorporate the effect of temperature and precipitation in the water demand, the following strategy is adopted.

First, a temperature and precipitation index is calculated using equation (2.30) and (2.31)

$$T_{index} = \frac{T_{\max} - T_{avrg}}{T_{\max} - T_{\min}} \quad (2.30)$$

$$P_{index} = \frac{P_{\max} - P_{avrg}}{P_{\max} - P_{\min}} \quad (2.31)$$

Where,

$T_{index} =$ Temperature index

$P_{index} =$ Precipitation index

$T_{\max} =$ Monthly maximum temperature

$T_{\min} =$ Monthly minimum temperature

T_{avrg} = Monthly average temperature

$P_{\max}$ = Monthly maximum precipitation

$P_{\min}$ = Monthly minimum precipitation

P_{avrg} = Monthly average precipitation

Once T_{index} and P_{index} are calculated, temperature and precipitation effect on water demand is calculated using equation (2.32) and (2.33)

$$TEMPE_i = 4.621 \times odchng \times T_{index} \times HH \quad (2.32)$$

$$PRECIPE_i = 4.621 \times odchng \times T_{index} \times HH \times P_{index} \quad (2.33)$$

Where,

$TEMPE_i$ = Temperature effect on water demand

$PRECIPE_i$ = Precipitation effect on water demand

HH = Household numbers in the city

For both the temperature and precipitation effect, the $odchng$ variable is calibrated to mimic the historical per capita water use. In the precipitation effect, we include the temperature index for interacting with precipitation. The coefficient 4.621 is the coefficient of $odchng\_reg$ estimated in the demand equation.

Xeriscaping Effect

The coefficient of the variable *xeriscaping* in the estimated regression is -3.97 for the months of April-November, and zero for other months. These coefficients are used to model xeriscaping effect as:

$$XERE_i = \begin{cases} -3.97\,XERP_i & for\ Apr - Nov \\ 0 & for\ Dec, Jan, Feb \end{cases} \tag{2.34}$$

Where,

$XERE_i =$ Xeriscaping effect in city *i*

$XERP_i =$ Proportion of household with xeriscaping in city *i*

Due to the lack of data on the percentage of household with xeriscaping, this variable was calibrated for per capita water use. The calibrated percentage of households with xeriscaping is 5%.

4.2.2 Industrial, Commercial, and Institutional Demand Model

Industrial, commercial, and institutional (ICI) use of water is lumped in one model. ICI water use $\left(W_t^{ICD}\right)$ is modeled based on NAICS sectors, distribution of employment in those sectors, and average water required per employee for those sectors.

$$W_i^{ICD} = \sum Emp_{is}^{est} W_s S_w \tag{2.35}$$

Where,

$Emp_{is}^{est} =$ Estimated employment in sector *s* of city *i*

$W_s =$ Sectoral water demand

$S_w =$ Seasonal weight

Total estimated employment $\sum Emp_{is}^{est}$ is determined by the growth rate of the industrial and commercial sector.

$$\sum Emp_{is(t)}^{est} = (1+g)\sum Emp_{is(t-1)}^{est} \tag{2.36}$$

Where g is the growth rate of the industrial and commercial sector. The modeled growth rates of these three cities are given in the Table A8. The initial employment $\sum Emp_{is(t-1)}^{est}$ in Albuquerque, Santa Fe, and Rio Rancho is 149,889.6; 23,000; and 1,660. Data on initial employment are 1975 actual data.

Total employment is distributed to 22 NAICS sectors presented in Table A9 using the formula:

$$Emp_{is}^{est} = \frac{Emp_{is}^{actual}}{\sum Emp_{is}^{actual}} \sum Emp_{is}^{est} \tag{2.37}$$

The data for Emp_{is}^{actual} were obtained from the Bureau of Labor Statistics (BLS) for the period of 1990-2010. We assume that the value of $\frac{Emp_{is}^{actual}}{\sum Emp_{is}^{actual}}$ after 2010 is the same as for the year 2009. Similarly, the value for the period of 1975-1989 is the same as the value for 1990. The value of W_s is borrowed from Gleick et al. (2003) and given in Table A9. Finally, the value of S_w is assumed to be 1 for May through September and 0.5 for the remaining months.

4.2.3 Population Model

The population model is divided into a total population and labor force components.

Total Population

A cohort-based population model to estimate annual population for the three cities was developed. Four types of demographic variables (fertility, mortality, aging, and migration) are considered the determining factors of population in the cities. Population is disaggregated into five-year age cohorts. The assumption behind the disaggregation is that it captures the heterogeneous effects on water consumption of fertility rates, mortality rates, migration, and occupation across the population. Initial county-specific population values for each cohort are obtained from the U.S. Census Bureau. Initial values pertain to 1975, as presented in Table A2-A4.

Aging in the demographic model occurs at the end of the simulation year, at which point a portion of each cohort 'advances' into the next age bracket. A uniform age distribution within each cohort is assumed such that at the end the simulation year one-fifth of each cohort, except for the >85 cohort, is removed and incorporated into the next bracket.

Fertility and Mortality

Fertility rate, defined as the number of live births per 1000 females, is calculated using equation (2.38).

$$F_k = 1000 \frac{\alpha_{kt}}{\nu_{kt}} \tag{2.38}$$

Where,

$F_k =$ Fertility rate in cohort *k*

$\alpha_{kt} =$ Total number of live births in cohort *k* during year *t*

$\nu_{kt} =$ Total female population in cohort *k* during year *t*

Fertility rates are used to estimate the total number of live births during each year of the simulation using equation (2.39). The number of live births is then added to the {*0-4*} age-cohort.

$$B_t = \sum_{1}^{k} \left(\frac{F_k \tau_k \phi}{1000} \right) \tag{2.39}$$

Where,

$B_t =$ Birth rate during year *t*

$\tau_t =$ total population in cohort *k*

$\phi =$ female proportion in the cohort

Information from the 2000 U.S. census is used to determine the portion of the population that is female for all cohorts with a positive fertility rate. On average, females compose 50.7% of the population in these cohorts (i.e. ϕ=0.507).

The mortality rate, defined as the number of deaths per 100,000 people, is calculated for each cohort using equation (2.40).

$$M_k = 100000 \frac{\omega_{kt}}{\tau_{kt}} \tag{2.40}$$

Where,

$M_k =$ Mortality rate in cohort *k*

$\omega_{kt} =$ Total number of deaths in cohort *k* during year *t*

$\tau_{kt} =$ Total population in cohort *k* during year *t*

Once the value of M_k is obtained using equation (1.34), number of deaths (D_{kt}) in each cohort is calculated during simulation using equation (2.41).

$$D_{kt} = \frac{M_k \tau_{kt}}{100000} \tag{2.41}$$

Once calculated, the number of deaths (D_{kt}) is subtracted from the corresponding cohort to obtain population for that cohort.

Migration

Another factor determining population change in the model is net migration. Net migration is the difference between in-migration and out-migration. Net migration is divided into international and domestic migration. For each of the three cities, international migration per year is assumed to be equal to the average U.S. migration that moved to three cities between 1991 and 2008. The average international migration during 1991-2008 to Albuquerque, Santa Fe, and Rio Rancho were 1,420; 82, and 82 persons per year respectively.

Domestic migration is modeled as a function of changes in employment, the average wage relative to the U.S. average wage, and the unemployment rate relative to the U.S. unemployment rate. These variables are constructed in the following way.

Change in employment in a year t is given as:

$$\Delta Emp_{it} = Emp_{it} - Emp_{i(t-1)} \tag{2.42}$$

Relative wage in a year t is measured as:

$$Relwge_{it} = \frac{[W_{USt} - W_{it}]}{W_{USt}} 100 \tag{2.43}$$

Relative unemployment is also measured in a similar fashion.

$$Relunemp_{it} = \frac{[U_{USt} - U_{it}]}{U_{USt}} 100 \tag{2.44}$$

Where,

$\Delta =$ Change in

$Emp_{it} =$ Employment in city i at time t

$Relwge_{it} =$ Relative wage in city i at time t in city i

$Relunemp_{it} =$ Relative unemployment in city i at time t

$W_{USt} =$ Weekly average wage in the US at time t

$W_{it} =$ Weekly average wage in a city i at time t

$U_{USt} =$ Unemployment rate in the US at time t

$U_{it} =$ Unemployment rate in the city i at time t

Employment and wage data were obtained from the Quarterly Census of Employment and Wage. Unemployment rates were obtained from the Local Area

Unemployment Statistics database. Once the variables were constructed, the relationship between domestic migration and these variables is established using multivariate regression analysis. The estimated regression equation is:

$$NM_{it} = 16500.03 - 0.725\Delta Emp_{i(t-2)} - 5470.419 Relwge_{it} + 1147.113 Relunemp_{it} \quad (2.45)$$

Equation (2.45) indicates that domestic migration is positively correlated with relative unemployment rate and negatively correlated with lagged employment and relative wage. A similar regression equation was estimated for international migration too. But none of the coefficients were significant, indicating international migration is governed by s different mechanism. The reason for this is that international migration is modeled in a different way as explained above.

Once net international and domestic migration are determined, they are distributed among age cohorts using cohort-specific constants calculated using equation (2.46) and employing data from the 2008 American Community Survey. These constants are presented in table A2-A4.

$$C_{ik} = \frac{\theta_{ik}}{\psi_i} \quad (2.46)$$

Where,

θ_{ik} = Number of people relocating into city *i* from cohort *k*

ψ_i = total number of people relocating into the city *i*

The net migration from cohort k is thus:

$$N_{ikt} = NM_{it} C_{ik} \quad (2.47)$$

Population Flows

In the demographic model, population change takes place according to equation (2.48).

$$P_{ikt} = P_{ik(t-1)} + B_{it} - D_{ikt} + Ageing_{ikt} + N_{ikt} \quad (2.48)$$

Where,

P_{ikt} = Population of cohort *k* in city *i* at time *t*

$Ageing_{ikt}$ = Net flow of population from cohort *k-1* to *cohort k* due to aging

It is important to note that population change due to fertility affects the {*0-4*} age-cohort only. Thus B_{it} equals zero for all other cohorts. Population estimates provide a basis for the residential water demand model. Moreover, there is feedback between the economic activities and population model because the economic activities component determines the economic conditions that drive domestic migration.

Labor Force and Skill Level

The size of the labor force for any given simulation year is determined using labor force participation rates (LFPR).

$$\eta_{ik} = \frac{\mu_{ik}}{\tau_{ik}} \quad (2.49)$$

Where,

η_{ik} = Labor force participation rate for city *i* and cohort *k*

μ_{ik} = Labor force from cohort *k* in city *i*

τ_{ik} = Total population in cohort *k* and city *i*

The estimated LFPR for each cohort is borrowed from Chermak et al (2006) and assumed to be constant throughout the simulation period for all three cities. During the simulation process the LFPRs are used to estimate the size of the labor force for each cohort using equation (2.50).

$$L_{ikt} = \eta_{ik} P_{ikt} \tag{2.50}$$

Where,

L_{ikt} = Total labor force of cohort *k* in city *i* at time *t*.

The demographic model also distinguishes among four different worker skill levels: unskilled, blue collar, white collar, and professional. Members of each age-cohort are classified by skill-level based on education level. It is assumed that unskilled workers have not finished high school, blue collar workers completed high school but have less than four years of post-secondary education, white collar workers completed a post-secondary degree requiring at least four years of additional education, and professionals completed a master's, professional, or doctorate degree.

The proportion of each skill category by age cohort is estimated using equation (2.51).

$$\lambda_{ikj} = \frac{\sigma_{ikj}}{\tau_{ik}} \tag{2.51}$$

Where,

λ_{ikj} = Proportion of labor force in cohort *k* and skill *j* in city *i*.

σ_{ikj} = Number of people in cohort *k* and skill *j* in city *i*

The estimated λ_{ikj} is borrowed from Chermak et al. (2006) and assumed to be constant throughout the simulation period for all three cities.

The product of λ_{ikj} and L_{ikt} gives the number of labor force participants in city *i* and age cohort *k* with skill level *j*.

$$K_{ikjt} = L_{ikt}\lambda_{ikj} \tag{2.52}$$

Commuting

Commuting, both entering and exiting cities, affects labor supply. The total labor force after adjusting for commuters is calculated as:

$$H_{kjt} = K_{ikjt} + \zeta_{i(entering)}K_{ikjt} - \zeta_{i(exiting)}K_{ikjt} \tag{2.53}$$

Where,

H_{ikjt} = Commuter adjusted total labor force in cohort *k*, city *i*, skill level *j*, at time t

$\zeta_{i(entering)}$ = Proportion of labor force entering the city *i*

$\zeta_{i(exiting)}$ = Proportion of labor force exiting the city *i*

Due to the data limitation, we assume constant value of $\zeta_{i(entering)}$ and $\zeta_{i(exiting)}$ for each city.

The values used for these two variables for three cities are presented in table A-5.

2.5 Calibration, Validation, and Scenario Evaluation

The reliability of a simulation model is established through its calibration and validation. Calibration is the process of adjusting a simulation model to produce

outcomes that mimic the historical data as closely as possible. During the calibration period, the model's parameters are manipulated to match the simulated and observed data. Validation, on the other hand, is the process of checking whether the parameters calibrated and the model as a whole reflect reality. A model is said to be valid if it can represent the system being modeled adequately (Casti 1997). However, it is not the case that a model is either valid or invalid; rather, there is always a certain degree of validity (Law et al. 1991). In the validation process, a simulated outcome is compared with an observed outcome using some standard measurement such as root mean square error.

The hydrological model runs on a monthly time step, and uses the period from 1975 to 1999 for calibration, 2000 to 2006 for validation, and runs forward from 2006 in scenario evaluation mode. The variables used in the model, and their values during calibration, validation, and scenario evaluation are presented in the Table A10. In the surface water model, mass balance in each reach described in equation (2.10)-(2.13) is calibrated to match observed data for the period 1975-1999, manipulating ungagged surface water inflows, riparian and agricultural ET, gaged inflows, and reservoir leakage to the underground system.

In the groundwater model, calibrated parameters are provided in Table 2.2. Parameter value ranges are provided for different reaches and groundwater zones. For example, the calibrated riverbed elevation for groundwater zone 2 is 5,213 feet above sea level (ft amsl) (Roach and Tidwell 2006a), while it is 5,159 ft amsl for zone 3. Details of the surface water and groundwater model calibration can be found in Roach and Tidwell (2006a, 2006b).

Table 2-2: Parameters Calibrated in Groundwater Model

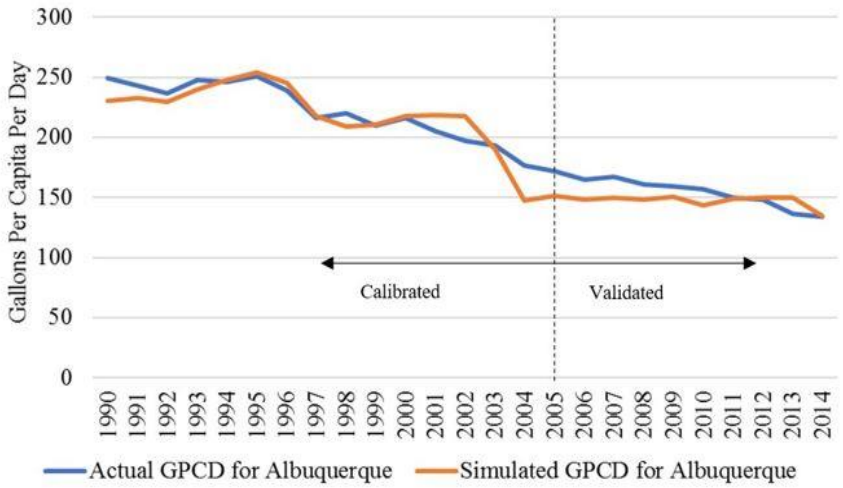
Parameters Calibrated	Variables for which Parameters Were Calibrated	Range of Calibrated Value
Riverbed elevation (ft amsl)	River, irrigation canal, and reservoir elevation	4,704-5,430
Characteristic distance (mile)	Flow to drains	0.005-1.1
Drain bed elevation (ft amsl)	Flow to drains	4,699-5,208
Surface elevation (ft amsl)	Riparian evapotranspiration from aquifer	4,716.5-5,436

2.5.1 Calibration and Validation of Economic Model

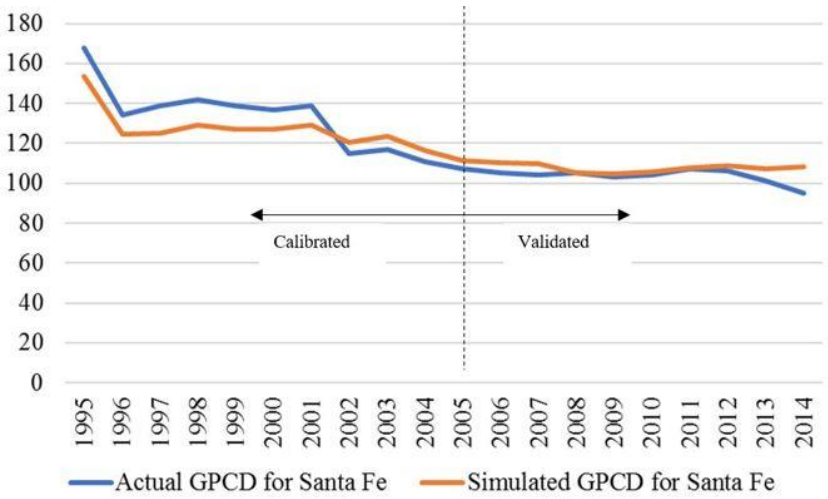
The economic model suffered from the lack of sufficient data. Unlike the hydrological model that benefits from historical data dating back to 1975, the economic model data is scarce and relies on a statistical model that is calibrated to per capita per day water consumption in the three cities. Unfortunately, data for this variable are not available before 1990. Similarly, there is a scarcity of historical data for water rates, too. Due to the data problem, the economic model is calibrated for the period 1990-2005 and validated from 2006-2014. The scenario evaluation period starts after 2014. As explained earlier, parameters calibrated for the economic model are: *constant* term of the regression model and *outdoor change*. These parameters are calibrated for per capita per day water consumption in Albuquerque, Santa Fe, and Rio Rancho. The calibrated constant terms for these three cities are: 3.443, 5.123, and 7.613, respectively. The rest of the residential demand model utilizes the parameters estimated using regression equation and city-specific values of the corresponding variables. Figure 2-11 shows actual observation and

simulated outcome for per capita per day water consumption during the calibration and validation periods.

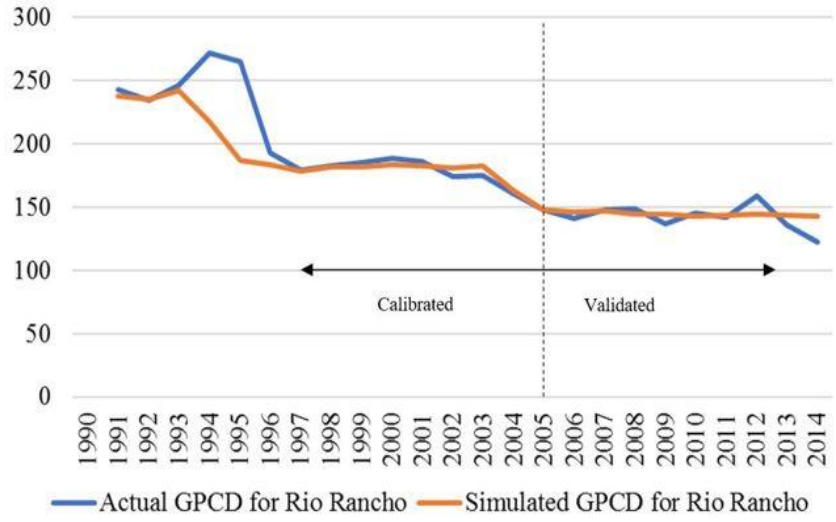
As explained earlier, the simulated per capita consumption of water is obtained by dividing total demand for water by total population. Total demand for water is a sum of residential and industrial demand. Residential and industrial demand for water, as explained in the economic model section, are determined by different characteristics of the city. For example, residential demand is determined by income, education, price, age, ethnicity, etc. Similarly, industrial demand is determined by total number of employed individuals in different industrial sectors.



A. Albuquerque



B. Santa Fe



C. Rio Rancho

Figure 2-11:Calibration and Validation of Economic Model

Figure 2-11(A), Figure 2-11(B), and Figure 2-11(C) show observed and simulated per capita per day (GPCD) water consumption in the cities of Albuquerque, Santa Fe, and Rio Rancho. The trend of GPCD in all three cities is declining. The peak in the Rio Rancho case for the year 1994 and 1995 is due to significantly more water sold by the city of Rio Rancho to Intel Corporation.[7] Several factors, which will be discussed briefly

[7] About 2,000 acre feet more water than in 1993 and about 3,000 acre feet more water than in 1996 were sold (Nims et al. 2000)

in a later section of this paper, are behind this trend. The calibrated section (up to year 2005) shows that the value of the calibrated parameters has been chosen in a plausible range, so that simulated behavior can represent actual behavior closely. The validated section (2006-2014) shows that the economic model is close to representing reality. The root mean square errors, which are expected to be as small as possible, are 11.33 *gpcd*, 9.6 *gpcd*, and 5.7 *gpcd* for Albuquerque, Santa Fe, and Rio Rancho, respectively. These values indicate that, for example, simulated per capita per day water consumption for Albuquerque will be within 11.33 *gpcd* of the actual per capita per day water consumption. The deviation of simulated *gpcd* from actual *gpcd* in Albuquerque, Santa Fe, and Rio Rancho 6.7%, 9.5%, and 7.2%.If the economic models for the three cities are compared based on root mean square value, then it can be said that the model for Rio Rancho is the best among the three models.

2.5.2 Simulation Scenarios

The term scenario for this study refers to various combinations of different exogenous variables that are imposed in the model to understand the future course of the groundwater-surface water-economic system. Scenario evaluation is important not only to understand the future of the system but also in policy planning. Because various scenarios provide policy makers tools to answer several *what if* questions, the outcomes can be used to analyze various policy options aimed at mitigating drought impact on water resources. Before discussing various scenarios considered in this paper, it is important to understand how the variable *drought* has been measured and how it has been used in the model.

Drought can be incorporated in a model in different ways. To analyze drought's hydrological and economic impact in the Colorado river basin under different policy scenarios, Booker (1995) took a hypothetical drought defined on the basis of average annual basin inflow in the Colorado river basin. Following Tarboton (1995), he took a 38-year preiod from 1579 to 1616 that included drought. The author defined year 1-year 9 as the base case period, year 10-year 16 as the early drouht period, year 17-year 22 as the critical drought, and year 23-year 38 as the recovery period for his analysis. The average annual basin inflows during base case, early drought, critical drought, and recovery period were 15.5 maf/year, 11.8 maf/year, 8.4 maf/year, and 16.8 maf/year. Similarly, Tweed et al. (2009), to analyze the impact of drought on a lake's condition in southeast Australia, defined a drought period as the one during which rainfall was less than long-term average rainfall. Maneta et al. (2009) created two drought scenarios in their model, reducing precipitaiton by 25% and 50%, and increasing evapotranspiration by 15% and 25%. Vicente-Serrano (2007) used standardized precipitation index (SPI) as a measure of drought to find spatial differences in the effects of drought on the natural vegetation and agricultural crops. In this study, 1950s drought in New Mexico was used as the measure of drought.

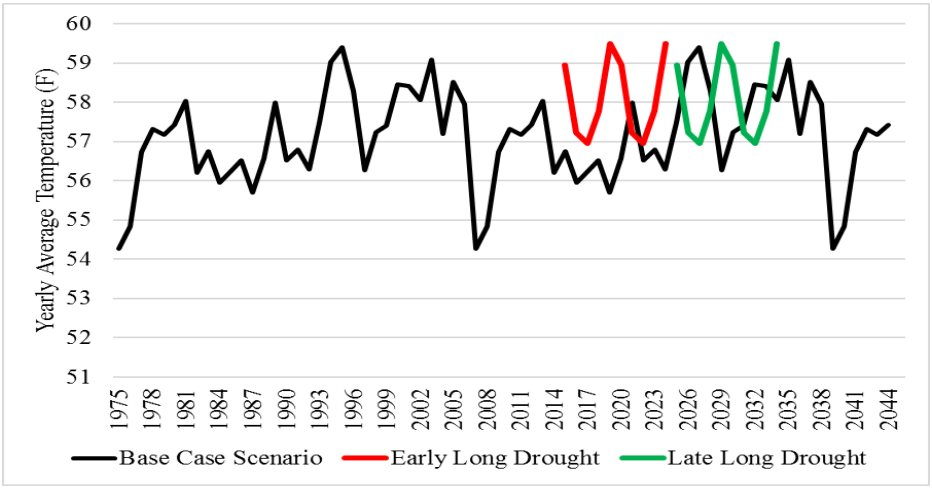
The drought of the 1950s was one of the more severe on record in the Southwest. A persistent pattern of below-normal precipitation began in 1952 and, except for minor interruptions, continued until early 1957 (Nace and Pluhowski 1965). The severity of the 1950s drought in New Mexico can be imagined from the fact that for seven consecutive years (1950-1956) annual precipitation was less than 12 inches, and in three of those

years (1951, 1953, and 1956) the annual value was less than 9 inches, an amount lower than in any year in the half century since then (Gutzler 2003).

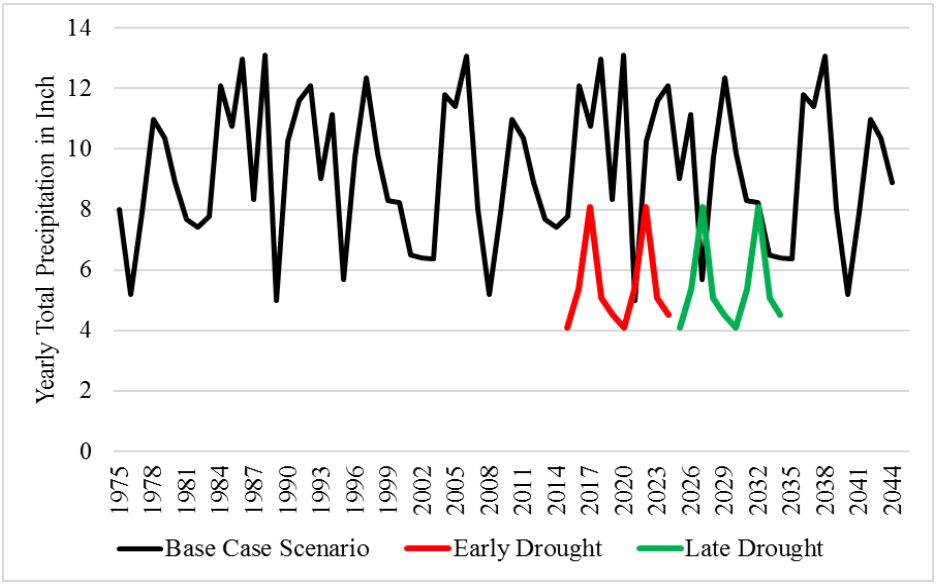
Four types of droughts are considered: early short drought (2015-2019), early long drought (2015-2024), late short drought (2025-2029), and late long drought (2025-2034). Duration of short and long drought are 5 years and 10 years. The intention behind considering early and late drought is that drought in the later period can cost society more due to increased population. Because the 1950s drought was severe, this study uses temperature and precipitation of 1950-1954 as the proxy for drought in simulation. To illustrate, for example, early short drought, 2015-2019 temperature and precipitation are replaced by the temperature and precipitation observed in 1950-1954. For early long drought, 2015-2019 temperature and precipitation are replaced by 1950-1954 data, and again 2019-2024 data are replaced by 1950-1954 data. The same mechanism is applied for late drought as well. Figure 2-12 shows the deviation of annual mean temperature and total annual precipitation during the drought period from the annual mean temperature and total annual precipitation of base case scenario when drought is imposed.

Panel A and Panel B of Figure 2-12 show the base case and drought period's temperature and precipitation, respectively. During the early short drought and early long drought period, average mean annual temperature is higher by 1.85^0F and 1.55^0F, respectively. These values are 0.59^0F and 0.78^0F for late short and late long drought. Regarding precipitation, average annual precipitation during early short and long drought is 4.95 inches and 4.96 inches less than average annual precipitation in the base case period. These values are 4.16 inches and 3.29 inches for late short and late long drought.

Based on deviation from base case temperature and precipitation, it seems that late drought is less severe than early drought.



(A)



(B)

Figure 2-12:Mechanism of Imposing Early and Late Drought in the Simulation

Once the drought variable is defined, several scenarios are constructed based on drought and other variables that are that can be considered by policy makers to mitigate drought impact. The economic variables considered for this study to construct scenarios are: price, population growth, and awareness. Analysis of the impact of drought and other

policy options on water resources is carried out comparing simulated outcome and outcome from the base case scenario.

Base Case Scenario: The base case scenario is constructed using levels of variables as described below:

***Hydrological model variables*:** All the variables that use historical data during calibration and validation period repeat historical data from 1975. In other words, for the base case period, historical data that is mostly climate and gage data is repeated starting from 2006 (i.e., year 2006 takes value of 1975, year 2007 takes value from 1976 and so on).

Economic Variables: While numerous scenarios can be created by changing values of variables and parameters used to construct economic model, this study considers only the variables presented in Table 4 for scenario construction. Variables related with industrial demand does not appear in the table because industrial demand is primarily determined industry type which has been assumed to remain unchanged from base case. Therefore, the base case period in economic model corresponds to the following level of variables Table 2.3.

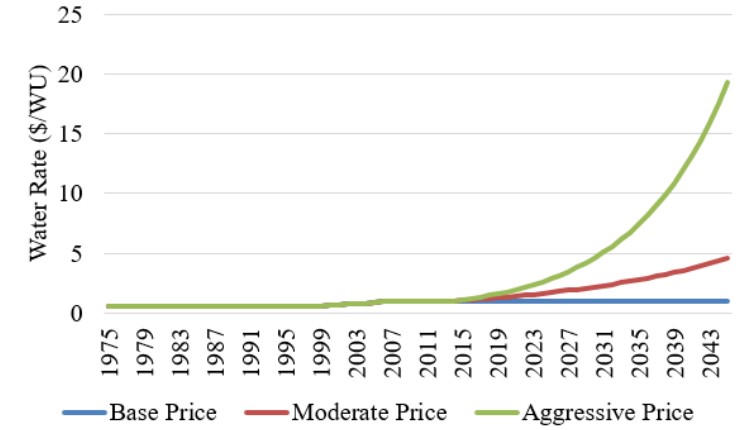
Table 2-3: Variables Used for Scenario Construction in Economic Model

Variables	**Base case Period Values**	**Values for Other Scenarios**
Price	Base price	Moderate price hike, Aggressive price hike
Population	Base population	Medium population, High population
Awareness	No awareness	Increased awareness

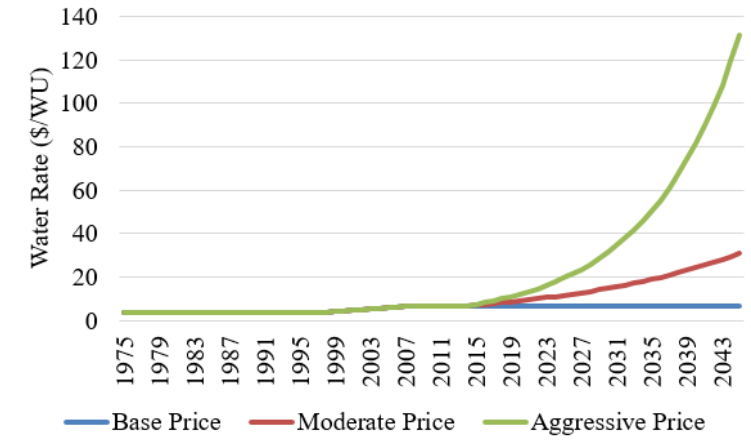
Price has been considered an important policy option to manage water resources (Dalhuisen et al. 2003, Mansur and Olmstead 2012, Krause et al. 2003). Three price scenarios have been considered for simulation: base price, moderate price hike, and

aggressive price hike. The prices for base case scenarios in Albuquerque, Santa Fe, and Rio Rancho start with $0.57/WU, $3.88/WU, and $2.04/WU, respectively, and increase by 6.5% per year in between 1998-2007.

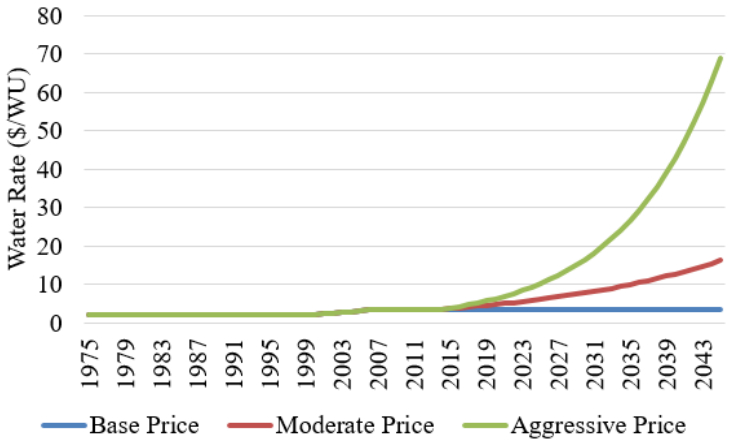
For the moderate price hike scenario, price is increased by 5% for the period 2015-2045. In the aggressive price hike case, price is increased by 10% for the same period. The price paths for the three cities and three scenarios are presented in Figure 2-13.



A. Albuquerque



B. Santa Fe



C. Rio Rancho

Figure 2-13:Price Path for Three Price Scenario

Population in the model is simulated as explained in the demographic model section. The initial population, population for 1975, was obtained from the U.S. Census Bureau's "Intercensal County Estimates by Age, Sex, Race: 1970-1980" (Table A11). The base case population stems from the initial population followed by a demographic model that is adjusted to match the population projected by the Bureau of Business and Economic Research (BBER) at the University of New Mexico. The projected population for the Middle Rio Grande reaches 1.2 million by the year 2045, a 130% increase from 1975. In medium population growth and high population growth scenarios, population increases by 1 percent and 5 percent over base case population from 2015 onward.

The education variable, as explained earlier, represents the percentage of total population with a bachelor's or master's degree. For the base case scenario, this percentage is 32.2%, 43.4%, and 27.2% for Albuquerque, Santa Fe, and Rio Rancho, respectively. In the high education scenario, this percentage is increased to equal 50% from the year 2015.

The awareness variable takes value 1 in the base case scenario, implying there is no change in awareness during the simulation period. Awareness measures the level of understanding of the general public in the MRG about the issue of water scarcity, and the level of knowledge and practice regarding water conservation. In the increased awareness scenario, its value gradually increases after 2014 by an annual increment of 0.2 until its value reaches 3 in the year 2024. After 2024, it remains constant at 3. Finally, the value of other variables presented in the table 3 can be changed using a sliding bar. However, for this paper, those values have been kept at the level of base case scenario. Figure 2-14 shows an example of a slider bar and switches created in the Powersim Studio. These slider bars and switches are used to create various scenarios of interest.

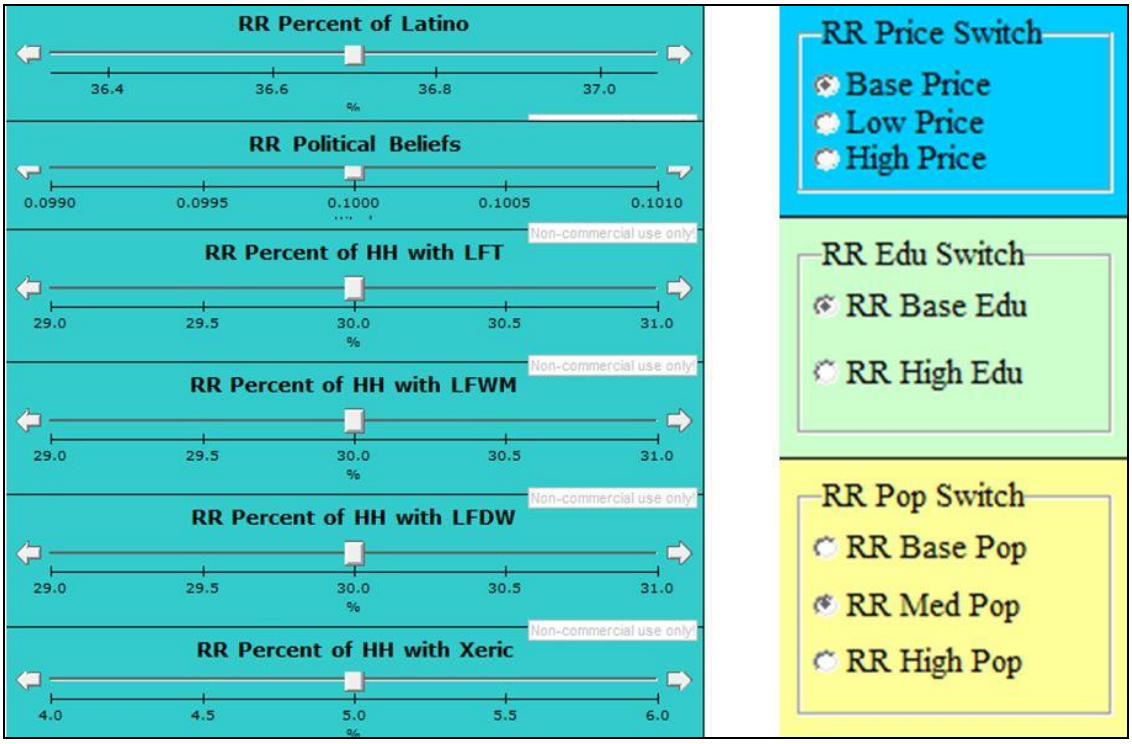


Figure 2-14: Example of Slider Bars and Switches Use in the Powersim Studio

2.6. Simulation Result

The simulation is carried out for the period of 1975-2045 in monthly time step. The results and discussion for the hydrological model without incorporating the economic model can be found in Roach and Tidwell (2006a), Roach and Tidwell (2006b), and Roach and Tidwell (2009). Although numerous scenarios can be simulated by changing the values of different variables and parameters used in the model, this paper is focused on how drought and other policy variables bring change in three variables: groundwater storage (aquifer volume), compact balance, and per capita per day water consumption. In this case, per capita per day water consumption is aggregated for the three cities (i.e., per capita per day water consumption in this section is the sum of total water demand in the three cities divided by the total population of the three cities).

2.6.1 Base case Scenario

Simulated results for the base case scenario are presented in Figure 2-15. The aquifer volume in the base case scenario declines from 1,733 million AF in 1975 to 1,727 million AF in 2045. The declining rate of aquifer volume is relatively small for the period of 1975-1985 and 2006-2016. During 1975-1985 total loss of groundwater was about 443,000 AF and the loss was 405,000 AF for the period of 2006-2016. Despite the larger population size in 2006-2016 period, smaller loss of groundwater may be due to the operation of San Juan-Chama project that started supplying water to Albuquerque from 2006.

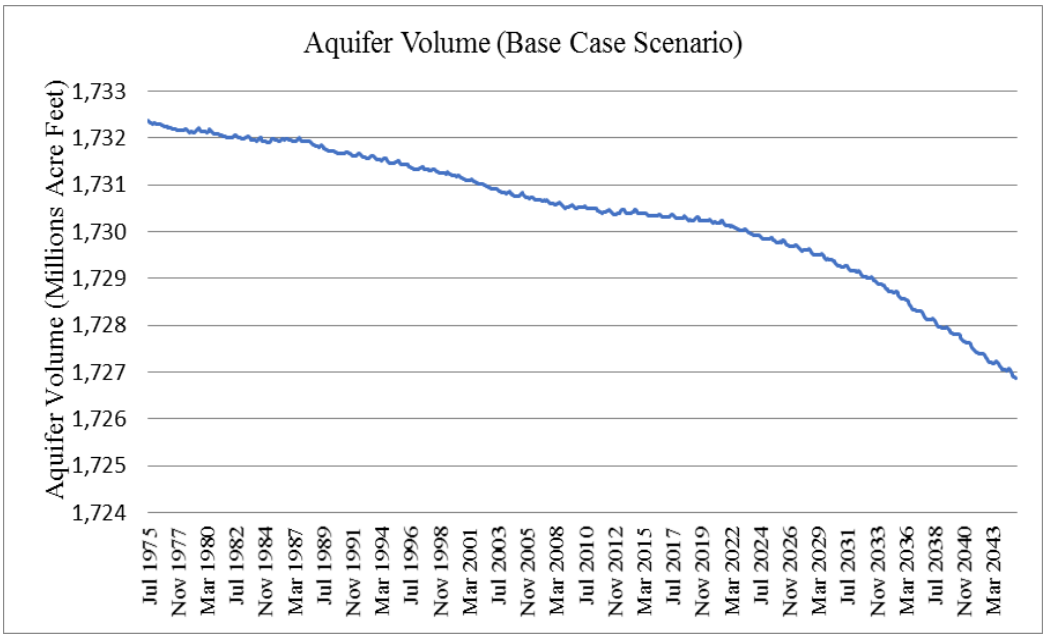
Compact balance, on the other hand, fluctuates during the whole simulation period to reach negative 704 thousand AF at the end of simulation period. Compact balance is determined by the amount of water delivered from the Rio Grande to the

Elephant Butte Lake. Negative compact balance means that New Mexico owes an equal amount of water to downstream users and it needs to be compensated in future years. Increasing negative compact balance after 2015 can be attributed to increasing population. Increasing population means increased diversion of river water that results in less water delivered to the Elephant Butte.

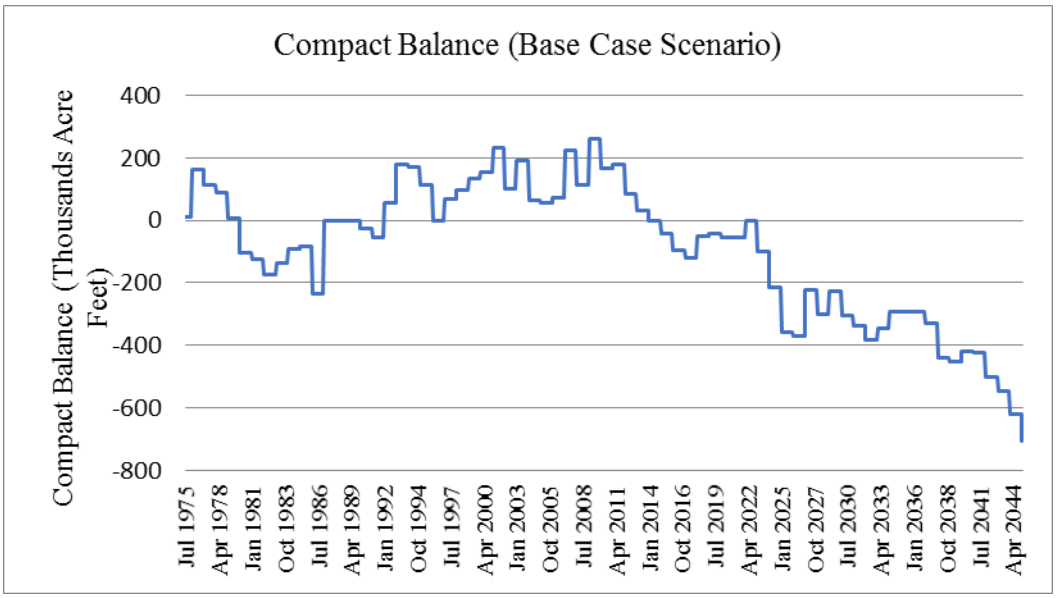
Per capita water consumption in the Middle Rio Grande[8] declined rapidly in between 1996 to 2007.Per capita water consumption in the Middle Rio Grande declined throughout up to 2007. After 2007, it was stable at around 150 gallons per capita per day (GPCD). Reason behind declining GPCD can be attributed to the aggressive water conservation program implemented after 1994. The programs were implemented in response to the revelation that the aquifer was much smaller than originally estimated, recharge was smaller and the aquifer was being mined. Some of the programs implemented in the Albuquerque were: mandatory summer watering restriction, rebates for low flow devices and rainwater harvesting etc. Similarly, the city of Rio Rancho implemented its firs water resource management plan that embodied several water conservation and awareness program. Santa Fe also started water conservation program in 1995 following a severe drought. Rebate, tiered water rates, mandatory toilet retrofit, and raising awareness are the some of the eater conservation program that Santa Fe is implementing. Stable GPCD after 2007 is due to the constant water rate. As seen in the Figure 2-15 (C), increases in water rates took place during 1998-2007. After 2007, the

[8] Throughout this paper, water consumption in MRG refers to the aggregate water consumption for Albuquerque, Rio Rancho, and Santa Fe.

water rate is constant, resulting in less variation in GPCD. Minor fluctuations after 2007 are due to the fluctuation in temperature and precipitation.



(A)



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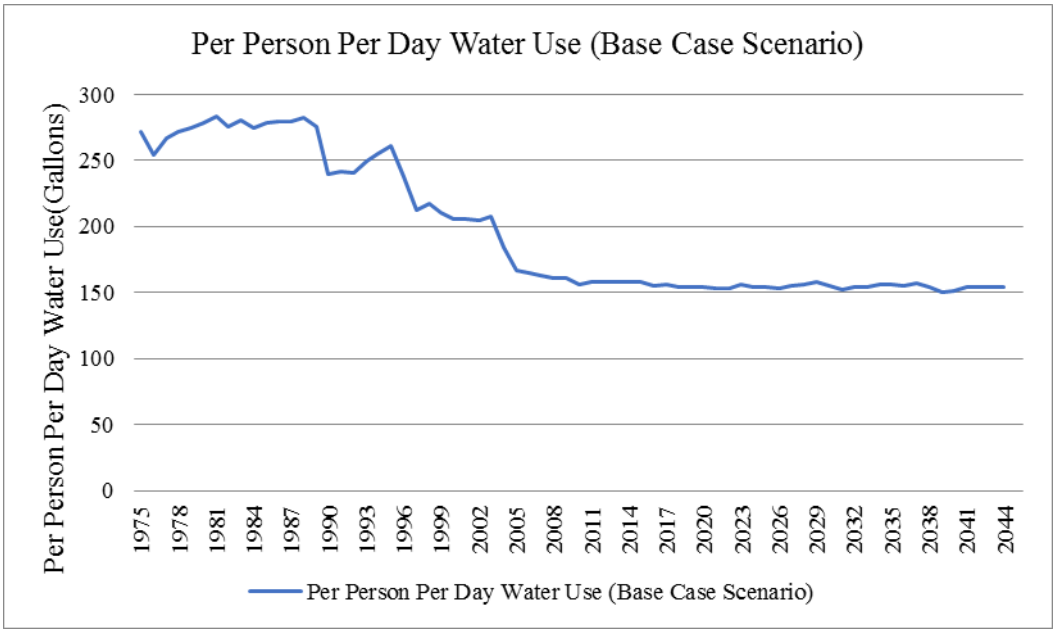


(C)

Figure 2-15: Aquifer Volume, Compact Balance, and Per Capita Daily Water Consumption in Base Case Scenario

Figure 2-16 shows a decomposition of total per capita water use into industrial per capita, outdoor per capita and indoor per capita per day water use. While Industrial and indoor per capita water use is almost constant throughout the simulation period, outdoor per capita water use rapidly declines up to 2009 and remains almost stable afterwards. Stable indoor per capita water use is plausible. However, rapid decline in outdoor per capita can be attributed to conservation initiatives taken by the authority On average, over the simulation period, industrial per capita and outdoor per capita water use are about 23% and 26% of the total per capita water use respectively.

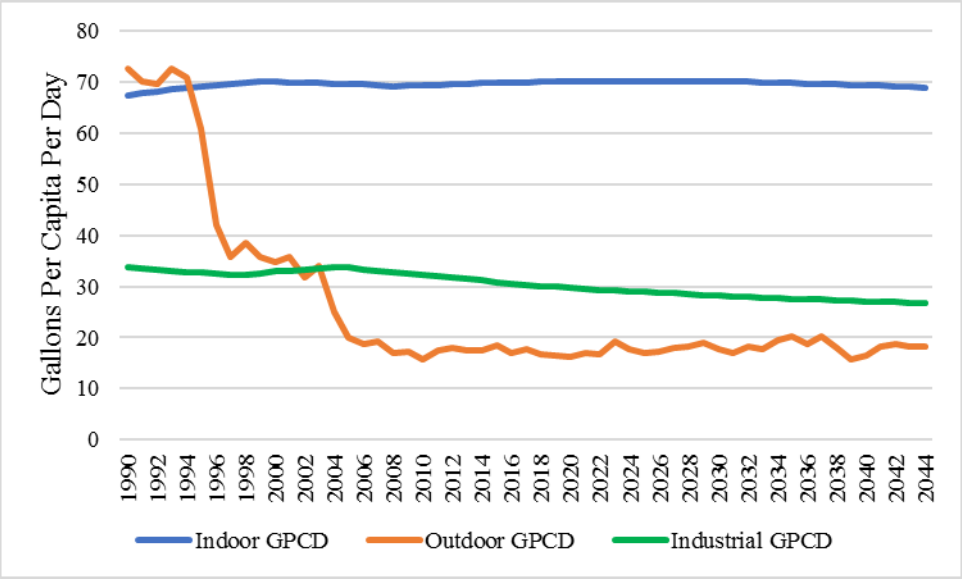
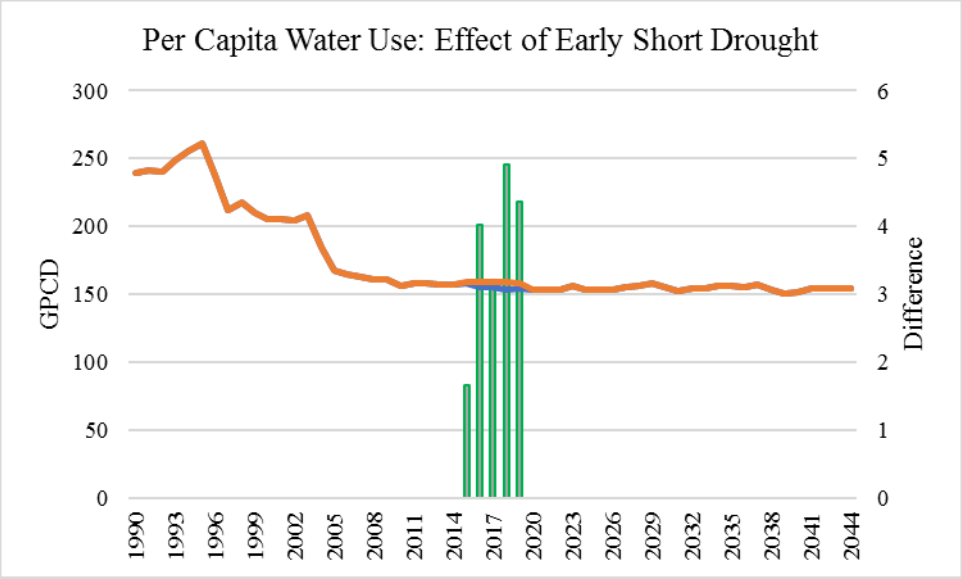


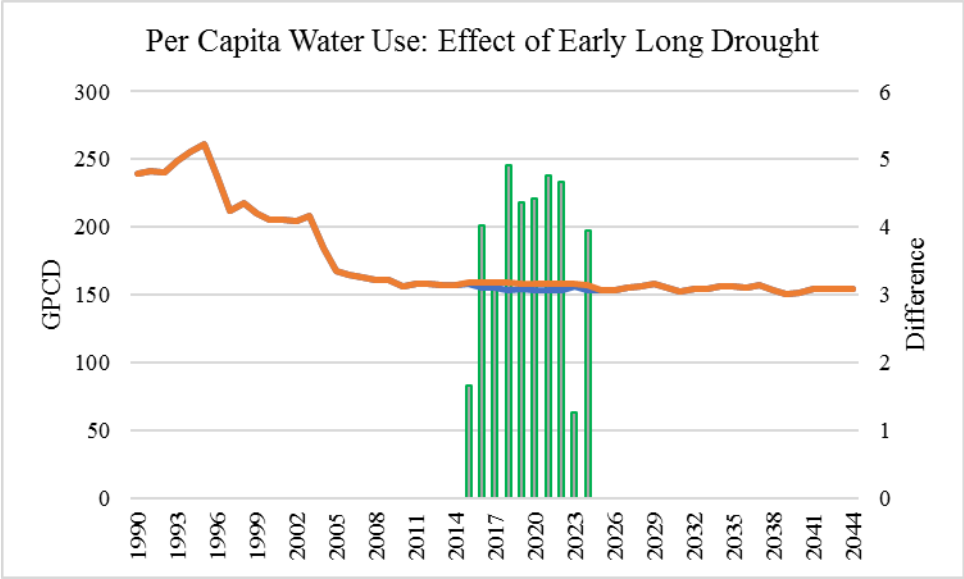
Figure 2-16:Decomposition of Per Capita Per Day Water Use

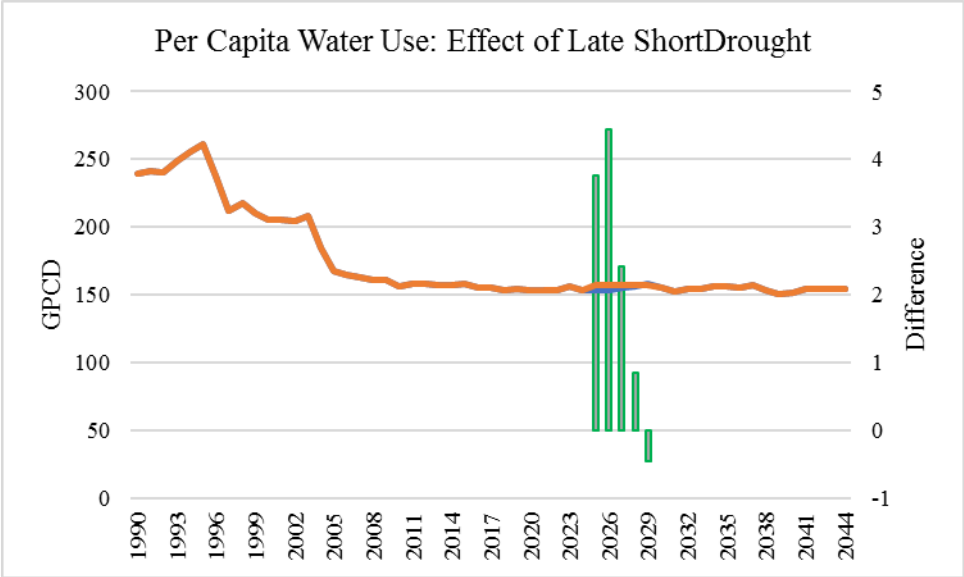
2.6.2 Impact of Drought

This study considers four types of drought; early short, early long, late short, and late long drought. The impact of each individual type of drought is discussed below.

Impact of each drought on per capita daily water use is presented in Figure 2-17.







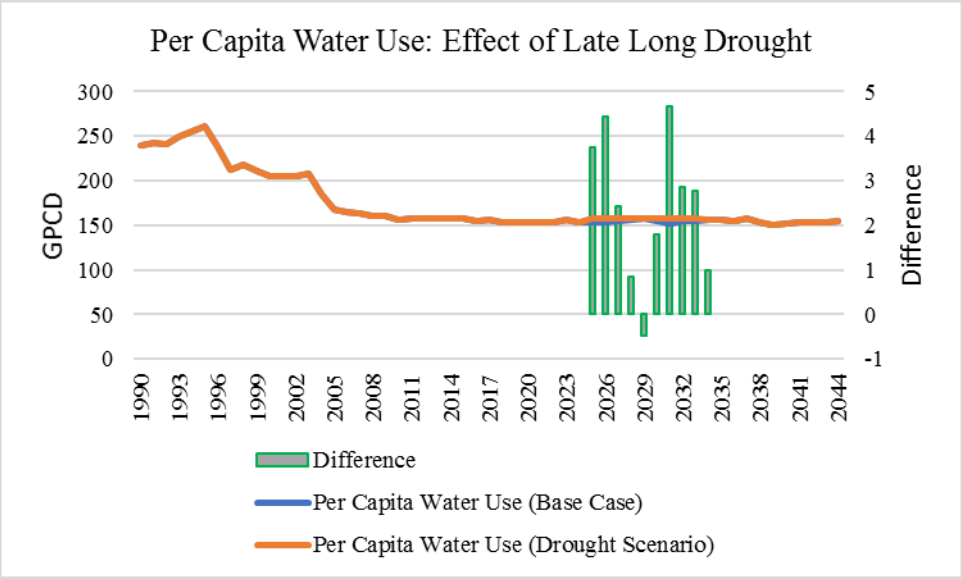
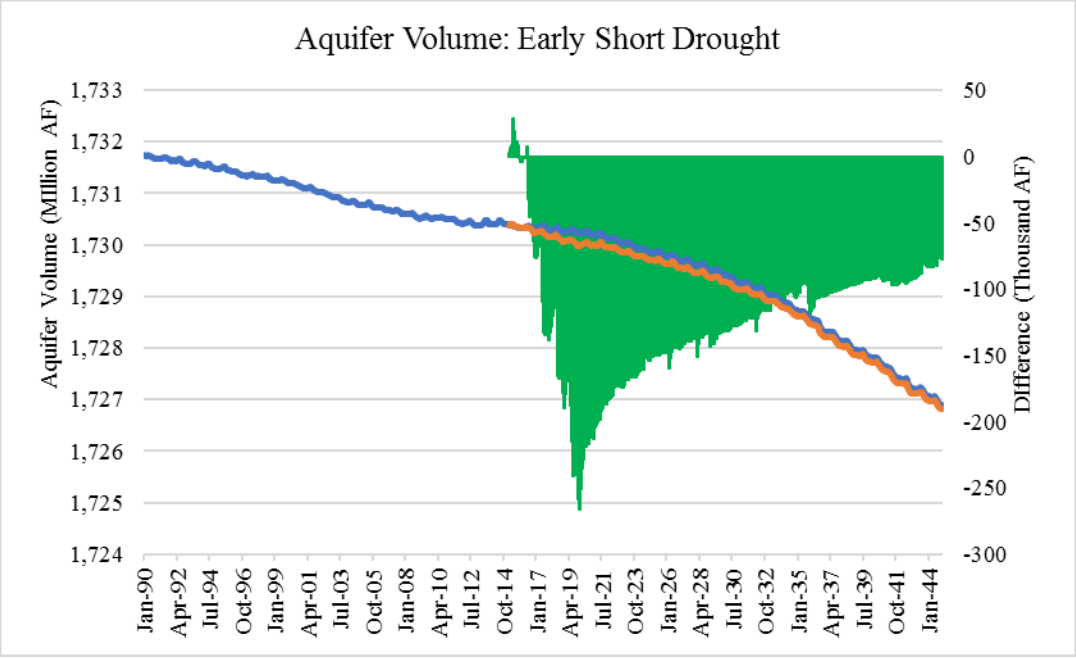


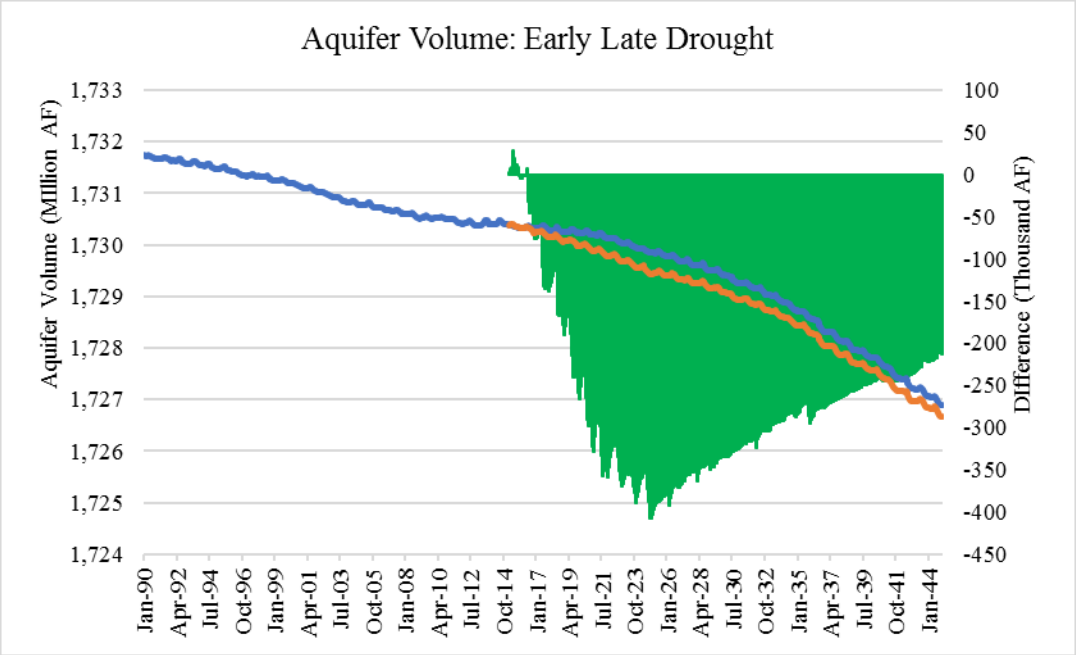
Figure 2-17: Effect of Four Types of Drought on Per Capita Daily Water Use

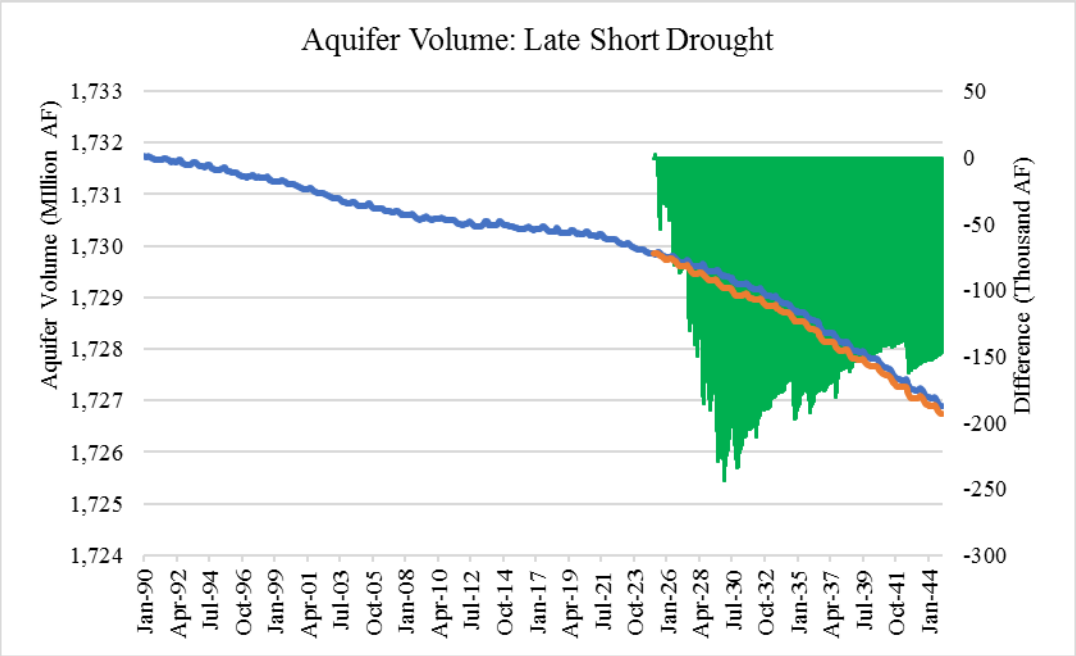
In Figure 2-17, the blue and brown lines represent the base case and drought scenario. Green bars represent the difference between the two scenarios. This color protocol will remain the same throughout the scenario evaluation.

All four graphs in Figure 2-17 reveal that a drought, as expected, results in an increase in per capita water consumption. While there is difference in the outcomes, depending on the timing and duration of drought, the results indicate that the increase in per capita consumption ranges from 1 to 4.8 gpd per capita. In the graph, it is seen that people consume at least 1 more gallon of water per day during a drought period. This equates to a total increase in water use by 79 thousand AF, 168 thousand AF, 92 thousand AF, and 194 thousand AF during the early short, early long, late short, and late long drought respectively . Here it is important to note that even if increases in per capita per day water consumption during early and late drought are almost equal, the total extra volume of water consumed during late drought is significantly higher due to higher population in the later period.

Figure 2-18 shows the impact of drought on aquifer volume. Aquifer volume is declines during the period of drought, whether it is early or late drought. The common trend in all four drought scenarios is that the aquifer volume gradually declines as the drought period goes on. Once the drought period comes to end, the aquifer volume starts to increase. For example, during the early short drought (2015-2019), aquifer volume declined by 4,200 AF in the beginning, reaching its peak at 266 thousand AF in the last month of the early drought period. The aquifer started to regain once the drought period terminated. Similar trends with different magnitudes prevailed in all four cases of drought. The largest decline in the aquifer is observed during the early long drought period. In this case, the aquifer declined by 408,372 AF in December 2024. One possible reason for the larger decline of the aquifer during the early drought rather than the later drought is that the severity of drought measured as the deviation of temperature and precipitation from base case scenario is higher in early drought than in late drought.







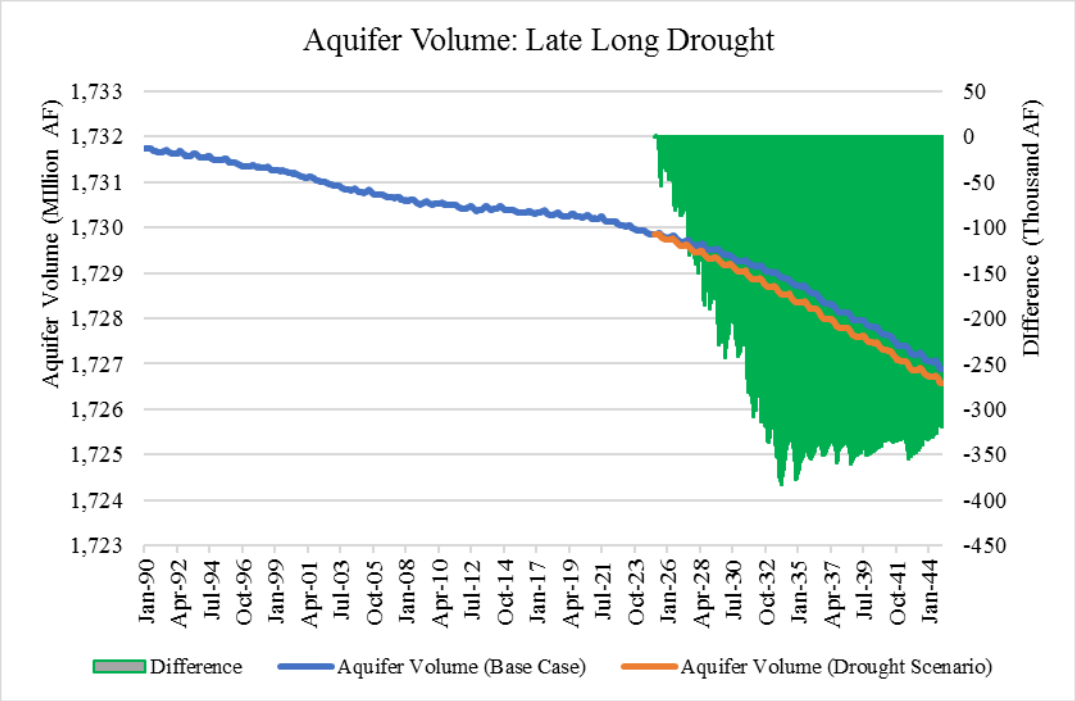


Figure 2-18: Impact of Drought on Aquifer Volume

The most striking feature of the drought scenario is that the loss of aquifer volume is perpetual in nature. Even if the aquifer starts regaining once drought is terminated, there is no full compensation of the loss incurred due to drought. This is evident from a gap prevailing between the red and blue lines at the end of the simulation in all four graphs of Figure 2-18 . The largest decline in the aquifer volume among the four drought scenarios at the end of the simulation is the late long drought. Figure 2-19 shows the decline in the aquifer volume at the end of simulation in four drought scenarios. The reason behind the largest decline in the aquifer volume at the end of the simulation period in the late long drought case is a larger population in the later period.

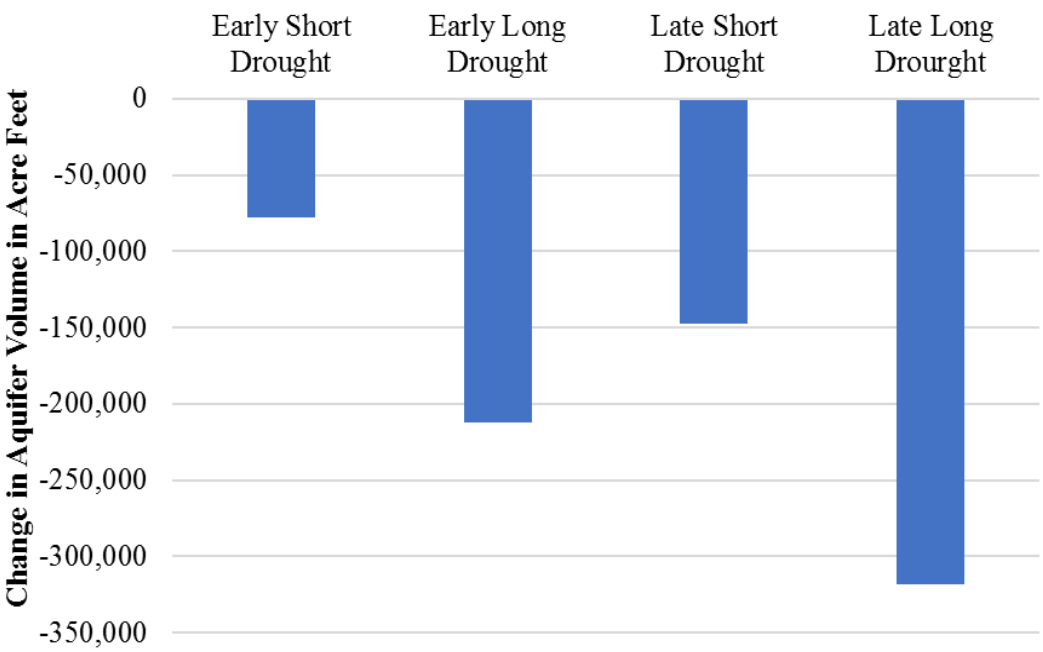
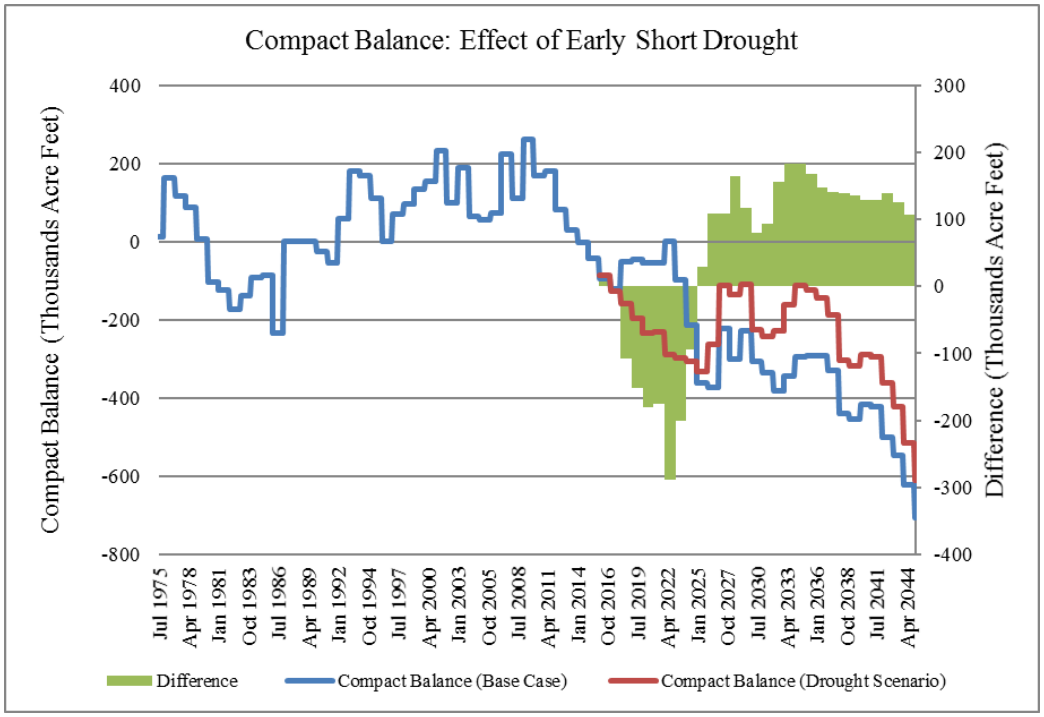
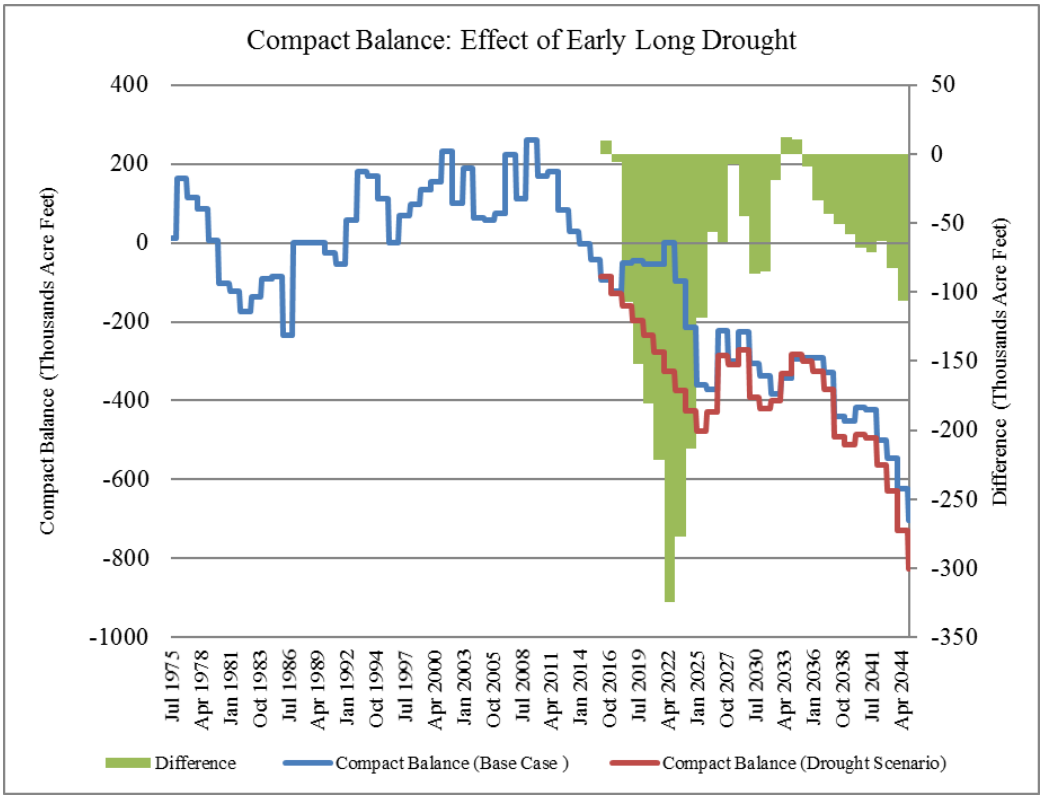


Figure 2-19:Change in Aquifer Volume at the End of Simulation

The consequence of the perpetual loss of groundwater is that the current drought imposes a cost for future, too. Declining groundwater volume means increasing pumping cost. Thus, today's drought is responsible not only for increasing today's pumping cost but also future pumping costs. Other costs that society bears due to perpetual loss of groundwater are its nonuse value, bequest value, and option value (Shultz and Lindsay 1990).





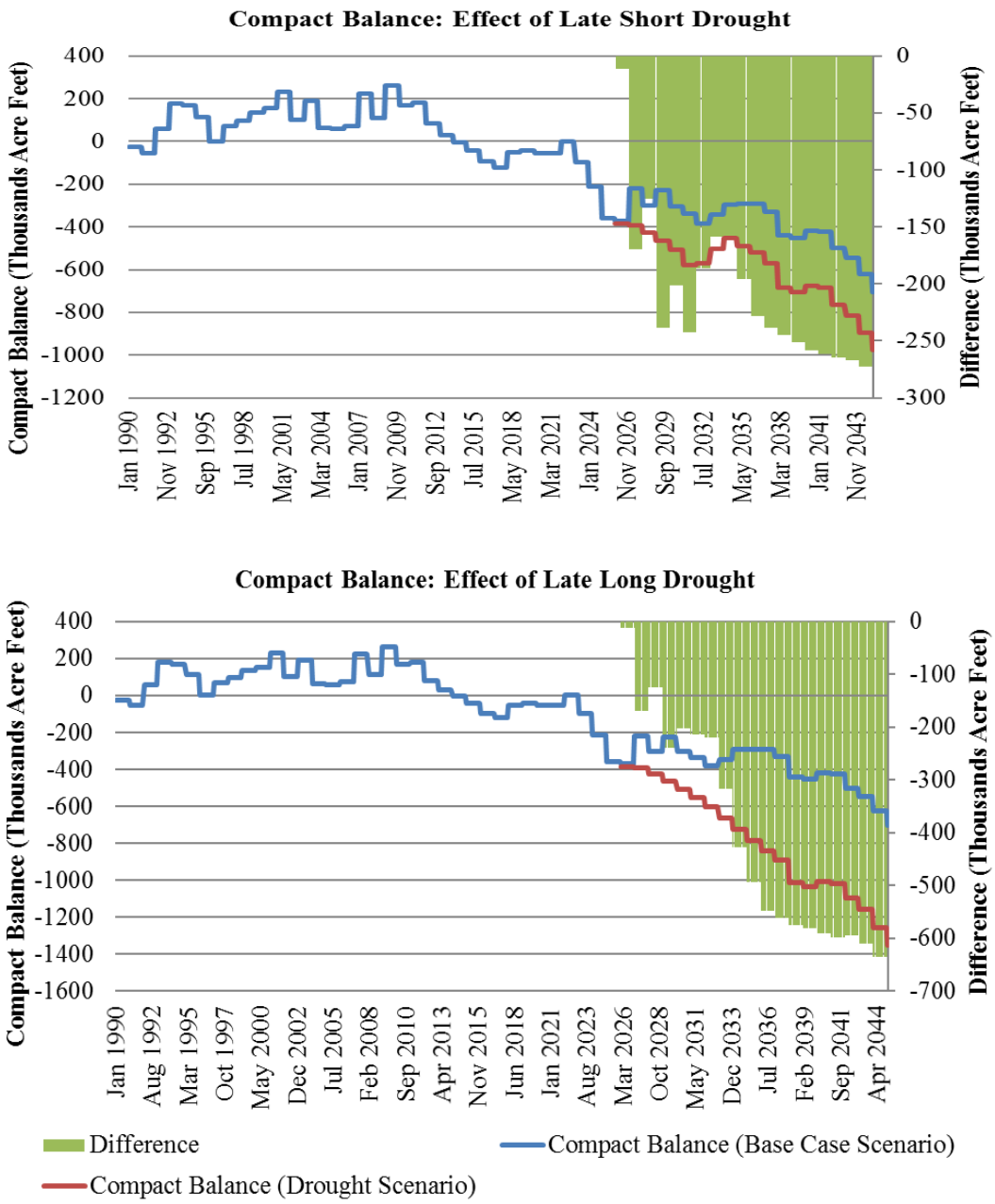


Figure 2-20:Drought Impact on Compact Balance

Figure 2-20 shows that the compact balance is more negative during drought periods. However, compact balance is relatively less negative compared to base case scenario for earlier and shorter drought. The first two graphs in Figure 2-20 show that the compact balance is more negative than base case scenario during drought periods. In the early short drought, the compact balance is less negative than base case scenario.

However, in the early late drought case the compact balance is almost the same as the base case scenario, even after drought. In the late drought case, the drought-impacted compact balance is always more negative than the base case scenario, even after drought is terminated. The point to note is that the late long drought creates larger negative compact balance than late short drought. The possible reason behind this phenomenon is, like in the case of aquifer volume, a larger population in the latter case. An increased population demands more water, which results in more diversion of river water for consumption, leaving less water to be delivered in the Elephant Butte.

The conclusions regarding drought's impact are that drought increases per capita water consumption, reduces aquifer volume, and puts more future liability on New Mexico for supplying water for downstream agents. The sustainable use of water resources requires saving water for future generations through water conservation. This means policy makers need to induce people to consume less water during drought periods. The question is which policy tools are effective for making people consume less water. The following sections evaluate some of the policy instruments that help to curb drought impact and compare their effectiveness.

2.6.3 Impact of Population Growth

Increasing population aggravates drought's impact. This is the reason that aquifer depletion is greater during later drought than early drought. The problem is more severe if the population growth rate is higher. Figure 2-21 shows the impact of population growth and drought on aquifer volume. The order of impact (from high to low aquifer volume) is (i) base case scenario, (ii) early short drought and moderate population growth (ESD and MPG), (iii) early short drought and high population growth (ESD and HPG),

(iv) late short drought and moderate population growth (LSD and MPG), (v) late short drought and high population growth (LSD and HPG), (vi) early long drought and moderate population growth (ELD and MPG), (vii) early long drought and high population growth (ELD and HPG), (viii) late long drought and moderate population growth (LLD and MPG), and (ix) late long drought and high population growth (LLD and HPG). This order of impact tells that, in terms of aquifer volume, duration of drought is the most important factor to be considered followed by timing of the drought and extent of population growth. In other words, long drought in the earlier period is costlier than late short drought. Population growth aggravates the problem in all cases.

On comparing drought impact on aquifer volume without population growth (Figure 2-18) and with high population growth (Figure 2-21), at the end of simulation it is seen that aquifer volume declines more in the latter case, by 17 thousand AF. Although 17 thousand AF is a small amount in comparison to total aquifer volume (about 0.001 percent), it is sufficient to show a negative impact of population growth. Simulation results show that similar trends prevail for other types of drought and population growth levels.

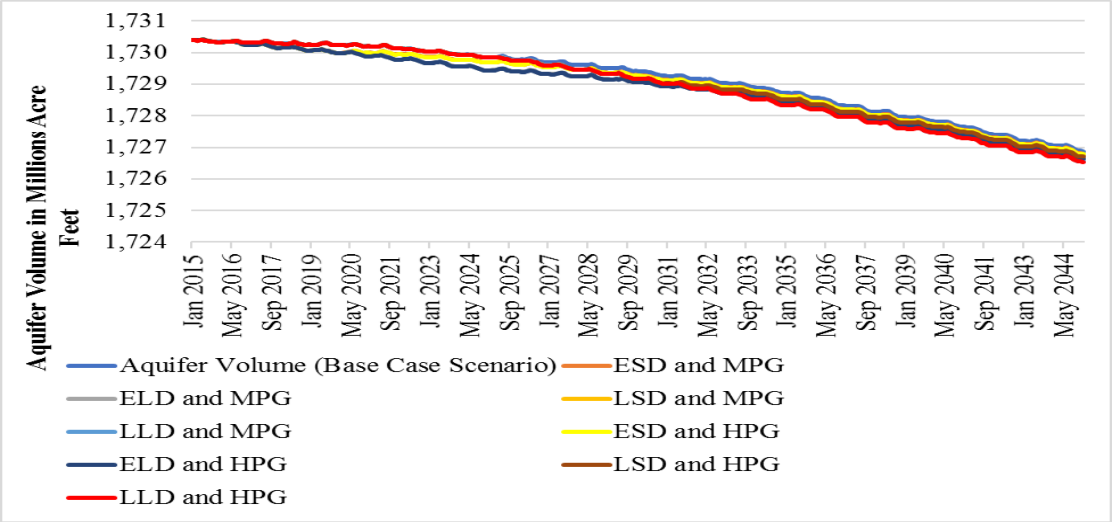


Figure 2-21: Impact of Drought and Population Growth in Aquifer Volume

Impact of drought and population growth on compact balance and per capita per day water use is presented in Figure 2-22 and Figure 2-23.

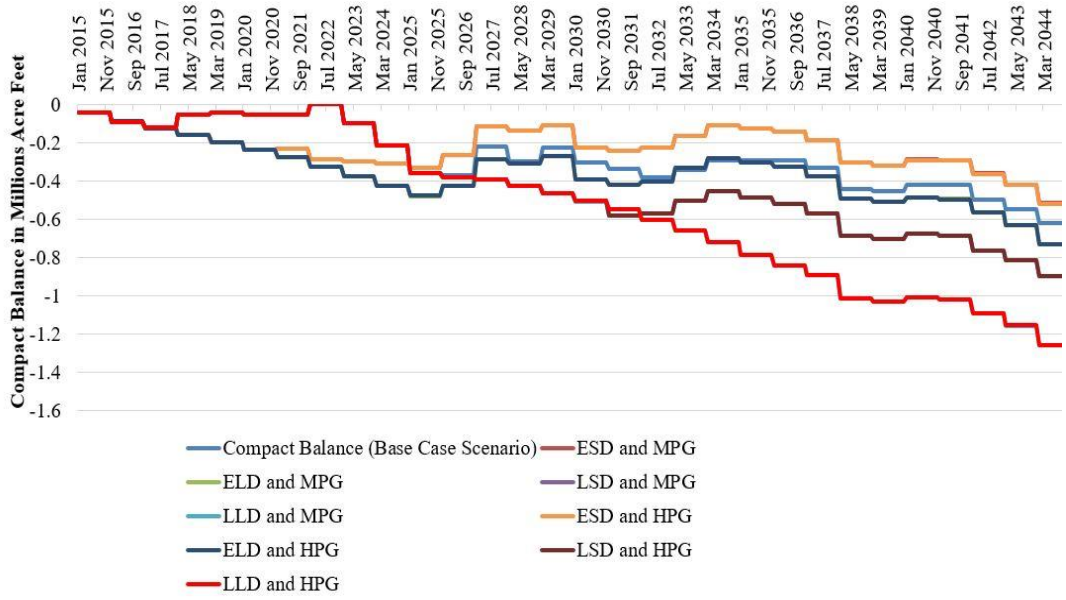


Figure 2-22: Impact of Drought and Population Growth on Compact Balance

The most negative compact balance at the end of simulation corresponds to late long drought and high population growth. It is interesting to see that the compact balance at the end of the simulation period corresponding to early short drought (with both

population growth rate scenarios) is more favorable than base case scenario. Figure 2-23 shows the compact balance at the end of the simulation period for various scenarios. In general, longer drought in later periods and higher population growth is responsible for more negative compact balance. The explanation is straightforward: Longer drought and higher population results in more consumption of water, leaving less water to be delivered for downstream users.

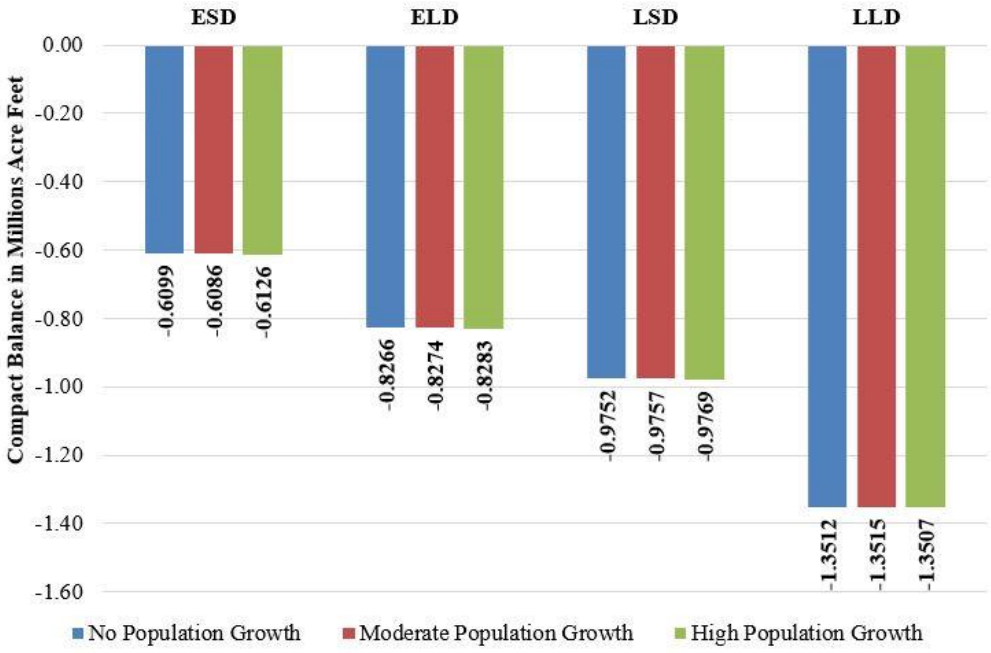


Figure 2-23: Compact Balance at the End of Simulation

Figure 2-24 shows the per capita per day water consumption with various drought and population growth scenarios. In the figure it looks like there are two blocks of graphs. The lower block of the graph belongs to high population growth rate and the upper block belongs to moderate population growth rate. This means, on average, that per capita per day water conumption is higher for moderate population growth rate.

Another feature revelaed by Figure 2-24 is that drought impact is temporary (i.e., once drought is terminated, the per capita per day water consumption returns to its long-

term path). In the figure it is seen that all the lines follow the trend of the black line (base case scenario). Increased population acts as shift factor. Population growth ultimately lowers the per capita water consumption at the level of 153 *gpcd* and 147 *gpcd*, corresponding to moderate and high population growth rates, respectively.

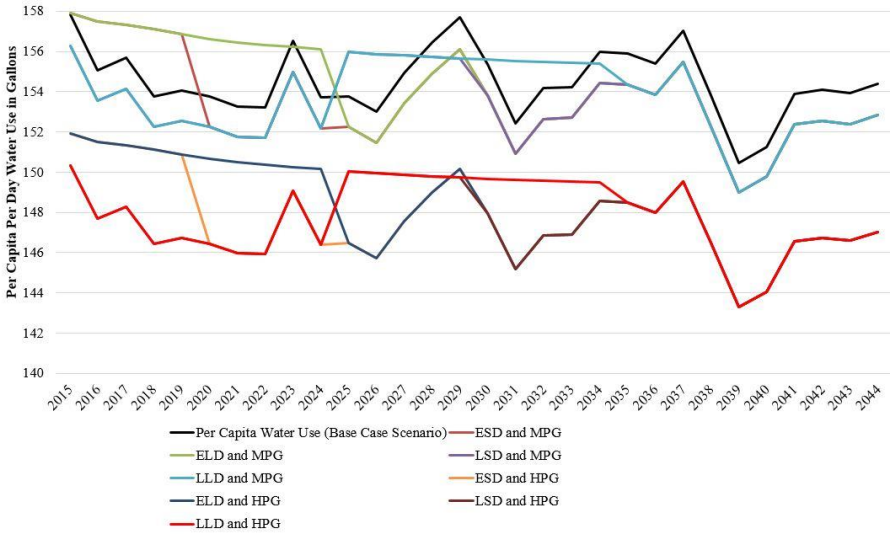


Figure 2-24: Impact of Drought and Population Growth on Per Capita Per Day Water Use

2.6.4 Mitigating Drought Impact: Price Hike and Awareness

Conservation of water and lowering consumption is the ubiquitous drought management strategy, especially in areas like the American West, where new supply development is limited. The variation lies in the tools used for lowering consumption. Traditionally, water rationing has been the ultimate tool for drought management (Lund and Reed 1995). However, rationing has costly welfare implications (Mansur and Olmstead 2012). Water rate adjustments (Mansur and Olmstead 2012), public awareness and educational programs (Wilhite et al. 2000), innovative water reuse, and efficient

devices (Willis et al. 2013) are some of the alternative strategies for demand management during drought. This paper discusses two alternatives: water rates and public awareness.

Figure 2-25 shows the impact of increasing water rate on per capita per day water consumption. Per capita water use continuously declines over time in all three scenarios. At the end of simulation, per capita per day water use is 154.37 gallons, 115.49 gallons, and 91.14 gallons for base case, moderate price hike, and aggressive price hike scenarios. Decline in water consumption with price hike shows that price policy can be an effective policy for conserving water during drought.

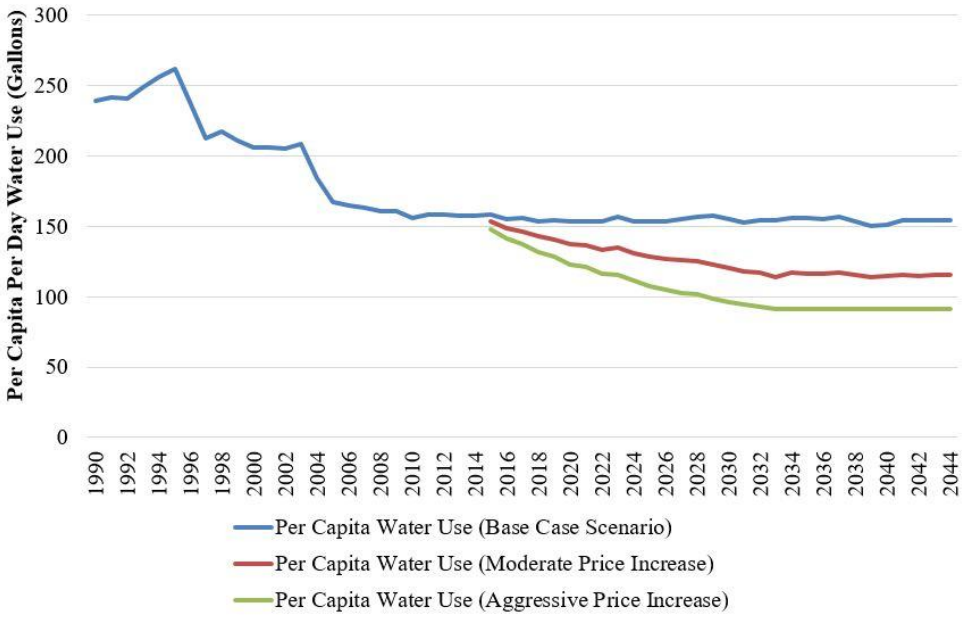


Figure 2-25:Per Capita Water Use in Various Price Scenario

Figure 2-26 depicts the impact of price hike on aquifer volume. Price hike and aquifer volume reveal inverse relationship. As the price of water increases, water demand decreases resulting in less pumping and more aquifer volume. Figure 2-26 shows that at the end of simulation, with moderate and aggressive price hike, aquifer volumes are 0.7 million AF and 1.1 million AF more than the base case scenario volume.

Figure 2-27 shows the impact of price hike on compact balance. Although there are high fluctuations in all three scenarios, compact balance with aggressive price hike is consistently less favorable than other two. Based on the compact balance at the end of simulation, the most favorable case is compact balance with moderate price hike (-0.688 million AF) followed by base case (-0.705 million AF) and aggressive price hike case (-0.756 million AF).

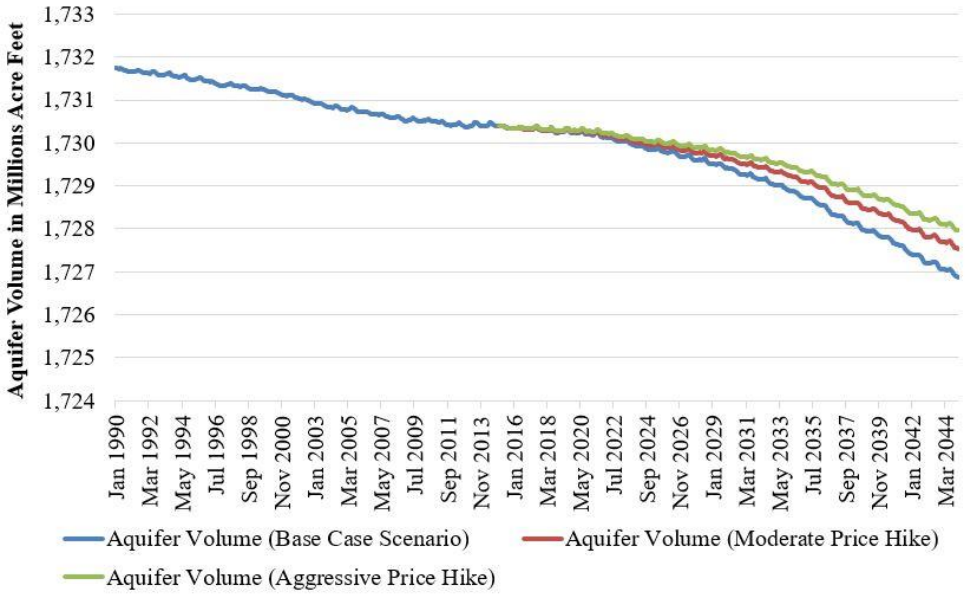


Figure 2-26: Impact of Price Hike in Aquifer Volume

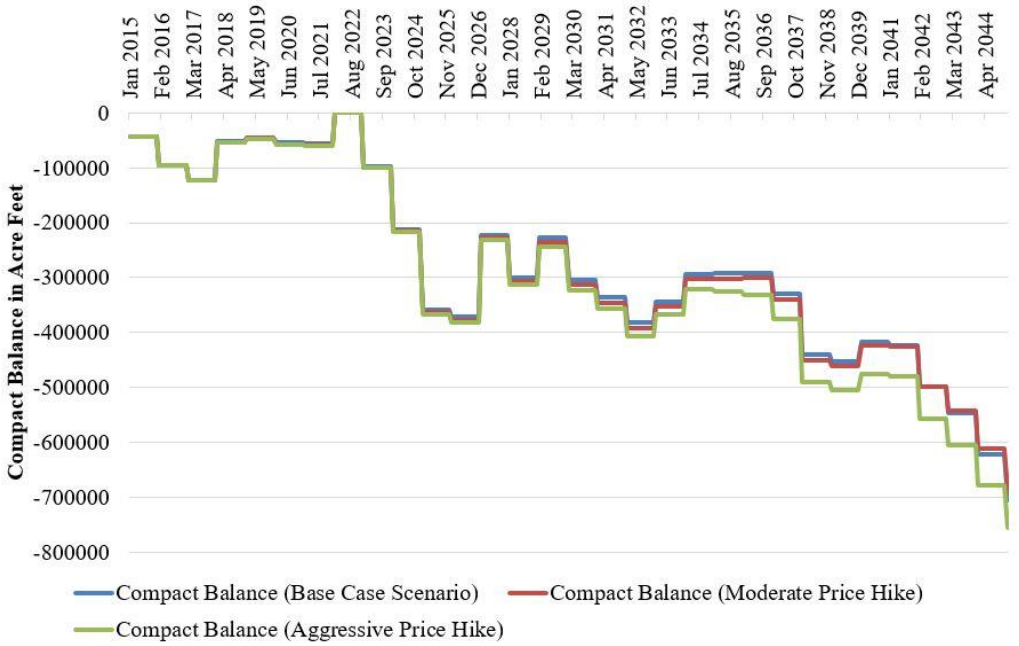


Figure 2-27: Impact of Price Hike in Compact Balance

The question is why a moderate price hike is more favorable than aggressive price hike for compact balance. One possible reason is that the compact balance is determined not only by the mainstream flow but also by return flow. Aggressive price hikes cause individuals to consume less water, resulting in less return flow. On the other hand, no price hike (base case scenario) induces more groundwater pumping so that more groundwater recharge from the river takes place than return flow to the river.

Increasing public awareness is another important method of conserving water. Several studies have shown that public awareness influences water conservation program participation (Adhikari et al. 2016, Fielding et al. 2013). Figure 2-28 shows the impact of increased awareness on aquifer volume. Aquifer volume starts to increase once awareness is imposed in the model. Awareness is responsible for saving about 88 thousand AF of groundwater (i.e., the difference between the base case and awareness scenarios) at the end of the simulation.

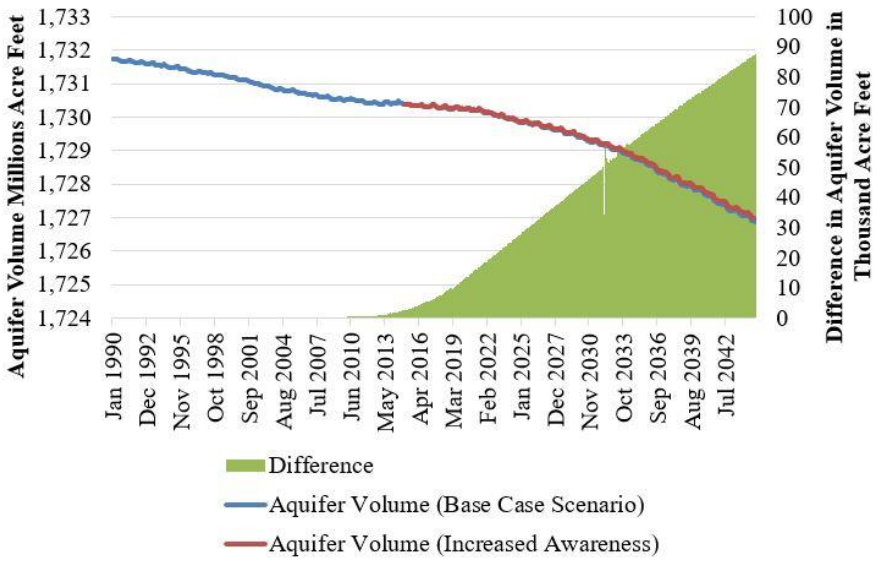


Figure 2-28: Impact of Increased Awareness on Aquifer Volume

Figure 2-29 shows the impact of awareness on compact balance and per capita water use. Compact balance is more negative throughout the simulation once awareness starts to increase in the model. At the end of the simulation period, compact balance with awareness is 732 thousand AF more negative than base case scenario. This may be due to less consumption resulting in less return flow.

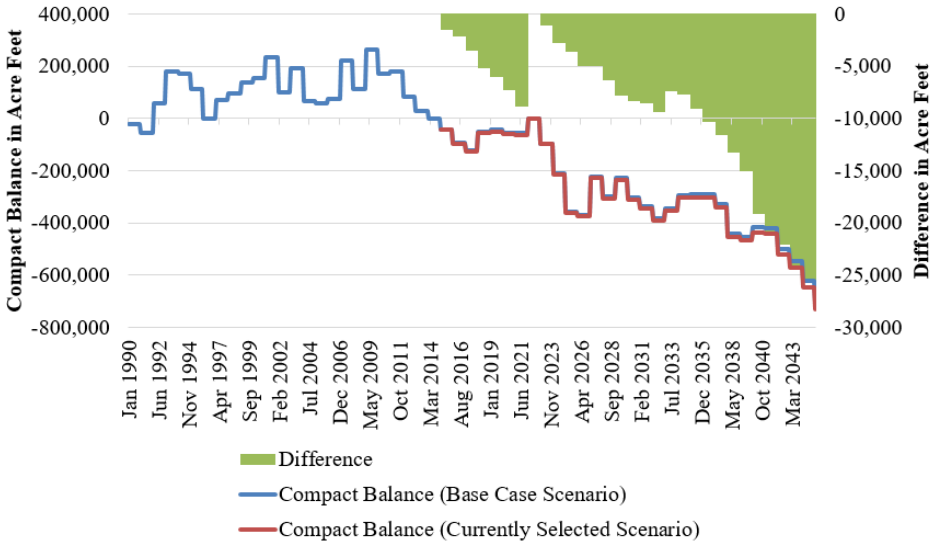


Figure 2-29: Impact of Awareness in Compact Balance

Figure 2-30 depicts the impact of awareness on per capita per day water use. As expected, awareness reduces per capita per day water consumption by about 4 gallons per day at the end of simulation. If this reduction is compared with price, the impact of price is much stronger than the impact of awareness. At the end of simulation, moderate and aggressive price hikes reduced the per capita per day water consumption by 39 gallons and 63 gallons, respectively. If the welfare implications, as explained by Mansur and Olmstead (2012), are ignored, then price is a more effective tool than awareness for reducing water consumption.

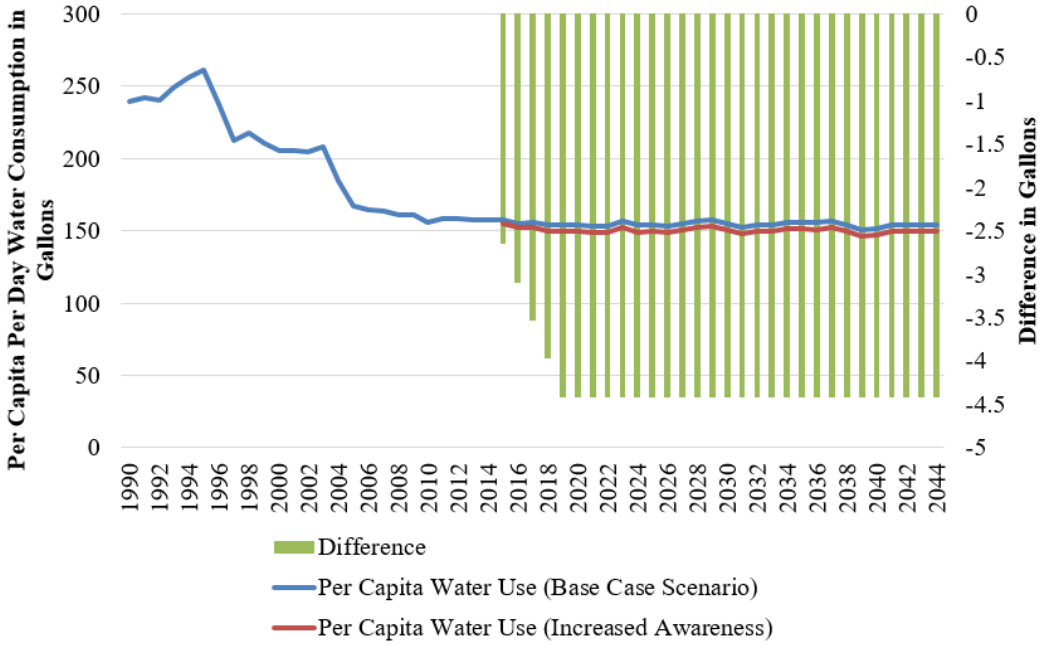


Figure 2-30: Impact of Awareness on Per Capita Per Day Water Use

Finally, how effective are price and awareness for combatting drought impact that is further aggravated by population growth? The answer is partially reflected in Figure 2-31, Figure 2-32, and Figure 2-33. These three figures show the impact of a moderate price hike, increased awareness, high population growth and two types of drought (early

long and late long) on aquifer volume, compact balance, and per capita per day water consumption, respectively.

As expected, Figure 2-31 shows that a price hike and awareness are very effective reducing the pressure of drought and population growth on groundwater. At the end of simulation, the aquifer volume is 1,726,875,409 AF, 1,727,396,731, and 1,727,294,390 AF for base case, early long drought with other, and late long drought with other[9] cases. This means that price hike and awareness can save groundwater such that there will be more groundwater for future generations than in the base case scenario.

Figure 2-32 demonstrates that the compact balance is more negative for two other scenarios in comparison to the base case scenario. The negativity of the compact balance at the end of simulation increases in the order of base case, early long drought (with moderate price hike, increasing awareness, and high population growth rate) and late long drought (with moderate price hike, increasing awareness, and high population growth rate). The levels of compact balance at the end of simulation for these scenarios are -704,503 AF, -873,295 AF, and -1,382,775 AF.

Figure 2-33 shows that the per capita per day water consumption throughout the simulation period is not considerably different for the two droughts scenarios (with moderate price hike, increasing awareness, and high population growth rate), but the difference is very large compared with the base case scenario. At the end of the simulation, both drought scenarios (with moderate price hike, increasing awareness, and high population growth rate) give 105 gallons per capita per day versus 154 gallons per capita per day for the base case scenario.

[9] Here *other* indicates medium price hike, high population growth, and increased awareness

The simulation results showed that price and awareness as water conservation tools have two opposite effects: They increase aquifer volume but make compact balance more negative. Now the plausible question is whether the Middle Rio Grande can achieve net saving of water by compensating compact balance using pumped groundwater. In Figure 2-32, at the end of the simulation, the difference between the base case scenario compact balance and both drought scenarios compact balance is more than 678,271 AF. This is the added responsibility to New Mexico for delivering water in Elephant Butte due to price hike, population growth, increased awareness, and drought. On the other hand, with the same factors, the increment of groundwater saving at the end of the simulation period due to price hike, population growth, increased awareness, and drought is only 418,980 AF. This means that even if all measures are adopted to reduce water consumption, there is a net loss of 259,291 AF of water due to drought.

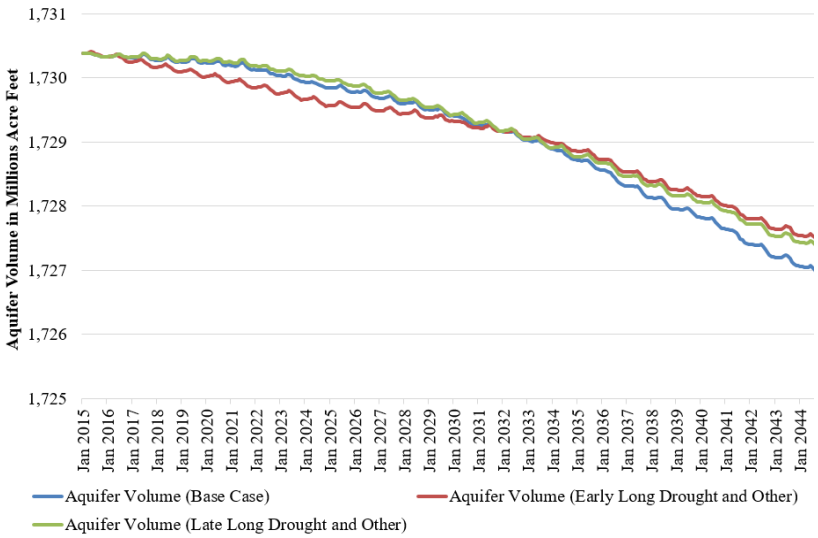


Figure 2-31: Impact of Population Growth, Awareness, Price, and Drought on Aquifer Volume[10]

[10] In the graph legends, *other* indicates for medium price hike, high population growth, and increased awareness.

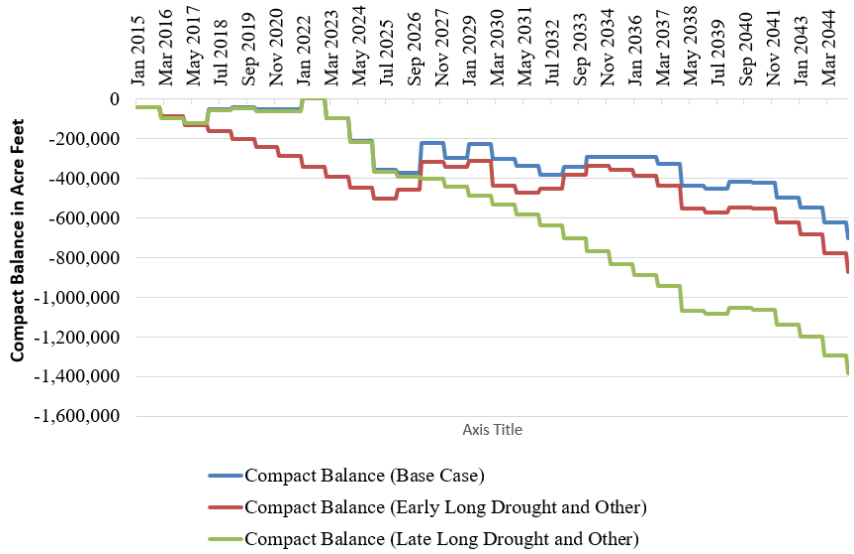


Figure 2-32:Impact of Population Growth, Awareness, Price, and Drought on Compact Balance

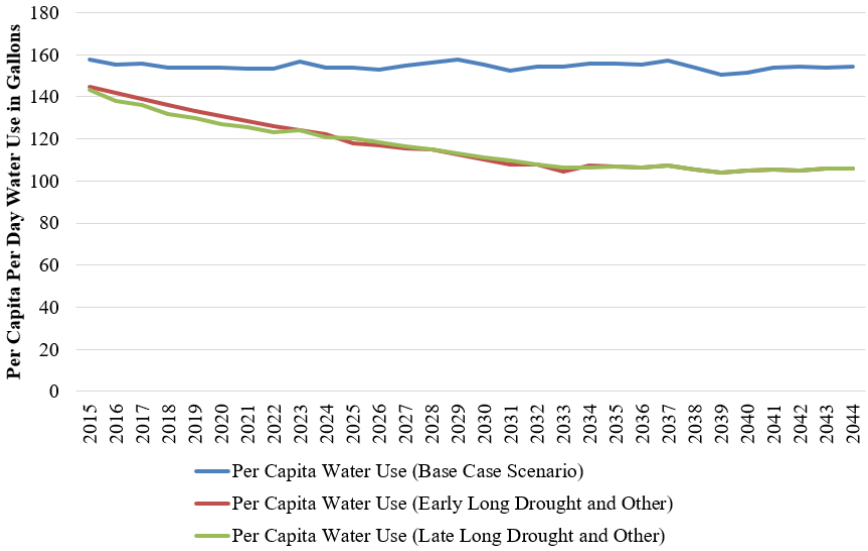


Figure 2-33:Impact of Population Growth, Awareness, Price, and Drought on Water Consumption

Although the results from the previous paragraph are a little bit pessimistic, it should not be expected that the total water volume will remain unchanged for the next 30 years. The number can be interpreted as the total consumption of water by 2045 is 259 thousand AF. This is not a huge amount, especially in the context of drought and population growth. If an aggressive price hike, instead of a moderate price hike as in

above case, was considered, then there would be a net saving of 113 thousand AF of water instead of a 259 thousand AF loss as in the moderate price hike case.

It is not possible to present graphs of all possible combinations of scenarios in the text. However, total aquifer volume, compact balance, and per capita water consumption at the end of the simulation period for all possible combinations of scenarios are presented in the table A12. The last column of table A12 shows the net saving of water at the end of the simulation period. Positive numbers represent saving and negative numbers shows loss over the simulation period. Table 2-4 summarizes best strategies, measured as the highest net saving of water, for different drought conditions. Net saving is measured using following formula:

$$Net\ Saving = \left(AV_{base(2045)} - AV_{newsce(2045)}\right) - \left(CB_{base(2045)} - CB_{newsce(2045)}\right) \quad (2.54)$$

Where,

$Net\ Saving =$ Net saving of water due to scenario other than base case scenario

$AV_{base(2045)} =$ Aquifer volume at the end of simulation for base case scenario

$AV_{newsce(2045)} =$ Aquifer volume at the end of simulation for scenario other than base case

$CB_{base(2045)} =$ Compact balance at the end of simulation for base case scenario

$CB_{newsce(2045)} =$ Compact balance at the end of simulation for scenario other than base case.

Table 2-4: Water Saving Maximizing Scenario in Various Drought Condition

Drought	Population	Awareness	Price	Water Saved (AF)
No Drought	Base Population	Increased Awareness	Aggressive Price Hike	1,062,500
Early Short Drought	Base Population	Increased Awareness	Aggressive Price Hike	1,049,072
Early Long Drought	Base Population	Increased Awareness	Aggressive Price Hike	690,777
Late Short Drought	Base Population	Increased Awareness	Aggressive Price Hike	626,892
Late Long Drought	Base Population	Increased Awareness	Aggressive Price Hike	127,037

Table 2-4 shows that in each drought scenario, maximum water is saved with base population, increased awareness, and an aggressive price hike. This result is plausible. Similarly, the quantity of saved water gradually decreases as the drought becomes longer and occurs in the later period. Here, saved water means net water remaining in the aquifer after compensating for the negative compact balance.

On an individual basis, an aggressive price hike is the most powerful variable to save groundwater and reduce per capita daily water consumption. Table 2-5 shows that the aquifer volume at the end of the simulation increases by 0.06% over the base case volume when there is aggressive price hike. The per capita water consumption with aggressive price hike decreases by 41% at the end of the simulation. The interesting outcome revealed from the simulated outcome is that the positive impact of awareness can outweigh the negative impacts of moderate and high population growth. Keeping all other variables at the level of base case scenario, if there is high population growth then the aquifer volume at the end of simulation will reach 172.7 thousand AF, a -17,731 AF

(-0.001%) less than in base case scenario. On the other hand, if there is an increasing awareness, the aquifer volume will be 1,094,255 AF more than in the base case scenario.

Table 2-5: Impact of Different Variables on Aquifer Volume, Compact Balance and Water Consumption Keeping Other Variables at Base Case Scenario Level

Scenario	Aquifer Volume (AF)		Compact Balance		Water Consumption (GPCD)	
	Value at the End of the Simulation	Difference with Base Case (%)	Value at the End of the Simulation	Difference with Base Case (%)	Value at the End of the Simulation	Difference with Base Case (%)
Base Case	1,726,875,410	0.00	-704,503	0.0000	154.37	0.00
Early Short Drought	1,726,797,463	-0.0045	-609,900	-13.43	154.37	0.00
Early Long Drought	1,726,663,277	-0.0123	-826,630	17.34	154.37	0.00
Late Short Drought	1,726,728,279	-0.0085	-975,190	38.42	154.37	0.00
Late Long Drought	1,726,556,900	-0.0184	-1,351,172	91.79	154.37	0.00
Moderate Population Growth Rate	1,726,871,834	-0.0002	-706,603	0.30	152.85	-0.99
High Population Growth Rate	1,726,857,678	-0.0010	-707,203	0.38	147.02	-4.76
Moderate Price Hike	1,727,538,969	0.0384	-688,336	-2.29	115.49	-25.19
Aggressive Price Hike	1,727,969,665	0.0634	-755,660	7.26	91.14	-40.96
Increasing Awareness	1,726,963,007	0.0051	-731,536	3.84	149.96	-2.86

Finally, Figure 2-34 and Figure 2-35 show the probability density function and cumulative probability density function of aquifer volume. These functions are estimated using 75,150 simulated observations.

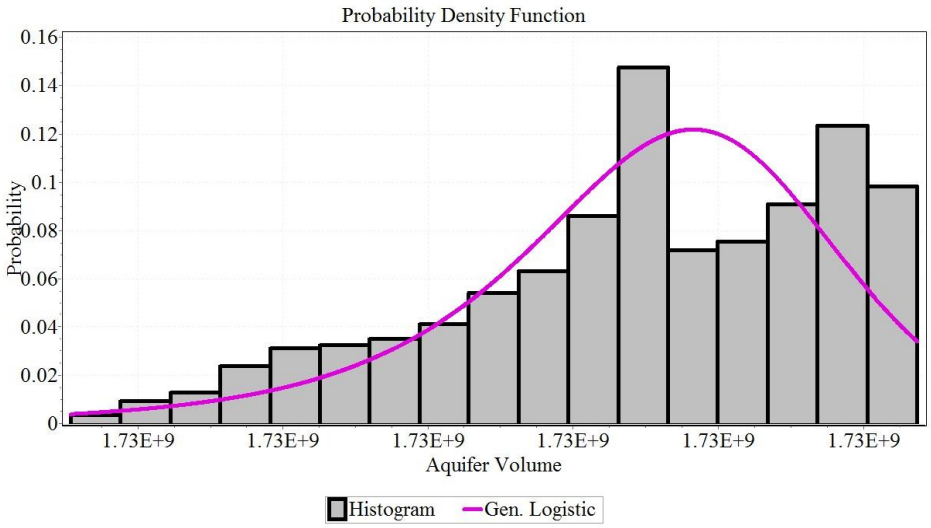


Figure 2-34:Probability Density Function of the Aquifer Volume

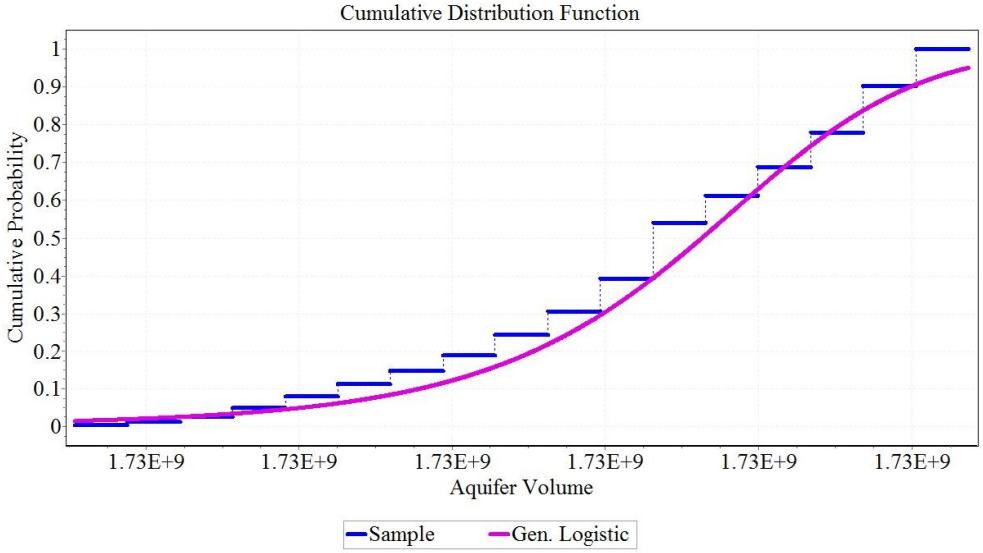


Figure 2-35:Cumulative Density Function of the Aquifer Volume

Aquifer volume follows the logistic distribution. The distribution shows that there is only 10 percent chance of having 1.732 billion AF or more water in aquifer.

2.6.5 Spatial Impact of Groundwater Extraction

Several studies have shown that groundwater pumping externality has spatial nature (Brozović et al. 2010, Pfeiffer and Lin 2012). The theoretical model described in section 3 also proves this fact. This phenomenon in the Middle Rio Grande is shown by measuring the impact of changing groundwater pumping in Santa Fe on the aquifer underneath Albuquerque and Rio Rancho.

Figure 2-36 shows the Albuquerque aquifer basin-- a reproduction of Figure 2-6. As has been explained above in section 3.1.2, this study divides this aquifer basin into 51 zones. Of these 51 zones, zone 14, 18, and 22 (the green shaded area) are underneath the Rio Rancho and zones 17, 19, 20, 24, 25, 28, 29, 30, 34, 35, 38, 44, and 45 (the purple shaded area) are fully or partly underneath Albuquerque. None of the zones in the Albuquerque aquifer basin are right underneath Santa Fe. Santa Fe is located above the Eapanola aquifer basin that is north of the Albuquerque aquifer basin. However, the Albuquerque and Espanola basin aquifers interact in terms of groundwater flow.

The spatial externality in this section is measured in terms of changing water table height and aquifer volume in the aquifer underneath Albuquerque and Rio Rancho. Two factors that influence groundwater pumping--population and awareness--are altered separately from baseline scenario for Santa Fe and Rio Rancho, and the spillover effect of this change on the water table height and aquifer volume in Albuquerque and Rio Rancho is calculated. The difference in water table height and aquifer volume from baseline scenario, measured at the end of simulation, gives the spatial externality. While a high population growth is expected to create a negative externality in the downstream city,

increased awareness and aggressive price hikes are expected to create positive externality.

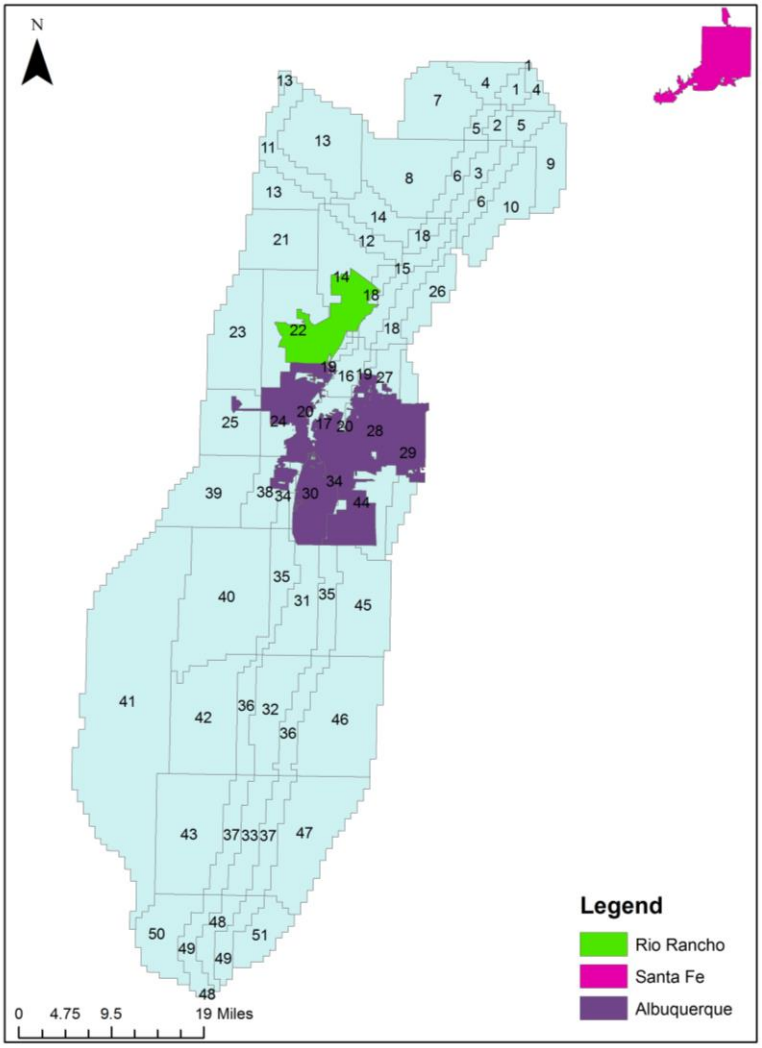


Figure 2-36: Aquifer Underneath Albuquerque and Rio Rancho City

Figure 2-37 shows the spread of the spillover effect of increasing population in Santa Fe over the aquifer basin underneath Albuquerque and Rio Rancho. As color changes from green to blue, the less the water table height is decreased from the base line scenario. The map shows that the largest decrease in water table height from the baseline scenario is in the northern part of Albuquerque, followed by the southern parts of Albuquerque and Rio Rancho. This is because the water table height decreases as much

as 1.5×10^{-5} inch. Although this is not a significantly large quantity, this number is large enough to reveal the spatial externality of water pumping. If Santa Fe had a very large population and/or was closer to Albuquerque, then this magnitude would be significantly large. Three other similar maps showing the impact of increasing awareness in Santa Fe and Rio Rancho and the impact of population increase in Rio Rancho are presented in Annex B.

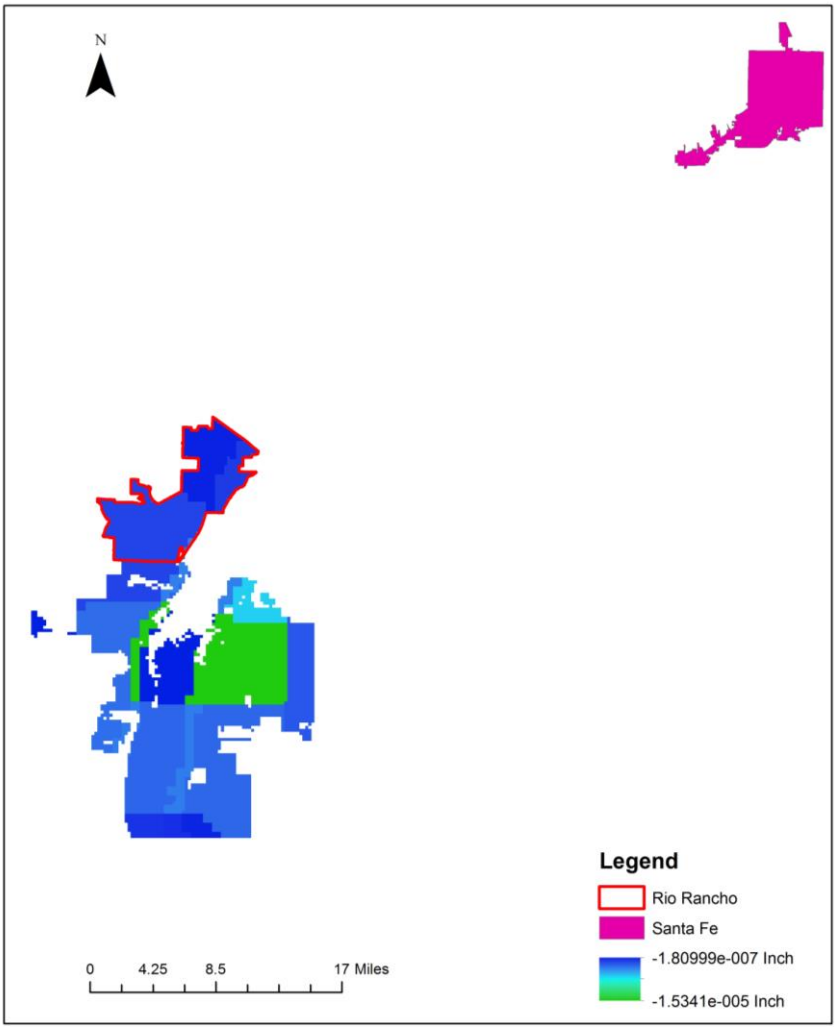


Figure 2-37: Impact of Population Increase in Santa Fe on Water Table Height in Albuquerque and Rio Rancho

Figure 2-38 shows the yearly spatial impact of high population growth and increased awareness in Santa Fe and Rio Rancho on total aquifer volume underneath

Albuquerque and Rio Rancho. As in the water table height case explained above, population growth has negative spatial impact and increasing awareness has positive impact on aquifer volume. While population growth in Rio Rancho causes a reduction of 13 thousand AF of groundwater in Albuquerque at the end of the simulation period, Santa Fe population impact is much smaller (i.e., only a 0.24 AF groundwater decline during the same period). The awareness impact is just opposite of the population impact. Awareness increase in Rio Rancho causes an upsurge in groundwater volume underneath Albuquerque by 5 thousand AF. This impact is only 16 AF for increasing awareness in Santa Fe.

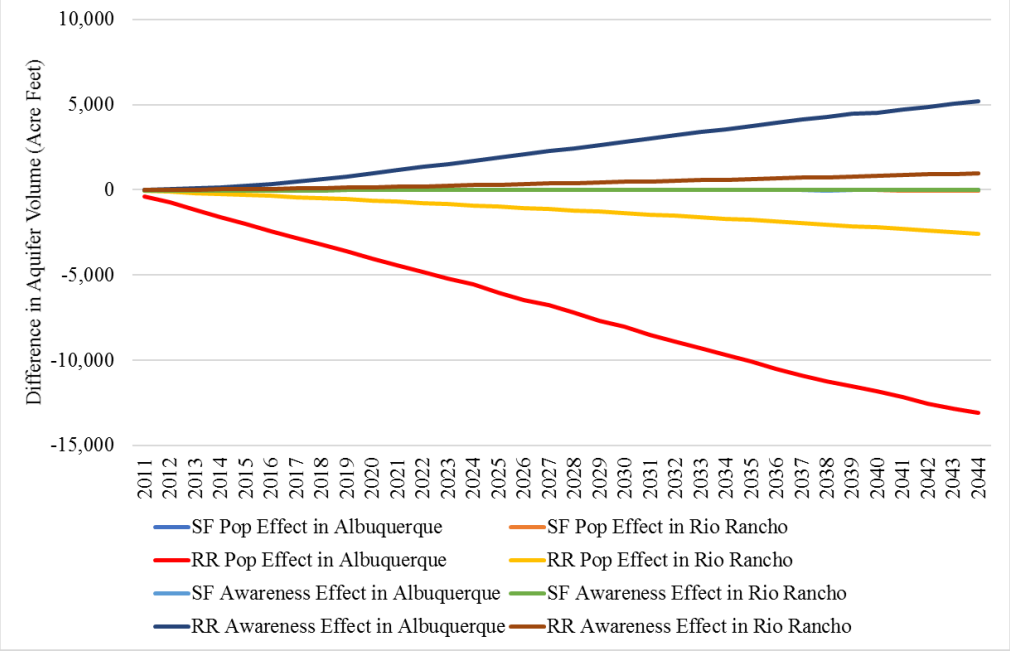


Figure 2-38:Spatial Impact of Awareness and Population Growth on Aquifer Volume

It is possible to convert the impact shown in Figure 2-38 to monetary terms. Brookshire et al. (2004) estimated the average market price for water in the Rio Grande water basin to be $2,118 in 1996 price. This price is equivalent to $2,798 in 2010 price[11].

[11] Adjusted using GDP deflator available at http://www.multpl.com/gdp-deflator/table

Multiplying the change in aquifer volume by this price provides the monetary value of the spatial externality. Figure 2-39 shows the total cost and benefit of increasing population and awareness in Santa Fe and Rio Rancho for the period 2011-2044.

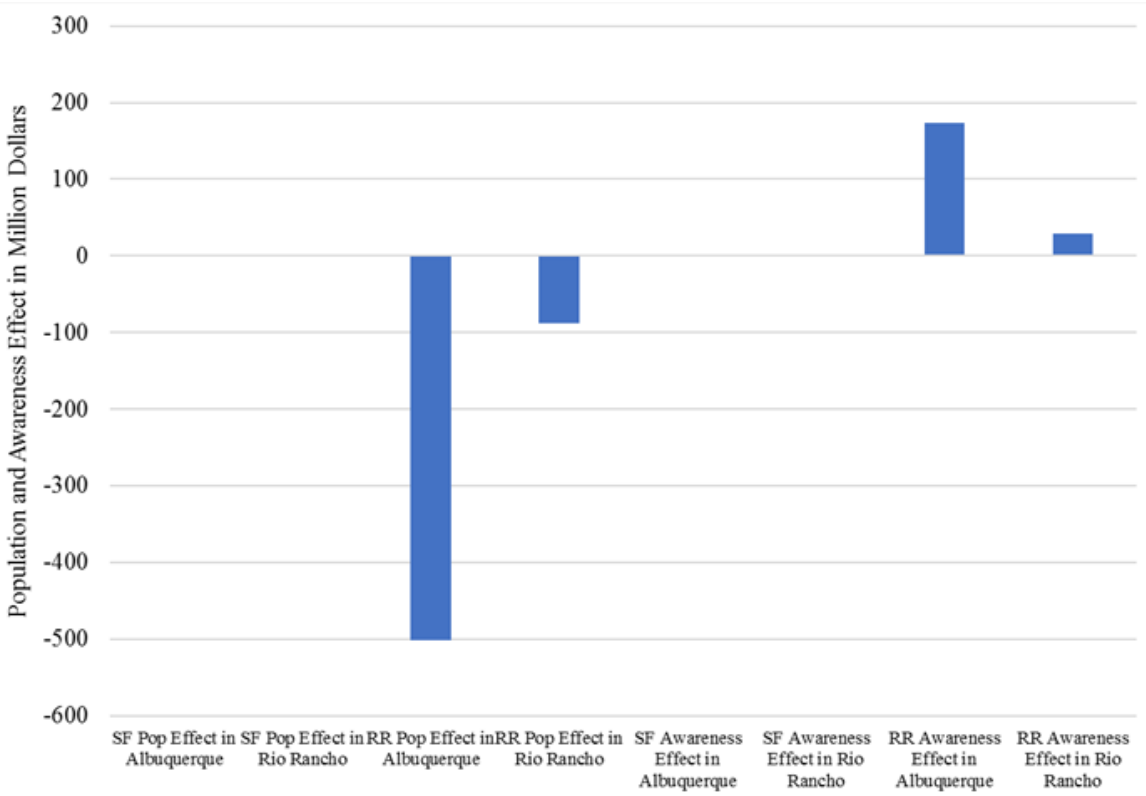


Figure 2-39:Population and Awareness Effect in Monetary Terms

Figure 2-39 shows that the Rio Rancho population effect in Albuquerque is about -$500 million. This is the cost incurred by Albuquerque for the period of 2011-2044 due to population increase in Rio Rancho. Similarly, the benefit accrued to Albuquerque for the same period due to increased awareness in Rio Rancho is $173 million. These costs and benefits to Rio Rancho itself are much smaller due to the smaller population in this city compared to Albuquerque. Santa Fe's impact in comparison to Rio Rancho's impact is negligible. This is because Santa Fe is located farther from Albuquerque than is Rio Rancho.

Figure 2-40 shows the cost accrued to Albuquerque and Rio Rancho due to an increase in population in Rio Rancho and Santa Fe each by 1 person. Each point in the graph represents the ratio of the monetary value of difference in groundwater volume in two scenarios (base case and high population growth) due to differences in the population in two scenarios.

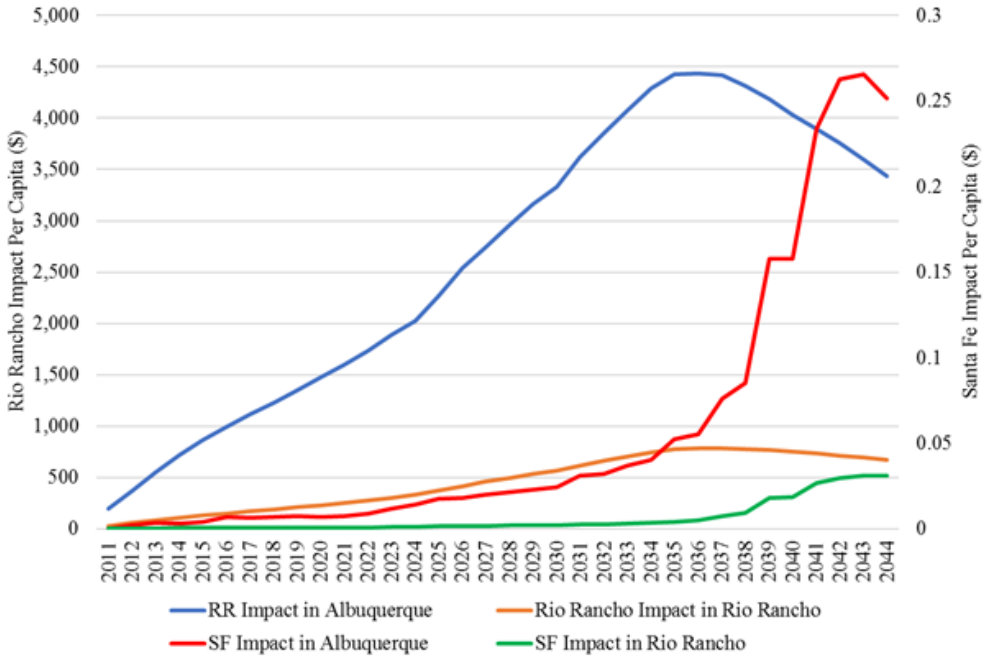


Figure 2-40:Per Capita Impact of Increasing Population in Rio Rancho and Santa Fe

The Figure 2-40 shows that an increase in population in Rio Rancho by one person creates costs to Albuquerque as much as $4,436 in the year 2036. However, this cost varies by year. On average, the costs incurred to Albuquerque due to population increases in Rio Rancho and Santa Fe by 1 person are $2,694 per year and $0.048 per year, respectively.

2.7. Summary, Policy Option and Conclusion

A drought has adverse consequences on water resources (i.e., consumption of water resources increases, leaving less water for future generations). A sustainable way of

using water resources requires meeting the needs of the present without compromising for future generations (i.e., the water system should remain productive indefinitely). This study, using a system dynamics modeling technique, simulates different drought and policy scenarios to see how water resources will be affected by droughts of different lengths and periods, and how the combination of various policy measures helps to manage stressed water resources.

The study area was the Middle Rio Grande watershed in New Mexico. Following the integrated water resource management approach, a hydro-economic model was developed for the study area to analyze the problem. The model considers three systems: groundwater, surface water, and economic systems. The model is both temporal and spatial and operates in monthly time step encompassing the period 1975-2045. Four different drought scenarios were considered: early short drought, early long drought, short late drought, and long late drought. Price, education, and population were considered as policy tools, and the impact was observed on aquifer volume and per capita per day water consumption.

The results showed that, in average, drought causes higher per capita per day water use and reduction in aquifer volume. However, compact balance showed a mixed result. Per capita water consumption during drought increased by up to 5 gallons per person per day. Aquifer volume was reduced by up to 318 thousand AF. Based on the aquifer volume at the end of the simulation, longer droughts are costlier than shorter ones, and later drought is costlier than earlier ones. Compact balance, on the other hand, gains during early short drought and becomes more negative during other drought scenarios.

Increasing population further amplifies the problem. The higher the population growth rate, the larger will be the impact on aquifer volume and compact balance. Aquifer volume will decrease by 3,576 AF and 17,731 AF by 2045 for moderate and high population growth rates, respectively. The compact balance will be more negative by 2,100 AF and 2,700 AF during the same period, respectively. Per capita per day water consumption, on the other hand, will decline by 1.5 gallons and 7.4 gallons, respectively.

While drought and population growth put pressure on water resources, water rate hikes and growing awareness work in the opposite direction. Keeping all other things constant, increasing price moderately increases aquifer volume by 663,559 AF at the end of simulation. This volume reaches 1,094,256 if the price hike is aggressive. Compact balance, on the other hand, gains with early short drought and a moderate price hike. The most negative impact on compact balance is posed by drought, except early short drought and aggressive price hike.

In all cases but moderate price hike and early short drought, compact balance became more negative than in the base case scenario at the end of the simulation. At the same time, aquifer volume increased with the implementation of drought-curbing policy (i.e., price hike and awareness). In this situation, one policy measure could be to compensate for compact balance through saved aquifer volume (i.e., pump groundwater and put into the Rio Grande so that there will be a net saving of water in the MRG). However, this mechanism works only with an aggressive price hike if the drought is late.

Scientists have predicted more severe and frequent droughts in the future that will result in acute water scarcity. Saving water for the future by curtailing current consumption can be an appropriate solution. This study found that price hikes and

increasing awareness can save water for future through reducing per capita consumption. Three cities considered in this study have already adopted these measures. Albuquerque Bernalillo County Water Utility Authority (ABCWUA) categorizes drought into three stages and applies public education programs, price hikes, rebate programs, and rationing methods at different stages of drought to reduce water consumption (ABCWUA 2012). Santa Fe has implemented various water conservation programs through city ordinances (SFCC 1987 § 25-2.2 Comprehensive Water Conservation Requirements Ordinance, SFCC 1987 § 25-5 Emergency Water Regulations Ordinance, SFCC 1987 § 14-8.4 Landscape and Site Design Regulations, City Water Budget Ordinance). Some of the programs include customer education and incentive programs, customer water conservation requirements, water rates, and incentives and other requirements that mandate new development and implement stringent water conservation measures and other steps to offset the new demand on the existing water system (City of Santa Fe 2015). Rio Rancho is also implementing similar plans such as public education, rebates, water rate, and utilizing an alternative source of water such as rain harvesting (City of Rio Rancho 2014).

Water management becomes complicated due to its spatial nature. Any water use activities in one area may have a spillover effect on other areas. This study found that groundwater pumping activity induced by population growth in Santa Fe and Rio Rancho (upstream cities) results into a decrease in the water table height and groundwater volume in Albuquerque (a downstream city). Similarly, an increase in awareness in upstream cities brings an increase in water table height and groundwater volume in Albuquerque. Such spillover effects spread unevenly in the entire basin and attenuate with distance.

Decrease or increase in groundwater volume in one city due to increase in population or awareness in another city is a cost (benefit) to the former city. Monetization of this cost revealed that an increase in population in Rio Rancho by 1 person creates a cost of $2,694 per year to Albuquerque. These findings have policy implications. For example, an increased awareness in Santa Fe causes an increase in the water table height in Albuquerque resulting in a decrease in pumping cost and saving resources. Part of such resources can be used to compensate for the cost of awareness-increasing programs in Santa Fe. Similarly, Albuquerque can claim a share of water revenue generated in Rio Rancho so that it can utilize such revenue for water conservation programs.

The model developed in this study has several limitations. The most important is the data availability. The economic model suffers from lack of long historical data. Availability of long historical data is important for a simulation model to improve its reliability and validity. Calibration of the economic model using limited data is the major limitation of this study. This model can be improved further through including more cities such as Los Lunas and Belen in the model, estimating the demand equation through a new survey that includes information on income too, including block rate structure in the water demand model, and using the actual historic water rate structure.

This study can be expanded in the future by adding uncertainties in the model. In the real world, there are uncertainties associated with several variables included in the model. For example, there are uncertainties regarding water price, population growth, and even uncertainties in parameters. However, the most important uncertainty is related to drought. Scientists have predicted more severe and more frequent droughts in the future, but there is uncertainty about the severity, duration, and frequency. Including this

uncertainty in the model will improve model outcomes and provide a better basis on which to formulate more reliable policy measures.

Chapter 3 : Linking Forest to Faucets in a Distant Municipal Area: Public Support for Forest Restoration and Water Security in Albuquerque, New Mexico

3.1. Introduction

Due to a mix of factors, catastrophic or high severity wildfire risk is increasing in the western United States (US) and elsewhere (Dennison et al., 2014). Annually, wildfire destroys millions of acres of forest and costs billions of dollars in the western US. In New Mexico, two wildfires burned about 350,000 acres in 2012, resulting in more than $47 million in suppression costs, while a single fire in 2011 (Las Conchas fire) had suppression costs of $48 million alone.; total damage costs are likely several times higher (Gorte, 2013; Hall, 2011). In addition to land disturbance, wildfire can be a major disturbance to watershed and water quality conditions (Ice et al., 2004; Guardiola-Claramonte, 2005; Loáiciga et al., 2001; Meixner and Wohlgemuth, 2004; Neary et al., 2005b; Pierson et al., 2001; Pinel-Alloul et al., 2002; Prepas et al., 2003; Smith et al., 2011). Impacts can include increased debris, sediment, nitrate, radionuclides and heavy metals, and fire retardant chemicals in surface water (Neary et al., 2005a). Post-wildfire water contamination can impose high treatment costs on downstream public water supplies, or a forced switch to scarce groundwater (Bladon et al., 2014; McCarthy, 2014).

For many communities, reducing the risk of high severity wildfires through forest restoration is vital for the sustainability of watersheds and securing safe drinking water (Dudley and Stolton, 2003). Identifying public support for generating revenues to cover the costs of restoration can be an important implementation barrier (Holl and Howarth,

2000). A variety of payment for ecosystem services (PES) models may be used to meet forest restoration objectives (Barbier and Markandya, 2013; Holl and Howarth, 2000). As such approaches are considered, the proximal relationship between watersheds and a community may influence public support. One might expect considerable public support when the distance between "forests and faucets" is minimal. For example, in the recent case of Santa Fe, NM, 82% of surveyed ratepayers in 2011 were willing to pay a charge of 65 cents per month ($7.80 annually) to protect the City's water supply from catastrophic wildfire, where two nearby reservoirs are surrounded by forest lands; a PES program was subsequently approved by the City Council (Bottorff, 2014; McCarthy, 2014). An unresolved issue is whether households in a relatively distant municipal area would significantly support wildfire risk reduction efforts to restore forest health and improve water security in their downstream community. For many relatively large urban areas, there is the distinct possibility that the majority of households are considerably distant, or spatially-removed, from needed restoration activities. In such a case, the issues can be exacerbated by the uncertainty of restoration activities, project costs, and design plans (Holl and Howarth, 2000). At least two types of uncertainty may be important: (i) uncertainty in the preferences of distant households for water security as an important collectively provided good ("preference uncertainty"); and (ii) uncertainty in the possibility that restoration activities across a forested landscape or watershed might actually deliver improved water security ("delivery uncertainty").

The objective of this research is to investigate public support for a Payment for Ecosystem Services (PES) model, including annual household willingness to pay (WTP) estimation, of a forest restoration program that improves water security in the

Albuquerque, NM metropolitan area. Using a contingent valuation (CV) survey approach, data from over 900 household responses was collected using a combination of mail and internet surveys in the fall of 2013. The random sample was drawn from Albuquerque homeowners, located nearly 40 miles (nearest aerial distance) from the nearest forested watershed supplying surface flows for Albuquerque drinking water supplies. Relative to the recent PES model implemented in Santa Fe, NM (Bottorff, 2014; McCarthy, 2014), which represents a much smaller component of the same larger watershed, the Albuquerque case involves a sample that is more spatially-removed from proposed restoration activities. The analysis also explores the effects of both preference and delivery uncertainty on WTP.

Econometric results for annual household WTP, estimated using a Double Hurdle modeling approach, indicate that the WTP value increases if respondents' perceive that water supply and fire risk are serious issues, and decreases if respondents are uncertain about their preferences and delivery outcomes of the program. The estimated program support is at least as large as the value estimated for similar activities in a nearby comparison located in the vicinity of forests that would receive wildfire risk-reducing treatments.

3.2. Background

3.2.1 Sustainability, Wildfire, and Watersheds, and Payments for Ecosystem Services

The sustainable wellbeing of human systems is connected to maintaining the health of natural systems. High-severity wildfires present significant risk exposure to interconnected natural and human systems in many areas of the southwestern US and elsewhere. Scientists forecast increasing wildfire severity and an expansion of the

wildfire season in the region (Liu et al., 2013; Liu et al., 2010; Westerling et al., 2006). Concurrently, increasing numbers of people (and property development) are moving into the flame zone, causing the wildland-urban interface (WUI) to expand (Theobald and Romme, 2007).

Wildfire suppression costs in the United States are trending upward (Abt et al., 2009). It is also becoming clear that suppression costs may represent only a small fraction of the total social costs associated with large high-severity wildfires (Gorte, 2013; Hall, 2011). Increasing wildfire risk due to climate change and a continued focus on suppression, rather than pre-fire hazard reduction, could further increase wildfire costs (Snider et al., 2006). Snider et al. (2006) found that it is more economically rational to spend $238-$601/ac for hazard reduction treatments, like prescribed burning and mechanical thinning, in the Southwest than to continue the policy of suppression. However, insufficient funding is an obstacle to implementing a policy focus on wildfire risk reduction (Hjerpe et al., 2009).

Effective forest restoration programs to mitigate wildfire are vital to improving water security. About 65 percent of the water supply in the American West comes from forests (Furniss et al., 2010). Additionally, in many areas groundwater sources are being pumped at rates much higher than aquifer recharge (McGuire et al., 2003). Thus, protecting surface waters and mountain front recharge for groundwater is critical. Forest restoration can contribute significantly towards reducing water treatment costs. For example, based on a study of 27 water suppliers in 2002, Ernst et al. (2004) reported that every 10 percent increase in forest cover in the source area leads to a 20 percent reduction in water treatment costs.

Critical sources for public drinking water systems often originate in mountain forests, either as the headwaters of river systems for surface water or through mountain-front recharge for groundwater. Due to a mix of inter-related human and natural factors (e.g., climate change, drought, beetle damage, 20th century fire suppression policy and the associated fuels build-up of small-diameter trees and vegetation, or the expansive growth of the WUI), many mountain forests in NM and elsewhere in the western US have become increasingly susceptible to high-severity wildfires. High severity wildfires can alter hydrologic systems, and degrade watersheds, while creating significant runoff, debris and water quality impacts downstream. Forest restoration to reduce or mitigate wildfire risk includes both mechanical thinning and prescribed fire, and in some cases letting fires burn. Given that montane forests are often important sources of surface water and groundwater recharge, forest restoration and watershed health become critically connected to downstream municipalities and the provision of drinking water supplies. Recognition of such connectedness is seen, for example, in the development of the federal "Forests to Faucets" program.[12]

The sustainability problem might be characterized as follows: We have significantly altered forest ecosystems in a negative way (degraded natural capital), increasing catastrophic wildfire risk while at the same time more and more people (and their physical capital) are moving into flame zones, and there remains considerable policy gridlock on suppression versus hazardous fuels treatments. How do we reintroduce

[12] The U.S. Department of Agriculture's Forest Service "Forests to Faucets" program aims to manage forested watersheds to maintain the invaluable services that natural infrastructure provides to local and downstream populations (Edmonds et al., 2013)

natural fire regimes at landscape scale while protecting at-risk communities and shift a greater proportion of costs away from federal taxpayers (in suppression costs) and onto communities (paying for ecosystem services) and homeowners (mitigation and insurance), while considering social equity and building social capital?

There is a need for a variety of new institutional arrangements for confronting this sustainability challenge and reducing wildfire risk (Reyers et al., 2015). Institutional arrangements are the formal rules and regulations, as well as informal norms, which can either foster or inhibit actions, such as forest restoration and fuel reduction (Steelman, 2008). New arrangements can range from collaborative public-private partnerships for solving multi-jurisdictional land ownership issues (Reyers et al., 2015), to creating new insurance or tax financing mechanisms (Prante et al., 2011). One available tool to help meet this sustainability challenge is the creation and implementation of PES models.

Responsibility for restoration costs is one of the most overlooked questions in restoration ecology (Holl and Howarth, 2000; Daugherty and Snider, 2003). PES represents a collection of approaches for financing restoration activities. Barbier and Markandya (2013) discuss three broad types or categories of PES: voluntary contractual agreements, trading schemes and public payment schemes. The first two categories require, beside other qualifications, that there are known agents damaging the environment. In public payment schemes (PPS), the government or some public entity or the community sets the broad restoration plan and mobilizes funds through fees, taxes, etc. A major feature of any PPS is that it can be applied even when there is not a well-defined property right. Such approaches may require legislation for creating new institutional arrangements, including funding mechanisms such as taxes or fees etc.

(Barbier and Markandya, 2013). Crucial questions for PPS-PES include deciding who should lead and who should pay and how the funding is to be collected, which depend on the level of complexity, jurisdiction and scale (Grigg, 1999). Identifying the full set of beneficiaries, even when spatially removed from wildfire risk, is an important part of finding possible funding solutions.

3.2.2 Study Area and the Rio Grande Water Fund

The study was conducted in Albuquerque, located in the Middle Rio Grande valley of New Mexico. Significant forested area begins about 40 mile north of the Albuquerque, where watersheds drain into the middle Rio Grande (Figure 3-1). Albuquerque is the largest metropolitan area in the state both in terms of area (190 square miles) and population (557,169 in 2014). Municipal water is supplied by the Albuquerque Bernalillo County Water Utility Authority (ABCWUA), the largest water utility in New Mexico. Most of ABCWUA's service customers are either residential (87%) or commercial (6%) (P. Jenkins, personal communication, January 15, 2015).

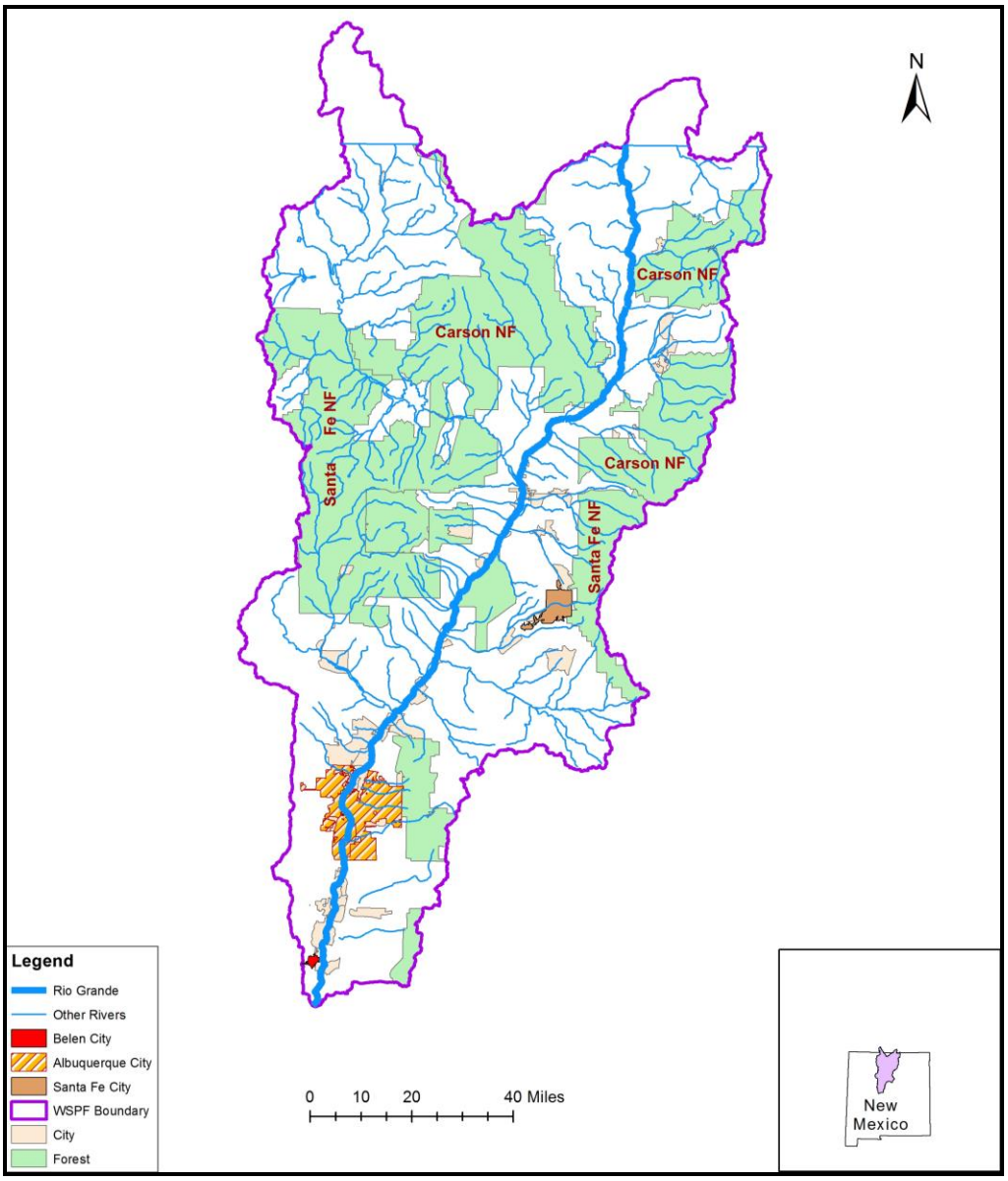


Figure 3-1:Proposed Forest Area for Treatment and the Study Area

Before 2008, water supply requirements for Albuquerque were almost entirely met by groundwater from the Santa Fe Group Aquifer, which underlies Albuquerque. Albuquerque began the process of switching to partial use of surface water after a 1993 U.S. Geological Survey report indicated the aquifer was much smaller than originally estimated, recharge was smaller and the aquifer was being mined (Water Science and Technology Board and National Research Council, 1997). The project to develop the

infrastructure to divert river water began in 2004 and went on line in 2008, and water tables have since been slowly rising. Since 2008, water supply has been met from both groundwater, as well as surface water from the San Juan Chama Project (SJCP). SJCP transfers water from the San Juan River Basin (in the Colorado River system) to the Rio Grande Basin. Surface water provides more than 40% of metropolitan Albuquerque's water supply and is projected to significantly increase going forward. This increased reliance on river water creates a new risk to municipal water supply security due to wildfire in the watershed.

The SJCP, as a participating project of the Colorado River Storage Project, taps the water from the San Juan River (Flanigan and Haas, 2008). New Mexico's share of water from the San Juan River is brought into the Rio Grande through the Chama River using a number of diversion dams, tunnels, and siphons (Olson, 2008). With property rights to 48,200 acre feet of water annually from the SJCP, Albuquerque then diverts and treats the surface water from the Rio Grande for distribution to municipal and industrial uses. All the rivers and tributaries that contribute water to the SJCP run through a large forested watershed, which combine with what are referred to as the "native flows" or drainage of the Rio Grande. While the movement from primary reliance on groundwater to surface water began to immediately reduce the depletion of groundwater, it also significantly increased the importance of wildfire risk to water supply security in Albuquerque and other Rio Grande communities. The impact of the 156,000 acre Las Conchas fire that erupted more than 100 miles north of Albuquerque in 2011 is an example.

Thunderstorms over the high-severity burn areas of the Las Conchas fire in 2011 produced massive ash and debris flows in the surrounding canyons draining directly to

the Rio Grande (Dahm et al., 2013). The debris flows deposited tons of debris into the Cochiti Reservoir, and significantly reduced the dissolved oxygen content in the Rio Grande all the way to Albuquerque and further south (Dahm et al., 2013). Following this event, in order to avoid costs of de-clogging equipment and treating sediment-laden river water, ABCWUA shut down its water intake from the Rio Grande and tapped more groundwater to make up for the deficit (Fleck, 2011; Postel, 2014). ABCWUA switched from surface to groundwater, using up approximately 40 days' worth of groundwater (Chermak et al., 2012; Matthews, 2013; McCarthy, 2014).

Forest restoration treatments of thinning and prescribed burning reduce the risk of wildfire by reducing hazardous fuels (Fulé et al., 2001). Figure 1 shows the forested area of northern NM, where watersheds drain into the middle Rio Grande, where Albuquerque is located. This area consists of approximately 1.7 million acres of fire-prone forests, where is has been recommended that 1-2% of fire-adapted forest landscapes be treated each year to change fire behavior (The Nature Conservancy, 2014). This necessitates about 30,000 acres of forest be treated each year.

Since 2012, The Nature Conservancy, an international conservation organization, has spearheaded planning efforts to create a 'Rio Grande Water Fund' (RGWF) in New Mexico, covering the area from Belen north to the Colorado border, for supporting the cost of mitigating wildfire risk through forest restoration. The RGWF represents a collaborative partnership among more than 40 organizations and agencies, with a comprehensive plan for wildfire and water source protection (The Nature Conservancy, 2014). The plan is to increase the pace and scale of forest watershed restoration by ten-fold over 20 years, with 30,000 acres per year for a total of 600,000 acres in the Rio

Grande, Rio Chama and tributary watersheds. It is estimated that this activity will need, in total, about $420 million over the 20 years (The Nature Conservancy, 2014). Early discussions of this proposed fund provided the motivation for this survey research.

An advisory board was formed in April 2013 to guide the RGWF in collecting private investments from individuals, businesses, corporations and foundations. As originally envisioned, it would potentially allow the full range of public and private entities (e.g., government agencies, water users, community stakeholders and others) to invest in the protection of the forests that supply water. The RWGF became active in 2014, without any participatory or parallel PPS; thus, to start, the Nature Conservancy will administer private and commercial donations to the RWGF, with an executive committee of diverse stakeholders and investors.

A variety of PES funding models have been mobilized around the world, including in the western US. Table 3.1 summarizes PPE-PES funding mechanisms for forest restoration in selected cities. The fundamental difference between the Flagstaff, and Santa Fe projects, especially, and the proposed restoration in the RGWF for the Albuquerque is that these cities are more directly bounded by, or proximal to fire-prone forests. For example, Santa Fe shares about two miles of its eastern boundary with Santa Fe National Forest and all Santa Fe residents have their home within eight miles distance from the forest. For residents of these cities, wildfire risks could impact not only the water supply but also health and property. This may encourage support for forest restoration activities. However, Albuquerque residents, who live a significant distance from the high severity wildfire risk area, do not experience property threats. Figure 3-1 shows that while Santa Fe abuts the boundary forest, Albuquerque is nearly 40 miles

(nearest distance) from the two major forests with high severity wildfire risk to its surface water supplies: the Santa Fe National Forest and the Carson National Forest.[13]

Table 3-1:Some Notable Water Funds for Forest Restoration in the Western US

City	Start Year	Total Fund	Partner Organizations	Watershed	Fund Collection Mechanism
Denver, CO	2011	$33 Million	Denver Water and US Forest Service	South Platte	Denver Water contributes half of the total fund and intends to roll the cost into future rate increases
Santa Fe, NM	2010	$4.3 Million	Santa Fe National Forest, City of Santa Fe Fire Department, City of Santa Fe Water Division, The Nature Conservancy, and the Santa Fe Watershed Association.	Santa Fe	Phase I: New Mexico Water Trust Board paid for first 5 years. Phase II: Expected to charge each water consumer at the rate of $0.13 per 1000 gallons per month.
Flagstaff, AZ	2012	$10 Million	State, City, and Coconino National Forest	Rio de Flag and Lake Mary Watersheds	Flagstaff voters approved a $10 Million bond to support the project.

Source: Carpe Diem West (2011), Margolis et al. (2009)

[13] Figure 1 shows that a part of eastern Albuquerque shares its boundary with Cibola National Forest lands, through which some streams and run-off pass to meet the Rio Grande. However, water supply diversions for Albuquerque are much further to the north. Further, the western slopes of the Sandia Mountains (to the east of Albuquerque) are not heavily forested. This reduces any proximal high severity wildfire risk to Albuquerque and its water supply.

3.3. Survey Method and Data Collection

Although there are a variety of validity and measurement issues (e.g., Carson and Hanemann, 2006; Carson, 2015), the survey-based contingent valuation (CV) method is widely used for collecting preference information on the provision of changes in public goods. There are numerous applications to forest and water resource issues. Mueller (2014) and Mueller et al. (2013) provide recent CV applications to forest restoration and water source protection.

The CV survey used in this study was administered to a sample of Albuquerque municipal homeowners. Survey design included several rounds of focus group discussions, conducted at the University of New Mexico, debriefing interviews, and pre-testing of the questionnaire with a sample of 100. The universe of observations selected for the survey was taken from a merged set of the Bernalillo County Assessor annual assessment data that were matched by address to residential accounts from ABCWUA. Of the original 190,298 total ABCWUA water accounts, which included commercial, business and homeowner household accounts, 113,602 accounts were matched to assessor data. From these homeowner household accounts 2,596 households were selected following systematic random sampling to ensure an equal percentage representation of resident households from each zip code of the Albuquerque. The initial questionnaire was mailed to sampled households between September and November 2013. Survey administration followed best practices with each household receiving up to five contacts (Dillman, 2007). Respondents also had the option to complete the survey online or via mail.

The response rate for the eligible sample was 37%.[14] In the context of a long-term downward trend of response rates to mail surveys (Connelly et al., 2003; Larson, 2005), this response rate compares with similar applications. The obtained rate fell between those recently obtained in the Mueller (2014) and Mueller et al. (2013) studies of WTP for forest restoration in Arizona which recorded 48% and 32% response rates, respectively. Loomis et al. (2000) reported a 26% response rate for a CV survey valuing ecosystem restoration near Denver.

The survey was distributed by the Department of Economics at the University of New Mexico, and was titled: Wildfire and Metropolitan Albuquerque's Water Supply: We Want to Know Your Opinion."[15] The cover page clearly expressed the intent and linking of forest restoration to water source protection and supply, requesting respondent input on: "a possible investment to reduce the threat of high-severity wildfire and thus reduce impacts on our water sources and supply." The survey included initial sections on: (i) "Your water supply"; (ii) How does high-severity wildfire affect Albuquerque's sustainable water supply? (iii) "Reducing the risk of high severity wildfire north of Albuquerque." Respondents were provided descriptive information about the sources of

[14] The eligible sample, was defined as the letters mailed less undelivered mail. Response rate was calculated as the ratio of total returned questionnaires (completed and partially completed) to the eligible sample.

[15] A full copy of the paper survey, and the actual map used in the survey, can be found at:

http://economics.thacher.us/Home/research2/surveys/wildfire-and-water/

water supply in Albuquerque, possible impact of wildfire on water supply and groundwater depletion in Albuquerque, importance of forest restoration to minimizing the risk, and the two basic methods (thinning and prescribed burning) of restoring forests. The initial sections also asked about respondents' perceptions of various issues including climate change, wildfire, water supply, and prescribed burning.

Then, the survey described a proposal for establishing a Water Source Protection Fund (WSPF). Respondents were informed that the fund would be used to pay for the cost of conducting forest thinning and prescribed burns on 30,000 acres per year in the forested area north of the Albuquerque, representing a tenfold increase from the current 3,000 acres per year.

Respondents were informed that the proposed fund would come from an annual fee imposed on homeowners:

A Water Source Protection Fund would come from an annual fee on homeowners in the Albuquerque metropolitan area and throughout the Middle Rio Grande. For example, the fees could be collected through water utility bills, property taxes, or insurance premium taxes.

Thus, although not specified in any way voluntary, the payment vehicle was left as a very general fee with several example options. Although this was consistent with the preliminary nature of the proposal at the time, if respondents hold strong preferences for or against different payment vehicles, this could be a source of potential bias. The explanation of the proposed fund included a map and information about the area to be treated and accountability measures.

Then, respondents were presented with 0 to 10 numerical scale and asked the following two delivery uncertainty questions:

Q#4. On a scale of 0 to 10, where 0 means "Not at all likely" and 10 means "Highly likely" and 5 is halfway in between, how likely do you feel it is that wildfires will impact your supply of drinking water if fire-prone lands in the watershed are not treated to reduce wildfire risk? Circle one.

Q#7. Suppose the Water Source Protection Fund is put in place and funds are targeted to minimize the risk of high-severity wildfire in the forested area north of Albuquerque. On a scale of 0 to 10, where 0 means "Not at all effective" and 10 means "Highly effective" and 5 is halfway in between, how effective do you feel the program would be in ensuring the sustainability of maintaining metropolitan Albuquerque's supply of water? Circle one.

Next, respondents were asked if they supported a WSPF and their views about the structure and mechanism of fund collection.

Right after these questions, respondents were asked an open-ended (OE) valuation question.

Q#11. Currently, overgrown brush and trees are removed from approximately 3000 acres/year in the larger watershed. The University of New Mexico is trying to figure out at what level, if any, metropolitan Albuquerque homeowners would support a Water Source Protection Fund to conduct land treatments on 30,000 acres/year in the same

area and reduce the risk of high-severity wildfire. A required annual fee of all homeowners could be targeted for this purpose. Different people might be willing to pay different amounts to the Water Source Protection Fund. What is the ***most*** *your household would be willing to pay* ***per year*** *to the Water Source Protection Fund? Fill in the blank.*

$_____*per year*

The valuation question was then immediately followed by a preference (un)certainty question:

Q# 12. On a scale from zero to 10, where 0 means "Completely uncertain" and 10 means "Completely certain" and 5 is halfway in between, how certain are you of your answer to ***Question 11****? Circle one.*

3.4. Modeling Considerations

Beginning with a traditional utility maximization perspective (Flores, 2003), consider a representative household whose objective is to maximize utility subject to income and current status of the forested watershed and wildfire:

$$\underset{x}{Max}\, U(X,Q) \quad s.t.\ P.X = M,\ Q = q^0 \tag{3.1}$$

where $X =$ vector of market goods, $Q =$ status of forest and wildfire, $P =$ vector of prices for market goods, $M =$ income of the household, $q^0 =$ current status of the forest and wildfire with overgrown brush and trees, and heavy fuel loads increasing the likelihood of high-severity wildfire that affects municipal water supply security and increases the depletion rate of groundwater . The solution to equation (1) gives demand

functions for marketed goods; $X^* = X(P,Q,M)$ and an indirect utility function; $U(X^*,Q) = v(P,q^0,M) = U_0$.

Now assume a proposed initiative for creating a WSPF whose objective is to mitigate wildfire risk in a relatively distant forested watershed through prescribed burning and mechanical thinning. Reduced wildfire risk will result in improved water security in an urban area. The fund will be generated by a required annual fee or tax on all homeowners in the urban area. Further assume that if the fund is materialized then the stated outcome is realized with certainty. The change in welfare of the household due to reduced wildfire risk and increased water security (moving from q^0 to q^1) is then incorporated in the indirect utility function as

$$v(p,q^0,M) = v(p,q^1,M-CS) = U_0 \tag{3.2}$$

where: q^1 is the improved environmental condition measured in terms of forest restoration, which reduces wildfire risk and improves water source protection to municipal drinking water supply; and U_0 is the reference level of utility. CS represents the Hicksian compensating surplus, and is the income adjustment that equalizes utility at U_0.

In equation (3.2), a change in Q from q^0 to q^1 is taken as if it will happen with certainty, as is common in many CV surveys. However, the outcomes of restoration projects are often uncertain due to factors such as scientific knowledge, changing socioeconomic and political environments, and stochastic events such as weather

patterns, etc. (Brookshire and Chermak, 2007; Glenk and Colombo, 2013; Pindyck, 2007).

There is growing concern over the impact of risky environmental outcomes on WTP responses (Glenk and Colombo, 2013; Rigby et al., 2010; Roberts et al., 2008). A risky outcome, which is also termed as delivery uncertainty (Glenk and Colombo, 2011), is a situation where there is some probability associated with the realization of the proposed good.

The fundamental theoretical underpinnings to incorporating delivery uncertainty while estimating WTP include expected utility theory (EUT) model (Von Neumann and Morgenstern, 1944) and the subjected expected utility (SEU) model (Savage, 1954). The difference lies in the nature of the probability, with EUT requiring known objective probabilities. The common feature is that the expected utility functions in both the models are linear in probability and probability is outside the utility function, implying that respondents do not have preference over probabilities. Several models have been developed to estimate WTP using EUT and SEU. Glenk and Colombo (2013) have compared several models derived from EUT and SEU and used them for incorporating delivery uncertianty to estimate WTP. Models explored include linear and nonlinear EUT and extended versions. The common result is that the inclusion of delivery uncertainty significantly affects results (Roberts et al., 2008).

In the present case, it is assumed that the representative household is risk neutral so that:

$$q^{*} = \pi q^{1} + (1-\pi) q^{0} \tag{3.3}$$

where π is the subjective probability of the change in q from q^0 to q^1 i.e. π is the household's perceived probability that establishing the WSPF and treating the forest will reduce wildfire risk to improve water security. Without losing any generality, equation (2) can be written as:

$$v\left(p, q^0, M\right) = v\left(p, q^*, M - CS\right) = U_0 \tag{3.4}$$

where U_0 is the reference level of utility and q^* expected condition of forest and wildfire, as explained earlier, after the intervention. CS in equation (3.4) is the Hicksian compensating measure, which also can be written as the difference between two expenditure functions:

$$CS = e\left(p, q^0, U_0\right) - e\left(p, q^*, U_0\right) \tag{3.5}$$

Here, CS represents the respondent's willingness to pay (WTP) adjusted for delivery uncertainty

3.5. Econometric Approach

Based on equation (3.5), WTP can be estimated using the following equation:

$$\ln WTP_i = g\left(M, \mathbf{X}, \pi\right) + e_i \tag{3.6}$$

In equation (3.6), the dependent variable, $\ln WTP_i$, is the log of the reported willingness to pay, $\mathbf{X}$ is a vector of household and socioeconomic characteristics and e is an error term. The subjective probability (π) enters into the equation as a separate variable. Subjective probability, referred to here as delivery uncertainty (π), is measured as the respondent's subjective assessment of the likelihood that not treating fire-prone lands in

the watershed will impact water supply (Q#4) and the effectiveness of the proposed WSPF in ensuring a sustainable water supply for Albuquerque (Q#7). Both of these probabilities, in the questionnaire, were obtained in a 0-10 scale, 0 being "not effective at all"/ "not likely at all" and 10 being "highly being effective"/ "highly likely".

In order to construct the delivery uncertainty variable, assuming independent or conditional probability, responses to Q4 and Q7 were subtracted from 10, the two probabilities were multiplied together, and this product was divided by 10. This makes delivery uncertainty a continuous variable ranging from 0-10, with 0 being fully certain and 10 being fully uncertain. Subtracting the responses from 10 allows the coefficient to be directly interpreted as the impact of delivery uncertainty on WTP.

The further issue of concern with equation (6) is that the error term (e_i) may be composed of two components η_i and μ_i where η_i the error due to the respondent's uncertainty (preference uncertainty), and μ_i is the usual error term.

$$\ln WTP_i = g\left(M, \mathbf{X}, \pi\right) + \eta_i + \mu_i \tag{3.7}$$

Traditional neoclassical theory assumes that an individual (or household) knows her utility with certainty. If this was the case, then a respondent would be able to express exact WTP for any environmental change (Hanemann et al., 1996). However, an individual's preferences may contain considerable uncertainty. Studies have shown that preference uncertainty may be a source of hypothetical bias (Champ et al., 2009; Ready et al., 2010). Similarly, Li and Mattsson (1995) state that ignoring preference uncertainty produces a measurement bias. A common approach to capture the respondent uncertainty in CV studies is to ask an (un)certainty follow-up question after the valuation question,

using either a numerical certainty scale or polychotomous choice scale (Akter et al., 2009).[16] As described in the survey method section, this study used a numerical scale to capture preference uncertainty,

A number of approaches have been adopted to deal with uncertainty response in dichotomous choice contingent valuation (DC-CV) formats.[17] However, there are very few CV studies that have incorporated respondent uncertainty in an open ended (OE) elicitation format. Notable exceptions are Håkansson (2008), Mentzakis et al. (2014), and Voltaire et al. (2013).[18]

[16] A good review of the various methods used to incorporate this data into econometric models of dichotomous choice CV (DC-CV) can be found in Shaikh et al. (2007). Meta-analysis results have shown that these efforts can help to minimize upward hypothetical bias (Little and Berrens, 2004; Broadbent et al., 2010).

[17]Approaches include: the weighted likelihood function model (Li and Mattsson 1995), the random valuation model (Wang, 1997), the fuzzy model (Van Kooten et al., 2001), the asymmetric uncertainty model (Champ et al., 1997), the symmetric uncertainty model (Loomis and Ekstrand, 1998), and the direct probability model (Berrens et al. 2002).

[18] Mentzakis et al. (2014) ask a certainty follow up to OE valuation question and use random parameters regression, treating respondent certainty responses as observed heterogeneity. Håkansson (2008) asks an interval OE WTP question with a certainty follow up question. WTP is then estimated by maximizing a likelihood function as in Jammalamadaka and Voltaire et al. (2013) use an interval OE question similar to Håkansson (2008) and calculate an uncertainty-adjusted WTP variable to estimate WTP.

Our study incorporates respondent's preference uncertainty in the analysis by calculating adjusted WTP, following the method adopted in the asymmetric uncertainty model (Champ et al., 1997) and the symmetric uncertainty model (Loomis and Ekstrand, 1998). While these methods originally were used to calibrate DC-CV responses, a similar strategy is used here to adjust the OE responses. In the asymmetric uncertain model, the original DC responses are recoded simply by multiplying the Yes (=1) or No (=0) by the certainty score. In the symmetric uncertainty model both Yes and No responses are recoded with their certainty level. A No response with perfect certainty stays as a 0, while a Yes with perfect certainty equals 1. A Yes response with a follow-up certainty response of, say, 60% is coded 0.6. In contrast, for a No response with a follow-up certainty response of 60% is coded 1−0.6=0.4.

For this analysis, the OE WTP response is multiplied by the probability obtained through the certainty follow up question. For example, if a respondent's WTP response is \$50 and she indicates that she is completely certain of her response, then the adjusted WTP will be \$50*1=\$50. If the respondent is only 10% certain to her response then the adjusted WTP is \$50*0.1=\$5. Thus the estimable equation is:

$$\ln WTP_i = \beta_0 + \mathbf{X}_i\boldsymbol{\beta} + \boldsymbol{\pi}_i\boldsymbol{\lambda} + \mu_i \tag{3.8}$$

where $\ln WTP$ is the log of the adjusted WTP, $\boldsymbol{\pi}$ is the delivery uncertainty, $\mathbf{X}$ is a vector of other control variables, and μ is the error term.

One approach to estimating equation (3.8) is ordinary least squares (OLS) regression. But, the sample data consists of 21% zeroes in the OE WTP responses. Using OLS to estimate equation (3.8) does not recognize the censoring of the WTP

responses and results in biased and inconsistent estimates (Amemiya, 1985). In the presence of such a large numbers of zero WTP responses, one possible econometric model is the Tobit, as has been applied in a number of OE WTP studies (Halstead et al., 1991; Whitehead, 2006). However, a Tobit model is highly sensitive to normality and homoscedasticity assumptions (Green, 2003). Testing showed that these two assumptions were violated in the data. Furthermore, a Tobit model assumes that a single mechanism governs both the "participation decision" (WTP>0 versus WTP=0) and the "amount decision" (the numerical amount of WTP, if it is positive) (Wooldridge, 2010). Another possible approach is the double hurdle model (DH), which is widely used to estimate WTP in the presence of protest zeros (Cragg, 1971).

A zero response can be either true zero or protest zero. While a true zero represents the true preference of the respondent who is indifferent to increasing the provision of a public good, a protest zero is the willingness to pay of those respondents who actually value the good positively but are not satisfied with different aspects of the survey such as the way questions were asked, proposed payment vehicles in the questionnaire, or the proposed institution to implement the project (Halstead et al., 1991). There is no easy method of identifying a protest bid. CV practitioners have used protest response criteria in an ad-hoc manner (Syme and Jorgensen, 1994; Jorgensen et al., 1999). However, a common approach of identifying a protest bid is to ask a series of follow up questions. For this study, respondents were asked to choose one out of ten reasons for their zero WTP response. If a respondent chose either "I don't believe my water supply is threatened

by high severity wildfire" or "I can't afford anything at this time," then the zero is considered to be a true zero, otherwise it is classified as a protest zero. Out of 170 total zero responses, about 27% were true zeros and the remaining were protest zeros. Respondents' with positive or true zero amount of WTP are considered to be participants, and those with protest zero are considered to be non-participants.

Given the presence of zeros and the violation of the required assumptions for the Tobit model, this analysis estimates equation (3.8) for lnWTP, accounting for uncertainty, with a Double Hurdle (DH) model.[19] In the DH model, a respondent makes a decision about willingness to pay only after she decides not to protest. The decision process is described as below:

$$\begin{aligned} &\ln WTP_i = \ln WTP_i^* \quad if\ \ln WTP_i^* > 0 \text{ and } P_i > 0 \\ &\ln WTP_i \quad \text{otherwise} \\ &ln WTP_i^* = X_i\beta + e_i \\ &P_i = Z_i\theta + u_i \end{aligned} \tag{3.9}$$

$\ln WTP_i$ is the log of observed willingness to pay for individual i, $\ln WTP_i^*$ is the corresponding latent value of individual $i's$ actual willingness to pay, $e_i \sim N\left(0,\sigma^2\right)$, X_i is the vector of the explanatory variables, P_i an indicator variable that takes a value of 1 when the individual participates (does not protest), $u_i \sim N\left(0,\sigma^2\right)$, Z_i is the vector of

[19] Since the Tobit model is nested in the DH model, it is also possible to test the use of DH model against Tobit model using a likelihood ratio (LR) test (Humphreys, 2010). We performed this test and concluded that the DH model provides a significantly better fit than the Tobit model, for all specifications. Tobit results are available upon request.

explanatory variables to explain the decision whether or not to protest (and thus participate) and β, θ are the vectors of estimable parameters.

DH assumes that the "participation decision" and the "amount decision" are determined by different mechanisms. The participation decision is estimated using Probit (participation equation), and the amount decision (amount equation) is estimated using truncated regression (Blundell and Meghir, 1987). The underlying theory behind the DH can be found in Cragg (1971), and Green (2003). While it is suggested that imposing exclusion restriction in a DH model is necessary (Newman et al., 2003), there is no guidance for exclusion criteria (Eakins, 2014). This study follows Pudney (1989), who opines that a participation decision is determined by psychological factors rather than by price and income, and excludes income from the participation equation.

3.6. Variables and Descriptive Statistics

Table 3-1 presents the definitions and descriptive statistics of the variables used in the analysis. The dependent variable in the participation decision is P; and the dependent variable in amount equation is lnWTP, the log value of the WTP. The variables CLIMATECHG, WATERSUPPLY, WATERCOST, FIRERISK, and TAXES are the perceived seriousness to the respondent (on a four-level Likert scale), respectively, of the following issues: climate change, water supply, price of water, wildfire risk, and taxes. Mean values of WATERSUPPLY and FIRERISK indicate that the majority of sample perceives water supply and wildfire risk to be relatively serious problems.

Table 3-2:Variable Definitions and Descriptive Statistics

Variable	Definition	Obs	Mean	Std. Dev.	Min	Max	Expected sign
P	1 if the respondent has true 0 or positive willingness to pay, 0 otherwise	611	0.85	0.36	0	1	
WTP	Willingness to Pay ($/year)	611	71.73	94.82	0	600	
UNCRWTP	Preference uncertainty adjusted willingness to pay($/year)	611	54.11	76.09	0	600	
CLIMATECHG	How serious a problem the respondent views climate change to be[a]	611	2.43	1.03	1	4	+
WATERSUPPLY	How serious a problem the respondent views water supply to be [a]	611	3.28	0.78	1	4	+
WATERCOST	How serious a problem the respondent views water rates to be [a]	611	2.31	0.99	1	4	-
FIRERISK	How serious a problem the respondent views wildfire risk to be [a]	611	3.09	0.84	1	4	+
TAXES	How serious a problem the respondent views taxes to be [a]	611	2.52	0.99	1	4	-
PRESCBURN	1 if the respondent supports prescribed burns to manage forest, 0 otherwise	611	0.75	0.43	0	1	+
MALE	1 if male, 0 otherwise	611	0.62	0.49	0	1	?
HHSIZE	Number of individuals in household	611	2.38	1.23	1	8	-
INCOME	Yearly household income ($1000). Respondents chose from 9 categories ranging from less than $14,999 to $200,000 and above. Converted to continuous variable taking middle values (and $200k at top).	611	81.72	43.99	7.5	175	+
COLL	1 if highest level of education is Associate or Bachelor's degree, 0 otherwise	611	0.38	0.49	0	1	+
GRAD	1 if highest level of education is graduate degree, 0 otherwise	611	0.35	0.48	0	1	+
YEARNM	Numbers of years lived in NM	611	33.79	18.96	1	85	?
DELIVUNCR	Delivery uncertainty measured in 0-10 numerical Likert scale (0 =fully certain, 10 =fully uncertain)	611	1.59	1.70	0	10	-

ɾert scale levels were: 1=Not Serious, 2= Somewhat Serious, 3=Very Serious, 4= Extremely Serious

The final perception variable, PRESCBURN, is a dichotomous variable that takes a value of 1 if the respondent supports prescribed burning as a forest restoration treatment method and 0 otherwise. There are two reasons behind including this variable. First, there are conflicting views on the importance of prescribed burning. Adopting prescribed burning to reduce the wildfire risk through reducing hazardous fuel buildup in a forest has been widely recognized as providing a low cost alternative for helping achieve restoration at significant landscape scale (Boer et al., 2009; Finney et al., 2005; Pollet and Omi, 2002). However, there are concerns about the usefulness of this method. Prescribed burning may have negative impacts on air quality (Haikerwal et al., 2015), may alter soil physiochemical properties and soil microbial communities (Williams et al., 2012), and increase soil erosion (Fernández et al., 2008). More importantly, a resident of the study area may potentially view prescribed burning negatively given the fire history in the area. In 2000, the Cerro Grande fire, which started from a prescribed burn treatment went out of control due to high winds. More than 200 homes burned in Los Alamos, a community located about in the forested area about100 miles north of Albuquerque (Brunson and Evans, 2005; Holloway, 2000; Nelson, 2002). Negative views on prescribed burning as a treatment method may negatively affect WTP.

The logic behind including perception variables in the model is to reduce omitted variable bias. It is quite possible that there is a divergence between perceived quality and the objective quality (presented in the survey) of the forest, wildfire risk, and water security. Thus ignoring such divergence may lead to the omitted variable bias and inclusion of perception variable in the model is a solution to the problem (Whitehead, 2006).

Demographic variables include INCOME, MALE, and HHSIZE. INCOME measures the yearly household income. MALE represents the gender of the respondent and takes value 1 if the respondent is male and 0 otherwise. HHSIZE is the family size of a household. COLL and GRAD are dichotomous variables to indicate education level of the respondent. COLL takes a value of 1 if the respondent's highest level of education is an Associate or Bachelor's degree and 0 otherwise. GRAD takes a value of 1 if the respondent's highest level of education is a graduate degree (master's, professional, and doctorate) and 0 otherwise. The latter was broken out to control any possible effect of the disproportionate number of respondents in our sample with graduate degrees. The base value is education less than an associate degree. The variable YEARNM represents the numbers of years the respondent has lived in the New Mexico.

Finally, DELIVUNCRN is a constructed index of delivery uncertainty. It is the household's perceived probability that the intervention (establishing the Water Source Protection Fund and treating the forest) will reduce wildfire risk to improve water security. As explained previously, it is the product of two uncertainty measures, converted into 0-10 scale: (i) uncertainty about the effectiveness of the protection fund in ensuring a sustainable water supply; and (ii) uncertainty about the impact of wildfire on water supply.

The expected signs of the variables are shown in the last column of the Table 2. In order to structure our analysis, we focus on two hypotheses tests with respect to uncertainty. Against the null of no effect, the first hypothesis, H_1, is:

$$H_1 : \beta_{DELIVUNCRN} < 0$$

The expectation is that people with a high level of uncertainty about the effectiveness of WSPF and the adverse impacts of wildfire on water quality (delivery uncertainty) will have a lower WTP. Future uncertainty has been found to reduce willingness to pay (Cameron, 2005).

Against the null of no difference, the second hypothesis, H_2, is:

$$H_2 : WTP_{without\,uncertainty} > WTP_{with\,uncertainty}$$

The expectation is that the WTP accounting for uncertainty (Model 2), including both delivery and preference uncertainty, will be significantly less than WTP without uncertainty (Model 1).

3.7. Results and Discussion

Table 3-3 presents the Double Hurdle (DH) model estimation results for both the lnWTP[20] (amount decision) and participation components. We focus this analysis on the amount decision results. Model 1 presents a DH specification that does not consider uncertainty, while Model 2 presents a DH specification considers uncertainty. The dependent variables of the amount and participation equations are lnWTP, and P respectively. The variable P takes value of 1 if the WTP is either a true 0 or positive and take the value 0 if it is a protest zero. In terms of goodness of fit, AIC and pseudo-R^2 measures indicate that Model 2 (considering uncertainty) fits better than Model 1 (without considering uncertainty).

The participation equation in both models show that the probability of participating (not protesting) decreases with an increase in perceived seriousness of

[20] Since the WTP responses contain 0 values, lnWTP was calculated using ln(WTP+1).

tax issues. If uncertainty is not considered then the probability of participating is significantly determined by all perception variables, education variables, and numbers of years lived in New Mexico. However, if uncertainty is considered, the probability of participating is determined only by delivery uncertainty, perceived seriousness of tax issue, and undergraduate level of education. Thus, uncertainty matters in participation. As shown below, uncertainty also matters in determining the level of WTP.

Focusing on the amount equation, across both Models 1 and 2, the sign and significance of the estimated coefficients are generally consistent with expectations. The positive and significant estimated coefficient on INCOME in both models reveals that the Water Source Protection Fund is a normal economic good; a household with a higher income would pay more for water security. The negative and significant signs on the perceptions of taxes (TAXES) and the price of water (WATERCOST) indicate that the more serious of a problem an individual views these issues to be, the lower the individual's WTP for establishing the Water Source Protection Fund.

The estimated coefficients of the education variables (GRAD and COLL) are not significant, and the estimated coefficient of GRAD has a negative sign in both Models 1 and 2. Although it is a contrary to the expectation, other similar studies also have found negative and insignificant coefficients of education-related variables (Hite et al. 2002; Moffat et al. 2011). Demographic variables such as household size (HHSIZE) and gender (MALE) do not affect the WTP significantly. Similarly, the estimated coefficient of the variable YEARNM is insignificant in both Models 1 and 2.

Table 3-3:Double Hurdle Estimation Results

	Model 1: Without Uncertainty		Model 2: With Uncertainty	
	Ln WTP: Amount Equation	P: Participation Equation	Ln WTP: Amount Equation	P: Participation Equation
CLIMATECHG	0.040	0.161**	0.004	0.067
	(0.047)	(0.075)	(0.054)	(0.080)
WATERSUPPLY	0.163**	0.256***	0.185**	0.056
	(0.067)	(0.087)	(0.076)	(0.095)
WATERCOST	-0.114**	-0.157**	-0.157***	-0.101
	(0.054)	(0.076)	(0.060)	(0.083)
FIRERISK	0.213***	0.268***	0.121*	0.151
	(0.063)	(0.086)	(0.073)	(0.094)
TAXES	-0.216***	-0.276***	-0.223***	-0.208**
	(0.054)	(0.077)	(0.060)	(0.084)
PRESCBURN	0.287***	0.270*	0.202*	0.137
	(0.108)	(0.144)	(0.122)	(0.156)
MALE	0.054	0.149	0.069	0.117
	(0.093)	(0.138)	(0.104)	(0.148)
HHSIZE	-0.032	0.026	-0.038	0.017
	(0.037)	(0.052)	(0.041)	(0.054)
INCOME	0.002*		0.003**	
	(0.001)		(0.001)	
COLL	0.080	0.284*	0.041	0.379**
	(0.116)	(0.155)	(0.129)	(0.167)
GRAD	-0.055	0.315*	-0.140	0.299
	(0.129)	(0.175)	(0.144)	(0.182)
YEARNM	-0.001	-0.007**	-0.003	-0.008**
	(0.002)	(0.003)	(0.003)	(0.004)
DELIVUNCR			-0.222***	-0.260***
			(0.045)	(0.044)
CONSTANT	3.069***	-0.147	3.514***	1.339**
	(0.342)	(0.466)	(0.420)	(0.554)
AIC	2109.960		1993.554	
Pseudo-R^2	0.081		0.916	
No. of Obs.	657		611	

Standard errors in parentheses

* p < 0.10, ** p < 0.05, *** p < 0.01

[a] Regression with uncertainty recodes WTP value using follow up uncertainty question (preference uncertainty) and includes delivery uncertainty as an independent variable.

All perception variables, with the exception of the seriousness of climate change are significant and have the expected positive sign across both models. For example, the estimated coefficient for FIRERISK is positive and significant in both models. Individuals who believe that wildfire risk is a serious problem have a greater WTP for establishing the WSPF. While the estimated coefficient on CLIMATECHG is positive in both models, it is not significantly different from zero. On a speculative note, the different significance status of the estimated coefficients on CLIMATECHG and FIRERISK may reflect the fact that the general public isolates the problem of climate change-affected outcomes like wildfire and drought from climate change. The estimated coefficient on PRESCBURN is significant with expected positive sign in both models. This indicates that people who support the use of the prescribed burning method of forest treatment are willing to pay more.

Focusing on the uncertainty model (Model 2) and turning to our first formal hypothesis, the estimated coefficient on the delivery uncertainty variable (DELIVUNCRN) is significantly negative (at the 0.01 level); the evidence supports hypothesis H_1. This implies that if respondents are uncertain about the outcome of the project i.e. if they are not sure about the effectiveness of the Water Source Protection Fund (WSPF) in minimizing the risk of wildfire and the impact of forest management on water supply, then they are willing to pay less.

The estimated mean and median annual household WTP values are presented in Table 3-4. The numbers in the bracket are the 95% confidence intervals. The mean and median WTP without considering uncertainty (Model 1) are $87.16/year and $52.67/year respectively. Similarly, if uncertainty is considered (Model 2) then the respective values

are reduced to $64.44/year and $37.76/year. The mean WTP with uncertainty is significantly lower than mean WTP without uncertainty (t value = 37.085, P value = 0.000). Thus, the evidence supports hypothesis H_2; accounting for respondent uncertainty lowers mean annual household WTP.

Table 3-4:Estimated Mean and Median Annual Household Willingness to Pay

	Mean WTP ($/year)	Median WTP ($/year)
Model 1: Without considering uncertainty	87.16 (84.81-89.51)	52.67 (51.06-54.29)
Model 2: Considering uncertainty	64.44 (61.57-67.31)	37.76 (36.16-39.37)

Note: The numbers in the parentheses represent the 95% confidence interval.

The estimate of annual household WTP (e.g., considering uncertainty, Model 2 in Table 4) for watershed restoration in this case can be compared and contrasted to other recent studies. Mueller et al. (2013) found an annual WTP of $183.50 (95% confidence interval, $153.97-$241.39) among Yavapai County, Arizona residents for Verde watershed restoration. However, the sample in this study included irrigators and is not directly comparable to our study sample. More closely, the estimated annual household WTP for watershed restoration in Flagstaff, Arizona is $58.68 per year (95% confidence interval, $57.48-$59.52) (Mueller, 2014), which is slightly lower than the mean estimates of this study.

Even more directly, while not a full blown CV study estimating WTP, a 2011 survey was conducted on water ratepayers in the City of Santa Fe, describing a similar water source protection fund as described here, and used to assess public attitudes toward local water supplies and potential steps to protect local water supplies (Metz et al., 2011). While a number of survey aspects are different, we can compare the proportions of household samples that would accept a limited set of monthly fees. The Metz et al. (2011) survey study did not directly calculate or provide WTP estimates, but asked a series of WTP questions for a sequence of four dollar amounts: $0.65, $1.00, $1.50, and $2.00.[21] The study reported only the percentage of respondents (out of total 402) who were willing to pay the different amounts asked. The percentage of respondents willing to pay $0.65, $1.00, $1.50, and $2.00 was 82%, 78%, 70%, and 64% respectively. To make a comparison, we calculated the percentages for our Albuquerque sample, based on the WTP estimated using the DH model with uncertainty, as 99%, 97%, 93%, and 89%, respectively. Thus, using the fitted mean sample characteristics in our data, the proportions for Albuquerque sample are in all cases actually *higher* than the Santa Fe study, for this limited set of dollar values. Thus, in this Rio Grande comparison case, even if people are living in a relatively distant but affected municipal area, they at least equally willing to support securing drinking water sources through forest restoration.

[21] Wording of the valuation question for the Santa Fe survey (Metz et al., 2011) was: "This program would be funded through a small charge on City water bills, based on the amount of water a household uses, that would average about _____ per month. Would you be willing to pay that amount to fund this program?"

3.8. Policy Implications and Conclusions

Econometric analysis of over 600 usable survey responses shows that household WTP responses for watershed restoration, to reduce wildfire risk and secure water supplies, are significantly affected by a number of plausible determinants. Accounting for both delivery and preference uncertainty was shown to reduce WTP, while a higher perception of the seriousness of water supply and fire risk problems increased WTP. These results point toward the role of public education, as well as pilot projects that demonstrate the effectiveness of watershed restoration.

Initiation of such public awareness programs has already begun in the region. For example, the 20-year Santa Fe watershed management plan, developed in 2009 and revised in 2013, identifies a public awareness program as one of the four key components to project success (Santa Fe Watershed Association, 2009). Similarly, the Rio Grande Water Fund implemented and outreach and educational plan in 2014 where a working group of education professionals was formed to "promote and support educational programs that engage people in protecting storage, delivery and quality of Rio Grande water with a focus on forest health, river ecology and a sustainable water supply" (The Nature Conservancy, 2014).

Results from the preferred model (Model 2) provide an annual homeowner household mean WTP estimate in the Albuquerque, NM municipal area of $64.44 (with a 95% C.I. of $61.57-$67.31), or about $5.40 per month. The corresponding median WTP was $37.76 ($36.16-$39.37), or about $3.14 per month. As compared above for the percentage of households willing to pay across a limited set of dollar amounts monthly, the results for our Albuquerque sample appear to compare favorably to recent (Metz et

al., 2011) survey evidence for similar watershed restoration support in the relatively high-income City of Santa Fe NM, with directly adjacent wildfire risk to city water supply reservoirs. This underscores the contribution of this analysis as showing that households in a relatively distant municipality would still have significant WTP to reduce wildfire risk and secure water supplies. Linking forest restoration needs to a large population of municipal faucets increases the scope for possible PPS-PES programs.

Turning to actual policy implementation, the Santa Fe City Council passed a PES municipal water bill tax in 2011; the implementation of the tax was delayed after obtaining several years of initial bridge funding ($1.6 million) from the state Water Trust Board. To our knowledge, while approved, the PES tax has not yet been implemented as of early 2016. As another point of comparison with an actual policy change, Denver Water has recently paired with the US Forest Service to spend $33 million over five years on forest restoration activities to protect water supplies; the expected annual household cost for residential users is $27, or approximately $2.25 per month (Denver Water, 2013; Gordon and Ojima, 2015; LaRubbio, 2015). This annual cost would be lower than the expressed annual household WTP in this Albuquerque study (but much closer to the estimated annual median WTP). Finding support in a relatively distant municipal population is also consistent with a very recent policy action in Arizona. At a much smaller initial scale, in May, 2015, the Phoenix City Council approved a three-year partnership with the National Forest Foundation to invest $200,000 per year in the Northern Arizona Forest Fund with the purpose of improving forest health and water quality in the Salt and Verde River watersheds (Ferris, 2015). The Phoenix case is an example of a relatively distant municipality supporting watershed restoration efforts more

than 100 miles away. Supporting such actions in July 2015, U.S. Senators Martin Heinrich (D-N.M.) and Jeff Flake (R-Ariz) introduced the federal bill S. 1780 in the US Congress, the Restoring America's Watersheds Act, to protect, restore, and improve the health of watersheds in National Forests. Importantly though, the bill would facilitate federal agency partnerships with private and community supported funds (e.g., using the funds on federal lands, or matching the funds).

In the Rio Grande and northern NM case, the proposed funding needed to reduce wildfire risk significantly is about $21 million per year (The Nature Conservancy, 2014). If we take the estimated mean WTP of $64.44 annually (Double Hurdle Model with uncertainty) as the amount to be collected from each household then, based on the number of total homeowner water accounts in municipal Albuquerque alone, the proposed Water Source Protection Fund may be able to collect about $7.32 million per year (or $4.29 million per year, using the more conservative estimated median WTP). We restrain from any further expansion of these results, since our sample and analysis are focused on the WTP of homeowner-households in municipal Albuquerque. However, there are rental residence accounts in metropolitan Albuquerque, business and industrial accounts, nearby irrigation districts, and other smaller communities that rely on water diversions from the Rio Grande. All of these other sectors and entities may be additional sources for possible revenue generation for the proposed Water Source Protection Funds. We leave this analysis to future research.

Subsequent to the time of this survey research, the RGWF proceeded ahead, coming into formal existence in 2014; it has been led by the Nature Conservancy and includes a wide variety of collaborators. Since 2014, the RGWF has been accepting

private donations, initiating selected pilot and demonstration restoration activities, and funding research, such as developing restoration priorities (McCarthy, 2014). While an important step, this might be expected to lack potential for achieving the needed funding scale on its own. Thus, there were significant collaborative efforts pointed towards the 2015 New Mexico Legislature, with attempts to establish some type of PPS-PES mechanism. In this connection, House Bill 38, with the purpose of, among others, creating a fund, establishing a board, and enacting the Forest and Watershed Restoration Act was eventually passed by both the NM House and Senate. The bill proposed an advisory "Forest and Watershed Restoration Board" with members representing various state departments, universities, commissions, federal offices, and the public. Similarly, the bill proposed to create a "Forest and Watershed Restoration Fund" that would consist of appropriations, distributions, gifts, grants, donations, income from investment of the fund and any other money credited to the fund. The fund was to be administered by the NM Energy, Minerals and Natural Resources Department, for projects recommended by the board, pursuant to the Forest and Watershed Restoration Act. A secure annual funding source for significantly scaling up restoration efforts was not identified, and initial allocations were primarily to initiate the fund. While the bill passed the NM Legislature, HB 38 was eventually vetoed by NM Governor, Suzanna Martinez, stating that "it was an unnecessary layer of bureaucracy and that state agencies should be in charge of those decisions" (Baker, 2015).

Although this recent 2015 NM legislative effort to design and enact a Public Payment Scheme form of a Payment for Ecosystem Services (PPS-PES) program in the Rio Grande watershed was ultimately unsuccessful, building new networks, institutional

arrangements, and associated funding mechanisms, is often a multi-year process. Economic benefit information can provide a significant input to this public dialogue. As those future efforts proceed, the results of this analysis demonstrate that households in by far the largest municipal area in NM hold significant economic values for watershed restoration activities that reduce wildfire risk, protect water sources and help secure water supplies, thus linking forest health to their faucets.

Chapter 4 : An Approach to the Estimation of the Economic Tradeoff between Natural Resource Development and Ecosystem Services Conservation: The Case of Unconventional Gas Production at the Piceance Basin, Colorado

4.1. Introduction

Currently, oil and natural gas accounts for 33% and 29% of primary energy consumption in the United States (US) (EIA 2017) and forecasts suggest this will increase by 48% and 50% respectively by 2025 (Kharaka and Otton 2003). Similarly, the US is the largest producer of natural gas in the world, thanks to production from tight oil and shale gas formations (Doman 2016). The increasing trend of the hydrocarbon development has become a key factor in land use changes in the US (Bernknopf et al. 2016). Exploration, extraction, and delivery activities of hydrocarbons result in changes in land use and land cover (LULC) that can substantially affect the spatial pattern of development and conservation of resources, and form and function of landscape interaction (Slonecker 2015). Several studies have documented the impact of hydrocarbon development on other natural resources, including air, water, vegetation, fish, and wildlife, as well as on heritage resources, and visual resources (Wilbert et al. 2008, Vengosh et al. 2013, Weltman-Fahs and Taylor 2013, Bureau of Land Management 2015).

Natural resource extraction is not an isolated activity; it has forward and backward linkages that affect all the natural resources in a location and potentially in a region. It is

an activity that, when combined with associated linkages, forms a system[22]. This means a complete analysis for assessing the impact of hydrocarbon development should consider the whole system including the human system rather than focusing on a single sub-system. The human system comes into the framework by putting non-market value for the ecosystem services that is altered by such development. This study is a Proof of Concept to assess and evaluate the nature of spatially variable and temporally dynamic disturbances to the landscape of the cumulative effects of shale gas production on habitat loss and impacts to species productivity and to changes to the quality and quantity of ecological resources. For the Proof of Concept, this study considers the impact of shale gas production on mule deer and fish population. While mule deer are affected through habitat fragmentation and habitat loss along with various other types of disturbances (e.g. noise), fish species are affected through water pollution caused by erosion that increases with development. The specific objectives of this study are: to demonstrate the potential spatial impact on wildlife and aquatic species from shale gas production with various well-pad densities, to estimate the spatial and temporal net social benefit of the development, and to offer the methodologies to analyze the spatial impact on ecological resources from shale gas production and to estimate the net social benefit of the

[22] For example, a hydraulic fracturing activity utilizes a sufficiently large amount of water that needs to be transferred from other sectors, say agricultural sector. Transfer of water from the agricultural sector to shale gas production creates an opportunity cost to the society. This is an example of a backward linkage. Similarly, on-site road construction in the shale gas production area affects wildlife negatively. Loss of wildlife has a negative impact not only from ecological viewpoint but also from the societal viewpoint. This is an example of forward linkage.

development. In an example of shale gas production in the Piceance Basin, Colorado, the approach is tested and is applied to demonstrate how natural resource development and collocated ecosystem services interact in the decision framework.

This study is in the form of a "Proof of Concept," which is defined as a development of a method or protocol to demonstrate its feasibility with the purpose to verify that the method or protocol has the potential of being used. This means the results reported based on the Proof of Concept are representative of the outputs but should be considered only as descriptive and not prescriptive. No policy implications are intended or implied. However, this proof of concept can be applied in different places with actual data. Populating the model with location specific data produce the result for the location that can be used by stakeholders to meet their objectives. For example, the Bureau of Land Management (BLM) may use the result to rank the land based on a cumulative net social benefit before leasing the land out.

Rest of the paper is organized as follows: Section 2 gives a description of the study area, and Section 3 develops the theoretical model. Section 4 presents the mechanism of spatiotemporal system dynamics model of this study. Section 5 describes different types of scenarios simulated and Section 6 presents results from the simulation. Finally, the conclusion is presented in Section 7.

4.2. Study Area: The Piceance Basin[23]

The Unita-Piceance basin is located in eastern Utah and western Colorado with an area of 28,898 square miles. It encompasses fully or partly Delta, Garfield, Gunnison,

[23] The maps 4-1 to 4-7 in this section were developed using shape files available at the websites of the USGS, BLM, COGCC

Mesa, Moffat, Montrose, Ouray, Rio Blanco, and Routt Counties in Colorado and Carbon, Duchesne, Emery, Grand, Sanpete, Sevier, Uintah, Utah, and Wasatch Counties in Utah. The Uinta-Piceance Basin contains five major total petroleum systems, in ascending stratigraphic order (USGS 2003); the Phosphoria, the Mancos/Mowry, Ferron/Wasatch Plateau, Mesaverde, and Green River Total Petroleum Systems (USGS 2003)[24]. An assessment shows that the basin holds, in average, 59.57 MMBO (million barrels of oil) oil (38.78 MMBO continuous oil and 20.39 MMBO conventional oil), 21,424 BCFG (billion cubic feet of gas) gas (21,211 BCFG conventional and remaining unconventional gas), and 42.77 MMBNGL (million barrels of natural gas liquids) natural gas liquid (37.84 MMBNGL conventional and remaining unconventional NGL) as reserves (USGS 2003). Exploration in the basin started in 1800's, the first field was discovered in 1890, and the first discovery was made in 1925 in the Ashley Valley Anticline[25]. Currently, more than 20 company operate in the basin with more than 25 thousand well permits in Colorado part of the basin only.

The United States Geological Survey (USGS) Oil and Gas Assessment Unit 50200263 (AU 50200263) in the Unita-Piceance province is the site for this study (Figure 4-1). AU 50200263 covers over 1,990 square miles, which is about 7% of the total area of the Unita-Piceance Basin, that lies in the eastern part of the province in western Colorado.

[24] Petroleum system is a unified concept that combines elements and process of petroleum geology, and all related oil and gas that originates from a pod of active source rock (Magoon and Dow 1991).

[25] Available at https://certmapper.cr.usgs.gov/data/noga95/prov20/text/prov20.pdf

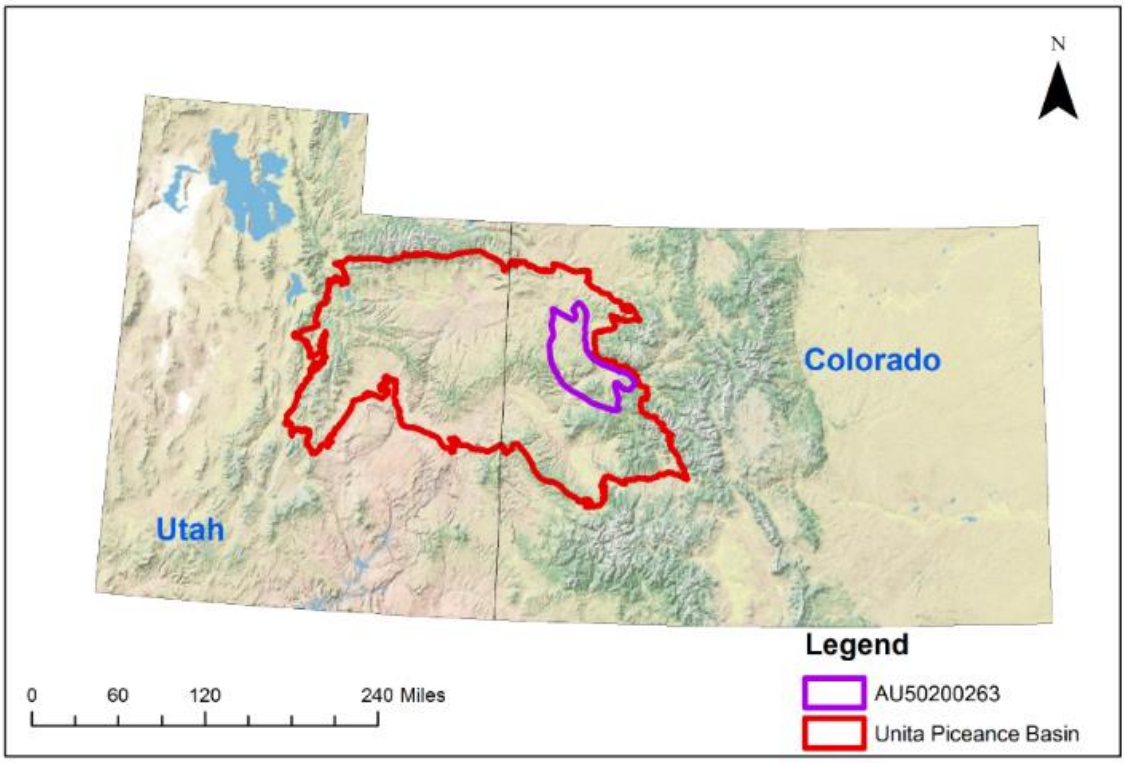


Figure 4-1:Study Area: AU 50200263 in Unita-Piceance Basin, Colorado

This assessment unit is well suited for the study as it possesses a number of characteristics that is important for a spatial study. This includes very active oil and gas development area, a large area of public land so that BLM has right to lease land, number of ecosystem services susceptible to energy development impacts, an abundance of geologic assessment data availability, and the site has multiple energy resources.

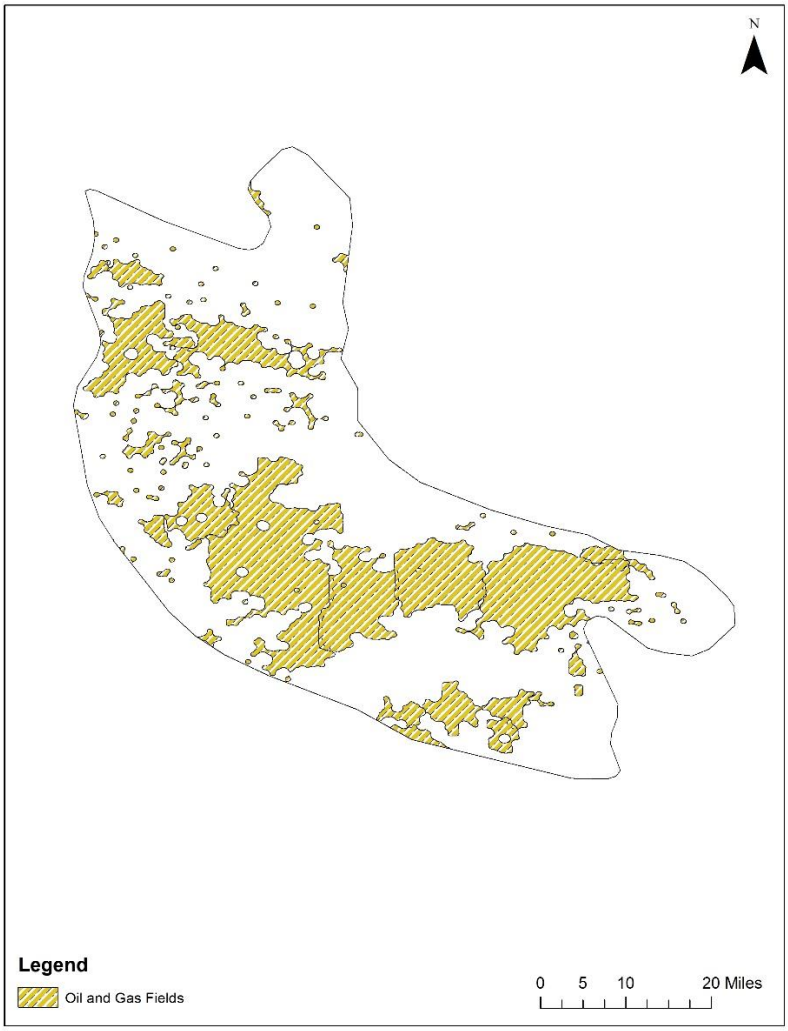


Figure 4-2:Oil and Gas Field in the Study Area

Figure 4-2 shows the oil and gas field, approximate boundaries of oil and gas fields defined by producing and/or plugged and abandoned wells within the field, in the study area[26]. Oil and gas field in the AU covers about one third (629 square miles) of the total area of the AU.

[26] The appropriate field designation for each well was decided on a well-by-well basis by Colorado Oil and Gas Conservation Commission staff.

Oil and gas leases in the study area are shown in Figure 4-3. The difference between field and lease is that a leased area might not have been used for oil and gas production. It means total leased area should be larger or equal to oil and gas field. In fact, 912 square miles have been leased out for oil and gas production (Figure 4-3) out of which only 629 square miles (Figure 4-2) have been utilized for development.

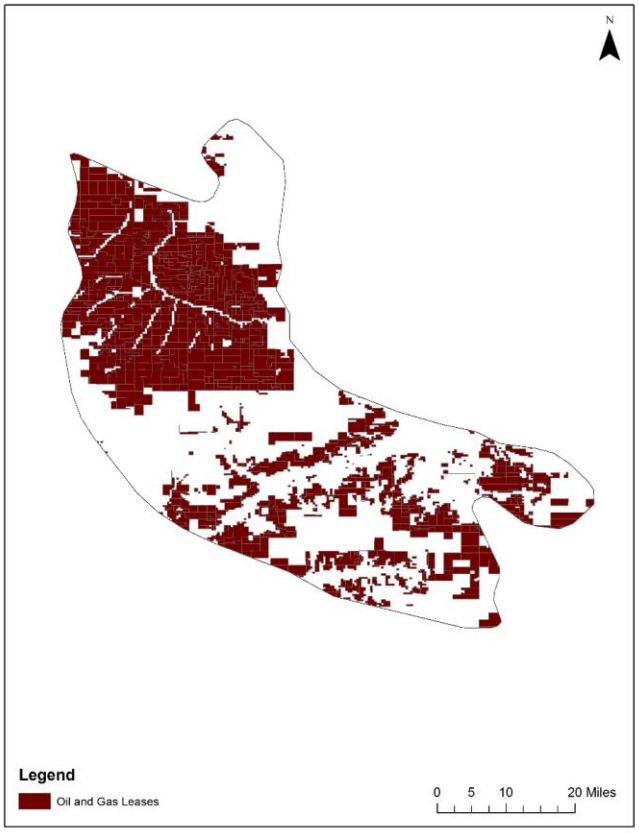


Figure 4-3:Oil and Gas Leases in the Study Area

There are more than 18,000 permitted and active oil and gas wells in the study area (Figure 4-4) with average measured depth (MD) 5,523 feet and average true vertical depth (TVD) 4,846 feet. Of the total wells, about 11,000 wells produce unconventional

and, about 1,800 wells produce conventional oil and gas. Remaining wells are permitted but not documented[27].

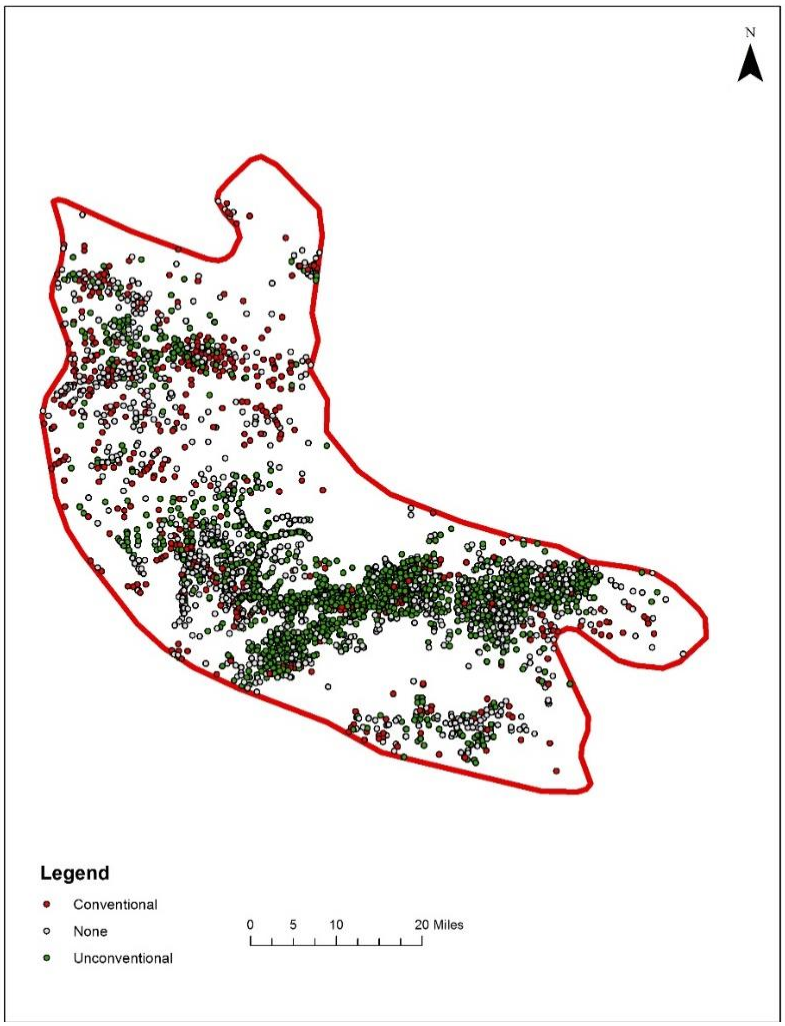


Figure 4-4:Oil and Gas Wells in the Study Area

[27] Wells are categorized into Conventional, Unconventional, and None. This categorization is based on the well data available in COGCC website (http://cogcc.state.co.us/data2.html#/downloads). If for any well $MD = TVD = 0$ then the well is considered "None". If for any well $MD > TVD$ then the well is considered "Unconventional". All other wells are considered "Conventional". Conventional wells have either $MD = TVD > 0$ or $TVD > 0$ and $MD = 0$

Of the total land in the AU50200263, the US Forest Service (USFS) owns the largest share of the land (64.56%) followed by private land (19.28%), and Bureau of Land Management (16%). Figure 4-5 shows the land ownership in the study area.

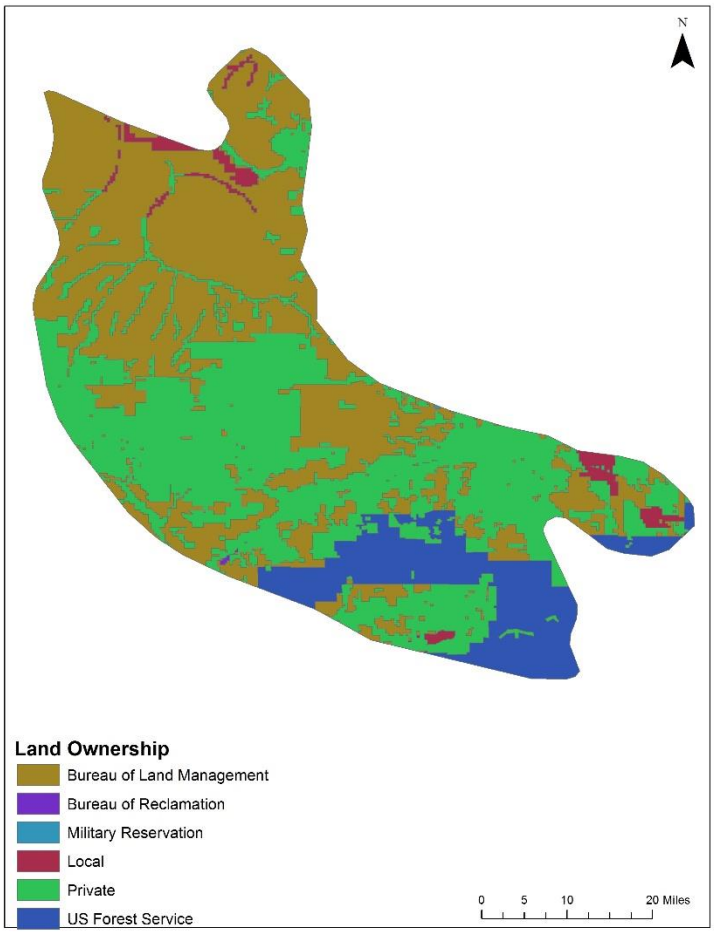


Figure 4-5:Land Ownership in the Study Area

There are a variety of ecosystem services susceptible to energy development impacts. Direct use ecosystem services include hunting, hiking, and grazing (Boone et al. 2011). Indirect use services include snow and water storage, nutrient cycling, vegetative land cover, and composition, which provide habitat for species of interest (Boone et al. 2011, Hoelzle et al. 2012, Martin 2012). There is riparian habitat for migrating waterfowl (USFWS 2006). Floodplains and wetlands provide water filtration, flood control, and

species habitat (BLM 2006, USFWS 2006). Wildlife species include mule deer, mountain lion, black bear, elk (USFWS 2006), wild horses (Turner 2015), and special status wildlife (BLM 2006, USFWS 2006) such as bald eagles, among others. This study considers the impact of shale gas production on mule deer and fish populations. Figure 4-6 shows winter range and winter concentration of mule deer in the study area.

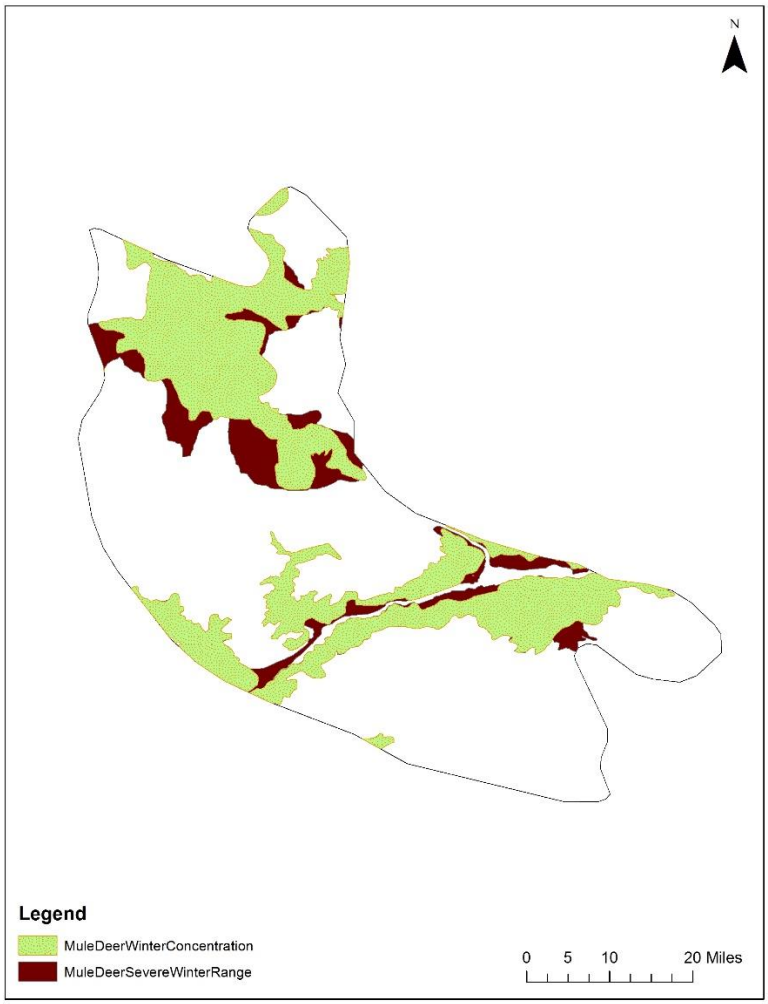


Figure 4-6:Mule Deer Range and Concentration in the Study Area

There is a significant relationship between oil and gas development and wildlife population. Oil and gas development affects wildlife and their habitat through the creation of roads, well pads, pipelines, pumping stations, and other infrastructures across

the landscape (Wilbert et al. 2008). Roads constructed for oil and gas development are responsible for habitat fragmentation, removal of habitat, and long-term displacement of species from the preferred habitat (Wilbert et al. 2008, Northrup et al. 2015). Figure 4-7 shows the 3,024.6 miles of the road network in the study area.

Figure 4-7:Road Network in the study area

4.3. Theoretical Foundation[28]

This section provides a theoretical basis for the system dynamics model where the objective is to find the impact of shale gas production on colocated ecological resources. As has been explained earlier, land disturbances, an outcome of resource extraction activities, affect local ecosystem negatively resulting in a social cost. Studies have shown

[28] Earlier version of section 4.3 and section 4.4 can be found in Bernknopf et al. (2014) as a baseline that provided a starting point for these section for the final version in this dissertation.

that mineral resource production impacts wildlife population negatively (Robel et al. 2004, Holloran 2005, Northrup et al. 2015). The theoretical model in this section considers these two issues. Dynamic optimization of net social benefit considering the spatial impact of resource use is the theoretical basis for this study. There are several studies that consider the dynamic spatial impact in their dynamic optimization model. For example, Pfeiffer and Lin (2012) develop a dynamic optimization model to show spatial externality of groundwater pumping. Janmaat (2005) develop a dynamic optimization model to discuss the optimal harvesting of fish, which move from one area to another depending on the stock of fish in each area. However, there is no study that employs a dynamic optimization model to find a relationship between hydrocarbon development (shale gas production) and ecological resources such as fish and mule deer.

Although an analytical solution derived from a theoretical model is the first best solution, in most of the cases it is non-tractable due to its complex structure. The complexity of a theoretical model increases when the functional form of its different components become more complex and when the model needs to include interdisciplinary issues. It is difficult to find a closed form solution for such models. However, a theoretical model is important for an empirical work because it provides a framework and a scope for the analysis. Theoretical model provides a basis for including variables and the direction of causality. This study develops a dynamic optimization model that provides the basis for the system dynamic model to examine the spatial impact of hydrocarbon development (shale gas production) on ecosystem services. The systems dynamics model is described in section 3.

We consider a social planner whose objective is to maximize net social benefit from shale gas production. The benefit from gas production can easily be determined by subtracting the cost of gas production from the revenue. But a social planner considers not the only market that provides information on private benefit and cost but also the non-market impact of shale gas production. Consider a shale gas AU with ecological diversity. The whole AU is divided into n grid cells. For the ease of exposition, let's assume that there is only two ecological resources in the AU, mule deer and fish. Several factors such as slope, vegetation, natural growth, etc., determine the size of mule deer population in a grid cell. However, once a cell is developed for shale gas production, its suitability as the mule deer habitat decreases. The development activity results in mule deer migrating to another cell. The number of mule deer migrating to another cell depends on the extent of the cell developed. Similarly, the fish population in the nearby river is also affected by the shale gas production activities via erosion. As the production level increases, the level of erosion and sediment load in the river also increases. Increased sediment load makes the river less suitable for fish to survive.

Let $M_{it}\left(q_{it}, G_{it}\right)$ is the number of mule deer in a grid cell i at time t that is determined by the quantity of gas produced in the cell i, q_i, and other features of the cell, G_i. Let θ_{ijt} represent the share of the mule deer in grid cell i which disperses into the grid cell j. θ_{ijt} can be a function of several factors such as stock of mule deer in other grid cells and other geophysical characteristics of those grid cells. But for the sake of simplicity, it is assumed that θ_{ijt} is determined by the quantity of gas produced in cell q_{jt} i.e. $\theta_{ijt}\left(q_1, q_2, ...q_n\right)$ such that $\frac{\delta\theta_{ijt}}{\delta q_{it}} > 0, \frac{\delta\theta_{jit}}{\delta q_{it}} < 0$. Here q_{it} is the volume of gas

produced in the cell i. If $q_{it} = 0$ then the cell i is not developed and the mule deer in that cell is determined solely by natural factors such as slope and vegetation cover. However, if q_{it} increases then the cell i becomes less and less suitable for habitat and mule deer gradually start to migrate from the cell to another cell. Here, it is important to note that the q_i is increased by adding more well pads and wells. In a particular well, the volume of gas produced declines over time following a decline curve equation such as one given by Arps(1945). The number of mule deer received by grid cell i from other grid cells is thus $\sum_{j \in I} \theta_{jit} M_{jt}$. The equation of motion describing the change in mule deer stock over time, $\dot{M}_{it}$, is:

$$\dot{M}_{it} = g_{it}\left(M_{it}\left(q_{it}\right), K_{it}^{D}\left(q_{it}\right)\right) + \sum_{j \in I} \theta_{jit} M_{jt}\left(q_{jt}\right) \tag{4.1}$$

$$\frac{\delta g_{it}}{\delta M_{it}} \gtrless 0, \quad \frac{\delta g_{it}}{\delta K_{it}^{D}} \gtrless 0, \quad \frac{\delta M_{it}}{\delta q_{it}} < 0, \quad \frac{\delta K_{it}^{D}}{\delta q_{it}} < 0$$

Here, K_{it}^{D} is the carrying capacity that is a function of production level. It is assumed that the land condition that also determines the carrying capacity of a cell remain unchanged to the area where no development activity takes place. $g_{it}\left(M_{it}\right)$ can take many forms (e.g. logistic growth, theta-logistic growth)

Turning to the fish population, let $F_t\left(\sum_{i=1}^{n} q_{it}\right)$ total fish stock in the river at time t that depends on the total gas production in the AU. Increased level of gas production increases erosion and sediment load that reduces fish stock in the river. Following the

approach in mule deer case above, the equation of motion describing the change in fish stock over time, $\dot{F}_t$, can be written as:

$$\dot{F}_t = f_t\left(F_t\left(\sum_i q_{it}\right), K_t^F\left(\sum_i q_{it}\right)\right) \tag{4.2}$$

Similar to mule deer case, change in fish stock in each time period is determined by net natural growth function f_t that depends on the stock of fish $F_t\left(\sum_i q_{it}\right)$ and carrying capacity $K_t^F\left(\sum_i q_{it}\right)$.

Value or benefit of mule deer (fish) for a society is the product of a willingness to pay for a mule deer (fish) and number of mule deer (fish). Although there are no existing studies to estimate the value of, specific to mule deer and fish, there is the potential for either a primary study for mule deer (fish) or a benefit transfer from another study. Let W_t be the value of one mule deer at time t. The benefit of mule deer existence in the cell i is thus $B_{it} = WM_{it}$. The value of fish is also determined by the similar approach i.e. $V_{it} = R_t F_{it}$ where V_{it} is the total value of fish, F_{it} is the fish population and R_t is the value of one fish. The private benefit of gas production in the cell i is a product of gas price and volume of gas produced, $p_t q_{it}$. The total cost of gas production in the cell i, $C_{it}(q_{it}, S_{it})$, depends on the stock of gas underneath the cell i and the volume of gas produced, q_{it}, where $C_q > 0, C_{qq} < 0, C_s < 0$. The cost function implicitly includes, besides others, the cost of water. Shale gas production consumes a huge amount of water that is transferred from other sectors (e.g. agriculture) to gas production sector. How

much water to transfer for gas production depends on the available water right to the gas producer and quantity of gas produced[29]. Water transfer from another sector produces an opportunity cost which is included implicitly in the cost function. It is also assumed that that there is no inter-cell flow of gas. The equation of motion for the stock of gas is:

$$\dot{S}_i(t) = -q_i(t) \tag{4.3}$$

Now a social planner's problem is to maximize net social benefit i.e.

$$\max_{q_i} NB = \int_0^T e^{-rt}\left[\sum_{i=1}^{n}\left\{p_t q_{it} + W_t M_{it} + R_t F_{it} - C_{it}\left(q_{it}\right), S_{it}\right\}\right]dt \tag{4.4}$$

Subject to equation (4.1), equation (4.2), equation (4.3), and

$$S_i(0) = S_{i0}, M_i(0) = M_{i0}, F_i(0) = F_{i0} \tag{4.5}$$

Omitting the time argument for the ease of exposition, the current value Hamiltonian for this problem is given as

$$\begin{aligned} H_c = & \sum_{i=1}^{n}\left\{p_t q_{it} + W_t M_{it}\left(q_{it}\right) - C_{it}(q_{it}, S_{it}\right\} - \lambda_{it} q_{it} \\ & + \mu_{it}\left[g_{it}\left(M_{it}\left(q_{it}\right), K_{it}^{D}\left(q_{it}\right)\right) + \sum_{j\in I}\theta_{jit} M_{jt}\left(q_{jt}\right)\right] \\ & + \psi_t f_t\left(F_t\left(\sum_i q_{it}\right), K_t^F\left(\sum_i q_{it}\right)\right) \end{aligned} \tag{4.6}$$

Here, λ, μ, and ψ are co-state variables that represent the shadow prices of natural gas, mule deer, and fish respectively.

[29] More precisely the amount of water used in the gas production depends on numbers of wells and number of fracs. However, increasing these two variables means increasing volume of gas produced. Therefoe it is assumed that the quantity of water transferred depends on the volume of gas produced.

Necessary conditions for this problem are:

$$\frac{\delta H_c}{\delta q_{it}} = p_t + W_t \frac{\delta M_{it}(q_{it})}{\delta q_{it}} - \frac{\delta C_{it}(q_{it}, S_{it})}{\delta q_{it}} - \lambda_{it} + \mu_i \left[\begin{array}{l} \frac{\delta g_{it}\left(M_{it}(q_{it}), K_{it}^D(q_{it})\right)}{\delta M_{it}} \frac{\delta M_{it}(q_{it})}{\delta q_{it}} \\ + \frac{\delta g_{it}\left(M_{it}(q_{it}), K_{it}(q_i)\right)}{\delta K_{it}^D} \frac{\delta K_{it}^D(q_{it})}{\delta q_{it}} + \frac{\delta \theta_{it}}{\delta q_{it}} + \sum_{j \in I} \frac{\delta \theta_{jit}}{\delta q_{it}} M_{jt}(q_{jt}) \end{array} \right] + \psi_t \left[\begin{array}{l} \frac{\delta f_t\left(F_t\left(\sum_i q_{it}\right), K_t^F\left(\sum_i q_{it}\right)\right)}{\delta F_{it}} \frac{\delta F_{it}\left(\sum_i q_{it}\right)}{\delta q_{it}} \\ + \frac{\delta f_t\left(F_t\left(\sum_i q_{it}\right), K_t^F\left(\sum_i q_{it}\right)\right)}{\delta K_t^F} \frac{\delta K_t^F\left(\sum_i q_{it}\right)}{\delta q_{it}} \end{array} \right] = 0 \quad (4.7)$$

$$\frac{\delta H_c}{\delta S_{it}} = r\lambda_{it} - \dot{\lambda}_{it} = -\frac{\delta C_{it}(q_{it}, S_{it})}{\delta S_{it}} \quad (4.8)$$

$$\frac{\delta H_c}{\delta M_{it}} = r\mu_{it} - \dot{\mu}_{it} = W_t + \mu_{it} \left[\frac{\delta g_{it}\left(M_{it}(q_{it}), K_{it}^D(q_{it})\right)}{\delta M_{it}} + \theta_{iit} \right] \quad (4.9)$$

$$\frac{\delta H_c}{\delta F_t} = r\psi_t - \dot{\psi}_t = R_t + \psi_t \left[\frac{\delta f_t\left(F_t(q_t), K_t^F\left(\sum_i q_{it}\right)\right)}{\delta F_t} \right] \quad (4.10)$$

$$\frac{\delta H_c}{\delta \lambda_i} = \dot{S}_{it} = -q_{it} \quad (4.11)$$

$$\frac{\delta H_c}{\delta \mu_{it}} = \dot{M}_{it} = g_{it}\left(M_{it}(q_{it}), K_{it}^D(q_{it})\right) + \sum_{j \in I} \theta_{jit} M_{jt}(q_{jt}) \quad (4.12)$$

$$\frac{\delta H_c}{\delta \psi_t} = \dot{F}_t = f_t\left(F_t\left(\sum_i q_{it}\right), K_t^F\left(\sum_i q_{it}\right)\right) \quad (4.13)$$

Taking time derivative of equation (4.7) gives

$$\begin{aligned}
&\dot{p}+\dot{W}M_q+WM_{qq}\dot{q}-C_{qq}\dot{q}-C_{qS}\dot{S}-\dot{\lambda}+\dot{\mu}\left(g_M M_q+g_{k^D}K_q^D+\theta_q+\sum_{j\in I}\left(\theta_{ji}\right)_q M_j\right)\\
&+\mu\left(\begin{array}{l} g_{MM}M_q^2\dot{q}+g_M M_{qq}\dot{q}+g_{K^DK^D}K_q^{D2}\dot{q}+g_{K^D}K_{qq}^D\dot{q}+\theta_{qq}\dot{q}\\ +\sum_{j\in I}\left(\theta_{ji}\right)_{qq}\dot{q}M_j+\left(\theta_{ji}\right)_q M_{jq}\dot{q}\end{array}\right)\\
&+\dot{\psi}\left(f_F F_q+f_{k^F}K_q^F\right)+\psi\left(f_{FF}F_q^2\dot{q}+f_F F_{qq}\dot{q}+f_{K^FK^F}K_q^{F2}\dot{q}+f_{K^F}K_{qq}^F\dot{q}\right)=0
\end{aligned} \tag{4.14}$$

In equation (4.14) all i and time arguments have been omitted for the ease of exposition. Solving for $\dot{q}$ gives the optimal time path for gas production.

$$\begin{aligned}
\dot{q}=\frac{\begin{array}{l}\dot{p}+\dot{W}M_q-C_{qS}\dot{S}-\dot{\lambda}+\dot{\mu}\left(g_M M_q+g_{k^D}K_q+\theta_q+\sum_{j\in I}\left(\theta_{ji}\right)_q M_j\right)\\ +\dot{\psi}\left(f_F F_q+f_{k^F}K_q^F\right)\end{array}}{\begin{array}{l} C_{qq}-WM_{qq}-\mu\left(\begin{array}{l} g_{MM}M_q^2+g_M M_{qq}+g_{KK}K_q^2+g_K K_{qq}\\ +\theta_{qq}+\sum_{j\in I}\left(\theta_{ji}\right)_{qq}M_j+\left(\theta_{ji}\right)_q M_{jq}\end{array}\right)\\ -\psi\left(\begin{array}{l} f_{FF}F_q^2+f_F F_{qq}\\ +f_{K^FK^F}K_q^{F2}+f_{K^F}K_{qq}^F\end{array}\right)\end{array}}
\end{aligned} \tag{4.15}$$

At this level of generality, the result is not directly comparable to intuition. However, the result tells that the optimal time path of shale gas production depends on several factors including mule deer dispersion, mule deer stock in grid cells, fish population and willingness to pay for mule deer, and fish. This gives a clear evidence that policy makers need to take ecosystem services into consideration before allowing land development for mineral resource extraction.

This theoretical model lays out a basic framework of how these factors can be taken into account while constructing the system dynamics (SD) model. Following the

theoretical model, the study area has been divided into 588 grid cells. The model is simulated for each individual cell before aggregating them for presentation. The SD model also considers two ecological resources, mule deer, and fish, whose population is affected by shale gas production. The difference between theoretical model and system dynamics model in this study is that the former is more aggregated than the later. For example; in the theoretical model there is no functional form for gas production but it is determined by standard equations in the SD model. Finally, the theoretical model was aimed to find a closed form solution for optimum level of gas production so that net social benefit is maximized. But it is not possible due to the complex structure of the equations. SD model, on the other hand, gives several solutions among which one can be an optimum solution.

4.4. Method

This study adopts the spatiotemporal system dynamics model that simulates various systems over space and time. The system dynamics model, an approach that integrates behavior of complex systems over time using stock, flows, and feedback loops, in this study assumes four systems interacting together over time. The four systems that are shown in Figure 4-8, also known as the causal loop diagram, include an ecological system, a geological system, a hydrological system, and an economic system. The figure summarizes how a change in one system drives changes to the other systems.

Production of shale gas falls under the geological system. Oil and gas production affects the other three systems through input requirements, outputs, and development activities. The ecological system affects the economic system through a change in the population of ecological endpoints i.e. mule deer and fish. In the loop diagram, the + and

– sign indicates that if an increase (decrease) in the level of one variable causes to increase (decrease) or decrease (increase) in the level of other variables. If both variables move in the same direction, then it takes + sign and vice versa.

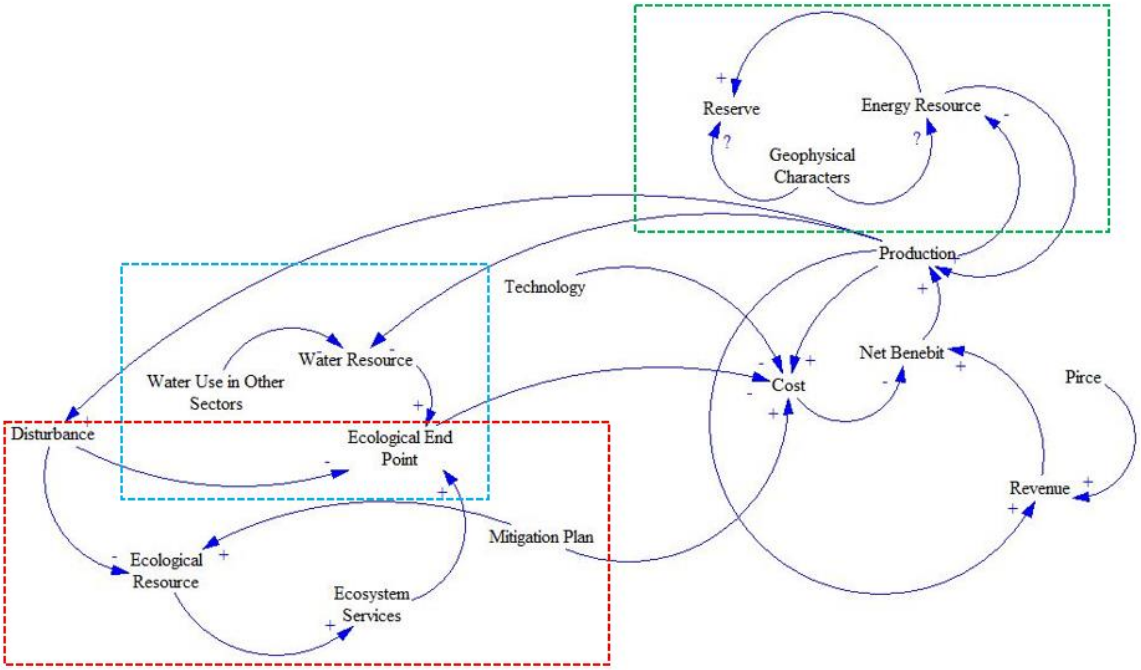


Figure 4-8:Causal Loop Diagram Showing Four Systems

The system inside the green broken-line-box, geological system, shows the geological elements responsible for determining shale gas extraction. The system inside the red broken-line-box, ecological system, shows the elements that are impacted by or impacts on other systems. The system inside the blue broken-line-box, hydrological system, exhibiting how water resources are used and the use of water resource affects the ecological system. The remaining part of the causal loop diagram represents the economic system.

The causal loop diagram shows that there is a tradeoff between the economic benefit from energy resource and other resources. An improvement in technology or price

of energy resources induces exploitation of more energy resource that in turn brings a disturbance to the specific land area and the collocated environmental attributes. A change in LULC brings a change in the ecosystem services that imposes a cost to society. The economic benefit derived from the energy production is reduced by the cost incurred due to altered ecosystem services. This cost along with production cost allows us to estimate net social benefit over time in a spatially explicit manner. This capability can be particularly useful to consider regional tradeoffs between development and conservation choices.

The implementation of spatiotemporal system dynamics model starts dividing the study area into 588 grid cells (Figure 4-9) using EXCEL and ArcGIS software. Each grid cell is square with an area of 2.9 miles^2. The choice of 2.9 square mile area was ad hoc. A simulation is carried out for each cell. The time step for a simulation is monthly and the simulation period is 2000-2028. Results are presented in annual increments and aggregated for the study area.

Figure 4-9:Division of the Study Area into 588 Cells

4.4.1 Geological System

The objective of the geologic system is to simulate the total unconventional gas production from the total stock of unconventional gas resource over a specified period of years and to determine resource development costs. This system is governed by two main equations: flow rate equation and declined curve equation. This study assumes that hydraulic fracturing is used for all unconventional gas development. This technology is a well-stimulation technique in which rock is fractured by a pressurized liquid. The process involves the high-pressure injection of a 'fracking fluid' (primarily water, containing chemicals, sand or other proppants suspended with the aid of thickening

agents) into a wellbore to create cracks in the deep-rock formations through which natural gas will flow more freely (Bernknopf et al. 2017).

The decline curve equation gives the volume of natural gas flow in time $t+1$ based on gas flow in time t and other parameters. This study uses the decline curve equation provided by Arps (1945) and written as[30]:

$$q_t = \frac{q_i}{\left(1+bD_i t\right)^{\frac{1}{b}}} \tag{4.16}$$

Where,

q_i = Initial gas flow rate (million standard cubic feet per month- *MMScf/Month*)

q_t = Gas flow rate at time t (*MMScf / Month*)

b = Arps decline Curve exponent

D_i = Initial decline rate (*per month*)

t = Time in months

There are various methods to determine the values for $b, D_i,$ and q_i. For the Proof of Concept the initial decline rate is assumed to be, $D_i = 70\%$ and the Arps decline Curve exponent $b = 1.1$. The value of an initial gas flow rate is determined by (Song et al. 2015).

$$q_i = \frac{T_{sc} Z_{sc} w_f h k_f}{T Z p_{sc} \mu x_f}\left(p_m^2 - p_w^2\right) \tag{4.17}$$

Where

[30] There are different types of types of decline curve equations and parameters of those equations take different value. This study borrows the equation and parameter values used to estimate gas production from a typical Haynesville well (Penner 2013).

$h = \text{Reservoir thickness}\left(m\right)$

$k_f = \text{Absolute permeability}\left(m^2\right)$

$p_m = \text{Pressure at the junction of two zone}\left(Pa\right)$

$p_w = \text{pressure of the production well}\left(Pa\right)$

$p_{sc} = \text{Standard state pressure}\left(Pa\right)$

$T_{sc} = \text{Temperature in standard of gas reservoir}\left(K\right)$

$T = \text{Formation Temperature}\left(K\right)$

$w_f = \text{Fracture width}\left(m\right)$

$x_f = \text{Fracture half length}\left(m\right)$

$Z_{sc} = \text{Gas compressibility factor under standard state}\ \left(\text{dimensionless}\right)$

$Z = \text{Gas compressibility factor under normal state}\ \left(\text{dimensionless}\right)$

$\mu = \text{Gas viscosity}\left(Pa\,s\right)$

Equation 4.17 generates a total flow in the rock fracture. To estimate the total flow rate in a well per day, we multiply equation 4.17 by the number of fractures (N). The value of parameters used to estimate equation 4.17 is borrowed from Song et al. (2015). These values are only for demonstration purpose in this proof of concept study. These parameter values can be replaced using actual data from the study area. Table 4-1 shows the employed parameter values in this study.

Table 4-1:Data Used for the Flow Rate Equation in the Proof of Concept

Nomenclature	Symbol	Value (Unit)
Reservoir thickness	h	$10(m)$
Absolute permeability	k_f	$5\times10^{-12}\left(m^2\right)$
Gas viscosity	μ	$2.7\times10^{-6}\left(Pa\,s\right)$
Standard state temperature	T_{sc}	$293(K)$
Formation temperature	T	$383(K)$
Pressure at the junction of two zone[31]	p_m	$2.01958\times10^{6}\left(Pa\right)$
Pressure of the production well	p_w	$2\times10^{6}\left(Pa\right)$
Standard state pressure	p_{sc}	$0.1\times10^{6}\left(Pa\right)$
Fracture width	w_f	$0.003(m)$
Fracture half length	x_f	$derived\ \ from the model\left(m\right)$
Gas compressibility factor under standard state	Z_{sc}	1
Gas compressibility factor under standard state	Z	0.89

Source: Song et al. (2015)

4.4.2 Ecological System

The ecological system is simulated for exploring the impact of shale gas production activities on ecological resources: mule deer and aquatic species (fish). Construction of a

[31] Song et al. (2015) suggest calculating this value using an equation. However, we calibrated this value to achieve the 10% estimated total volume of undiscovered continuous gas (with 95 percent chance of at least the amount) in Unita-Piceance province i.e. 1,215 BCFG. According to USDI and USGS (2003) volume of such gas is 12,145.49 BCFG in Unita-Piceance province and we assume the study area (AU 200263) is only 10 % of the total area of the Unita-Piceance.

new road creates a disturbance for mule deer habitat, which causes a decline in mule deer populations. Several studies have examined this mechanism. (Northrup et al. 2015, Buchanan et al. 2014, Wilbert et al 2008). Similarly, activities associated with unconventional gas development can lead to sediment loading in the rivers in the AU that could affect aquatic species populations. Road construction may cause an increase in erosion, which could increase sediment loads in the Colorado River or adjoining rivers resulting in a decline in aquatic species.

The total number of mule deer in each cell is determined by the probability of resource use in each cell estimated using an abbreviated version of the Northrup et al. (2015) model. According to Northrup et al. (2015), "the probability that an animal (*n*) chooses a resource unit (*y*) represented by a suite of habitat covariates (x_y) from a set of available alternative resource units (*J*), represented by suite of habitat covariates (x_j) at time *t* "is given by

$$P(RU) = \frac{e^{\mathbf{x}'_{ytn}\boldsymbol{\beta}_n}}{\sum_{j=1}^{J} e^{\mathbf{x}'_{jtn}\boldsymbol{\beta}_n}} \tag{4.18}$$

Where $\mathbf{x} = \{slope, elevation, d\_rds\}$ and $\boldsymbol{\beta} =$ Vector of coefficients

This study does not incorporate all the covariates found in Northrup et al. (2015). Only slope, elevation, percent of tree coverage and distance to roads were considered due to data limitations. The coefficient for slope (0.05), elevation (0.69), percent of tree coverage (0.08) and distance to roads (0.17) are borrowed from Northrup et al. (2015). Following steps are employed to calculate the mule deer population in each cell for every

year. An important feature of equation (4.18) is that even if the distance to the road is zero, i.e. exactly on the road, there will be some probability of finding mule deer.

The following steps are followed to determine number of mule deer in each cell, and the associated cost is calculated.

i. Initial mule deer population in the study area is assumed 4,200[32].

ii. Pre-development probability is calculated for each cell using Northrup et al. (2015) equation dropping the *distance to road* explanatory variable. The variable *distance to the road* is dropped where it is assumed there were no roads constructed before the gas production started in the year 2000.

iii. 4,200 mule deer are distributed in each cell in the proportion of the probability corresponding to the cell. Total numbers of mule deer in each cell is given by;

$$Muledeer_i = \frac{probability_i}{\sum_{i=1}^{588} probability_i} total\ muledeer \tag{4.19}$$

iv. Once development starts then the probability of resource use in each cell are altered due to the construction of the road. At this point, the *distance to road* explanatory variable is included in the regression and probability of resource use for each cell are calculated for

[32] BLM(2015) estimates the deer population in the Piceance basin to be 40,000-45,000. Total area of the AU 200263 is about 10% of the area of the Piceance basin. It is thus assumed that the population of mule deer is also 10% of the total mule deer population (taken 42,000) in the Piceance basin.

every year and total mule deer population is distributed according to the new probability as explained in step iii.

v. Total mule deer population for each year is determined by the average probability of the study area. The average probability and mule deer population for each year determined by using following formula.

$$\left(Average\ Porbability\right)_t = \frac{\sum_{i=1}^{588} probability_i}{588} \tag{4.20}$$

$$\left(Mule\ deer\ population\right)_t = \left(Average\ Probability\right)_t \times \left(Mule\ deer\ population\right)_{t-1} \tag{4.21}$$

Once the mule deer population for each cell and for each year is calculated, the social cost of changing mule deer population due to natural gas production is calculated using the following method.

i. In the first step, the base value of mule deer population (value of 4,200 mule deer) is calculated.

$$Base\ Value\ of\ Muledeer = CS \times Colorado\ Population \tag{4.22}$$

Here, the consumer surplus of mule deer is estimated using meta-analysis. The meta-analysis as described in Bernknopf et al. (2017) shows that the CS for mule deer is $68/year/person. The Colorado population is assumed to be constant in the 2000 census population.

ii. Next, the percentage change in mule deer is calculated for each year using the following formula.

$$\left(Percentage\,Change\,in\,Mule\,Deer\ \right)_t = \frac{\left(Initial\,Mule\,deer\right)-\left(Mule\,deer\right)_t}{\left(Initial\,Mule\,deer\right)} \tag{4.23}$$

iii. The percentage change in mule deer population value is used to update the consumer surplus value for the corresponding year using the formula.

$$\left(Consumer\,Surplus\right)_t = \left[1-\left(Percentage\,Change\,in\,Mule\,Deer\ \right)_t\right]\times \left(Initial\,Consumer\,Surplus\right) \tag{4.24}$$

iv. Updated consumer surplus value in step (iii) is now used to calculate the value of mule deer for that year using the formula

$$\left(Value\,of\ Muledeer\right)_t = \left(Consumer\,Surplus\right)_t\left(Colorado\,Population\right) \tag{4.25}$$

v. Finally the social cost of mule deer for a year is calculated as the difference between value of mule deer for the year calculated in the step (iv) and base value of mule deer calculated in the step (i)

$$\left(Social\,Cost\,of\ Muledeer\right)_t = \left(Base\,Value\,of\ Muledeer\right)-\left(Value\,of\ Muledeer\right)_t \tag{4.26}$$

Once the social cost of mule deer is calculated, it is discounted by using 3% discount rate.

Fish population and the associated social cost are calculated following similar methodology applied in the mule deer case above. The fish population is assumed to be a function of sedimentation load in the river which itself is a function of river volume and erosion quantity. Estimation of the erosion due to road construction in the development area is based on an equation from Anderson and Macdonald (1998).

$$Erosion = 0.0057\times slope\times drainage\,area + 0.034 \tag{4.27}$$

Once the erosion level is estimated then, it is assumed that 0.1%[33] of the sediment is delivered to the river. Based on this assumption, the sediment load in the river using the following formula is:

$$Sedimentation = \frac{0.001 Erosion}{River\,Volume + 0.001 Erosion} \tag{4.28}$$

Information on sedimentation load allows us to estimate fish population. According to Hausle (1973), the mean survival rate of Brook trout is 100%, 50%, and 10% if the sediment percent in the river is 0%, 10%, and 20%. These parameters are used to estimate a reduction in the fish population in the Colorado River near AU 200263 assuming initial fish population to be 4,318 fish/mile[34]. Based on the estimated fish population for each year and change in the fish population, associated social cost is calculated following the following steps.

i. In the first step, the base value of fish population (value of 4,318 fish per mile) is calculated.

$$Base\,Value\,of\ Fish = CS \times Colorado\,Population \tag{4.29}$$

[33] This value needs to be a function of tributary inflows. However, in the proof of concept, the tributary inflows have not been modeled explicitly. Therefore the value was assumed for making the impact of erosion in the study area on the fish population in the Colorado River minimal. Taking larger fraction would inflate the impact.

[34] This value is borrowed from Ewert (2015). This document has been replaced by new document that contains data from 2007 only. According to the new document, the trout population per mile is 3,976 in 2016.

Here the consumer surplus of fish is estimated using meta-analysis as explained in Bernknopf et al. (2017). The meta-analysis as described in Bernknopf et al. (2017) shows that the CS for fish is $72.5/year/person. The Colorado population is assumed constant at the 2000 census population.

ii. Percentage change in fish population is calculated as:

$$\left(Percentage\,Change\,in\,Fish\right)_t = \frac{\left(Initial\,Fish\,Population\right)-\left(Fish\,Population\right)_t}{\left(Initial\,Fish\,Population\right)} \tag{4.30}$$

iii. The percentage change in fish population value is used to update the consumer surplus value for the corresponding year using the formula.

$$\left(Consumer\,Surplus\right)_t = \left[1-\left(Percentage\,Change\,in\,Fish\right)_t\right] \times\left(Initial\,Consumer\,Surplus\right) \tag{4.31}$$

iv. Updated consumer surplus value in step (iii) is now used to calculate the value of fish for that year.

$$\left(Value\,of\;Fish\right)_t = \left(Consumer\,Surplus\right)_t\left(Colorado\,Population\right) \tag{4.32}$$

v. Finally, the social cost of fish for a particular year is calculated as the difference between value of fish for that year calculated in step (iv) and base value of mule deer calculated in the (i)

$$\left(Social\,Cost\,of\;Fish\right)_t = \left(Base Value\,of\;Fish\right)-\left(Value\,of\;Fish\right)_t \tag{4.33}$$

Once the social cost of fish is calculated, it is discounted by using 3% discount rate.

4.4.3 Hydrological System

Hydrological system in this study considers not the detailed hydrological cycle and water budget but the economic cost of transferring water from other sectors to hydraulic fracturing. It is assumed that the consumptive use of water occurs in three broad areas within the AU: 1) natural gas development, 2) other humankind uses, i.e., residential, industrial commercial or agricultural use and 3) ecosystem services, i.e., wildlife or aquatic species, forests, in-stream flows, lakes and so forth. For the given amount of water, increased consumption in one sector results in reduced consumption in another sector i.e. there is the opportunity cost of consuming water.

In the hydrological system, it is assumed that groundwater is withdrawn only if river water is not sufficient to meet the demand. River volume is assumed to be 2,758 $ft^3 / \sec$, the combined volume of the Yampa River and White River[35]. Total water consumption in Piceance basin that includes water used for commercial, domestic industrial, irrigation, livestock, and other purposes is assumed to be 36,673 $gallon / second$ [36]. For the hydraulic fracturing purpose, total water used per well is assumed to be 4,662,636 gallons/well (Gallegos et al. 2015). Once the total water used in hydraulic fracturing is obtained, it is decomposed into water transferred from different

[35] Source: //https://en.wikipedia.org/wiki/White_River_(Green_River) and https://en.wikipedia.org/wiki/Yampa_River

[36] Water use in the counties where Piceance basin encompasses. Counties are: Moffat, Rio Blanco, Garfield, Mesa, Pitkin, Delta, Gunnison, and Montrose. Source of water use data: http://co.water.usgs.gov/infodata/wateruse.html

sectors using water strategist data[37]. Assuming hydraulic fracturing as an environmental sector, there was 57% transfer from agriculture to the environmental sector with an average price of $54.25/acre feet, 41% percent transfer from urban to the environmental sector with an average price of $28.96/acre feet, and 2% percent transfer from environmental to environmental sector with average price $0.57/acre feet. These percentages and prices were used to decompose total water use into a quantity of water transferred from different sectors and estimate water cost.

4.4.4 Economic System

The economic system is modeled to simulate the total cost, total revenue, and net revenue value of unconventional gas production that includes direct development and production costs and revenues and the social costs associated with impacts to collocated natural resources.

Total cost is classified into two categories (i) Development and Production Cost, and (ii) Social Cost. Drilling, land acquisition, taxes (severance and ad valorem tax), and water use are the primary extraction cost components. One important component of total cost is the social cost associated with a change in an ecological endpoint or an ecosystem service that has already been explained in the ecological system section. Development and production cost is governed by the following equations.

[37] The water strategist data is publically available from The Bren School of Environmental Science and Management and can be accessed at http://www.bren.ucsb.edu/news/water_transfers.htm.

$$Development\ and\ Production\ Cost = Sand\ Cost + Tax + Completion\ Cost + Acquisition\ and\ Leasing\ Cost + Pad\ Cost + Investment + Royalty + Water\ Cost + Road\ Cost + Horizontal\ Drilling\ Cost \quad (4.34)$$

Where

$$Tax = Advalorem\ Tax + Severance\ Tax$$

$$Pad\ Cost = Cost\ per\ Pad \times Incremental\ Pad$$

$$Inverstment = Vertical\ Drilling\ Cost + Horizontal\ Drilling\ Cost$$

$$Verticle\ Drilling\ Cost = Incremental\ Well \times Well\ Depth \times Drilling\ Cost\ Rate$$

$$Horizontal\ Drilling\ Cost = Incremental\ Well \times Linear\ Distance \times Drilling\ Cost\ Rate$$

$$Road\ Cost = Road\ Cost\ Rate \times Total\ Road\ Length$$

$$Water\ Cost = Water\ Price \times Total\ Water\ Used$$

$$Sand\ Cost = Total\ Sand\ Used \times Sand\ Cost\ Rate$$

In equation (4.34) the *tax* that is levied on oil production in Colorado is the sum of severance tax and property tax (Headwater Economics 2014). This study follows Headwater Economics (2014) to calculate these two taxes:

*Severance Tax = (((Gross Prod. Value * .95) * .05) + 300,000) – (Prior year Property Tax * .875)*

*Property Tax = ((Prior Year Assessed Value * .95) * .87) * (.058636)*

According to Headwater Economics (2014), "Oil and natural gas are assessed at 87.5 percent of net production value, which is defined as gross production value less

transportation and processing costs (assumed at five percent)." In this study, for the sake of simplicity, the current year gross production value is assumed to be the assessed value. Data used in this section and corresponding sources are summarized in Table 3.2.

Table 4-2:Data Source and Variable Values Used in the Economic System

Variable	Value	Source
Production to Gathering	$473,000	Hefley et al. (2011)
Completion	$200,000	Hefley et al (2011)
Acquisition and Leasing	$2,100,000	Hefley et al. (2011)
Permitting	$10,000	Hefley et al. (2011)
Cost Per Pad	$400,000	Hefley et al. (2011)
Formation Depth	11,000 ft	Pierce (2015)
Drilling Cost Rate	51 $/ft	Sell, Murphy and Hall (2011) (Minimum drilling cost for vertical well)
Road Cost Rate	$16296/Acre	http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5279284.pdf
Sand Cost Rate	$400/ truckload[38]	http://dougclack.com/price-list.html

Total revenue from unconventional gas production is calculated by multiplying total gas produced by the natural gas spot market price. The gas price data comes from the website of the U.S. Energy Information Administration (EIA)[39]. The data is the monthly Henry Hub Natural Gas Spot Price measured in $/MMBTU. $/MMBTU converted in to $/MCF by using a conversion factor of 1.028 (i.e. $/MCF = 1.028 $/MMBTU) available at the US DOE Energy Information Agency website[40].

[38] A typical well pad is assumed to use 130 truckload Sand (Pierce 2015)
[39] https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm
[40] https://www.eia.gov/tools/faqs/faq.cfm?id=45&t=8

4.4.5 Uncertainty

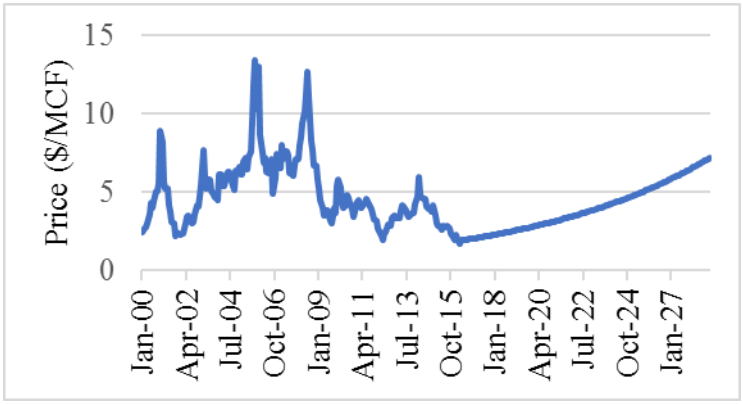
Uncertainty is an important aspect in the mineral resource estimation, exploration, and exploitation (Dominy et al. 2002, Emery et al. 2006). Some of the important uncertainties discussed in literature are uncertainty in estimation of mineral resources and ore reserves (Dominy et al. 2002), price uncertainty (Bukhari and Christopher 2012), technological uncertainty (Emery et al. 2006), economic uncertainties (Schiozer et al. 2004), and policy uncertainties (Hellström and Jacob 2011). This study includes price uncertainty in the analysis for the demonstration purpose. Price uncertainty is one of the most important factors to consider for hydrocarbon (shale gas) production. This is because the decision to produce hydrocarbon in ultimately guided by economic interest. It is obvious that a firm will not be interested producing shale gas if the market price is very low and extraction is not reasonably justified.

Schiozer et al. (2004) suggest 11 steps to follow for incorporating uncertainties in a simulation model. According to the paper, the usual approach to capturing uncertainty is to start with three levels for each uncertainty variable: medium (M), a pessimistic (P), and an Optimistic. However, this study uses Monte Carlo Simulation approach to incorporate price uncertainty.

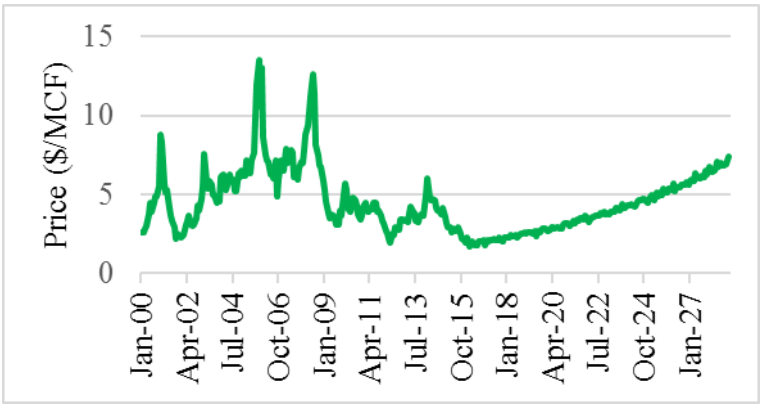
Monte Carlo Method, as explained in Dienemann (1966), price is described in terms of a probability distribution, which is then treated as a theoretical population from which random samples are obtained. The method of taking such samples are referred to as Monte Carlo Method Dienemann (1966). Dienemann (1966) describe Monte Carlo Method for simulating cost uncertainty. Here the procedure is explained for price uncertainty.

Suppose the price uncertainty is described by the probability density function $y = f(x)$. A cumulative distribution function can be plotted using this probability density function (PDF). The vertical axis of the PDF measures probability whose value ranges between 0-1 and the horizontal axis measures sample price (x). To implement the Monte Carlo Method, a random number between 0 and one is picked up, and the corresponding value of price (x) from the CDF is recorded. This recorded value of price (x) is the sample value of price. This process is repeated numerous times to get a sample of the price that approximates the price uncertainty. Illustration of the methodology is discussed below.

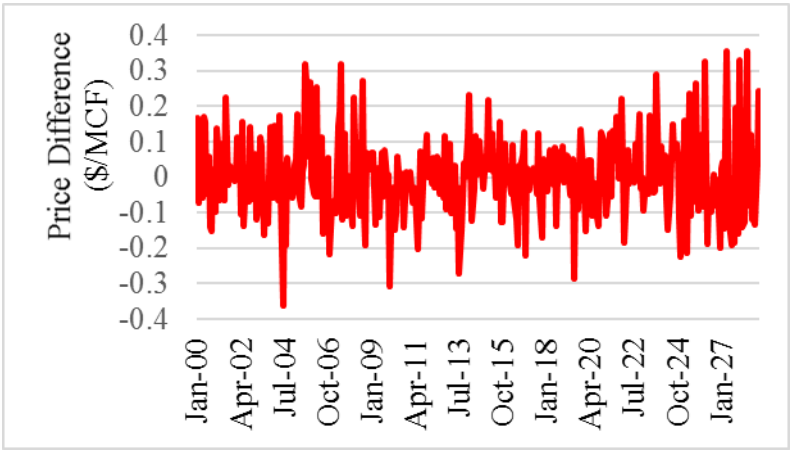
This study uses the monthly Henry Hub Natural Gas Spot price. It is also assumed that monthly price is normally distributed with mean equal to the price of the month and variance equal to three times of the mean.The simulation is carried out for 1,000 times, and the average of the 1,000 outcomes is taken as the price with uncertainty. Figure 4-10 depicts the actual gas price, gas price with uncertainty, and the difference between two prices. The difference is the gas price with uncertainty minus actual gas price.



(A) Actual Price



(B) Price with Uncertainty



(C) Price Difference (Uncertainty – Actual)

Figure 4-10:Actual Gas Price and Gas Price with Uncertainty

4.5. Scenario Evaluation

Evaluation of the impact of hydraulic fracturing on collocated resources and their net social benefit for different scenarios were developed, which includes a base line scenario. The following chart shows the development scenarios.

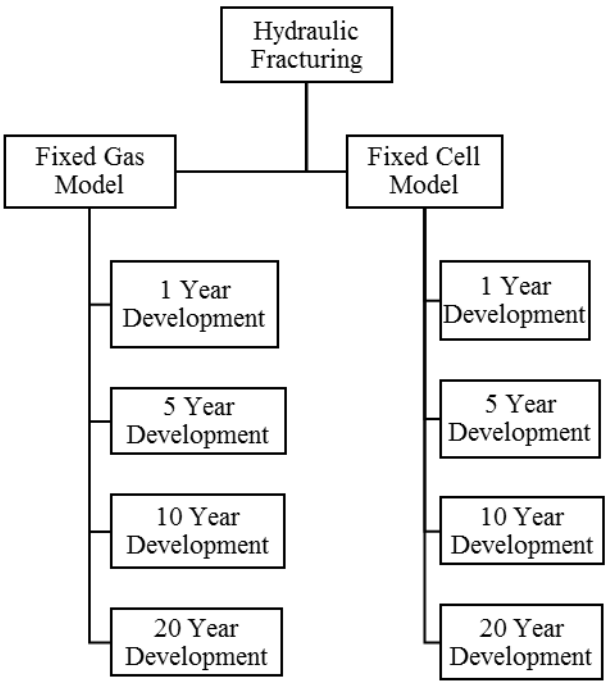


Figure 4-11:Chart Showing Various Scenarios

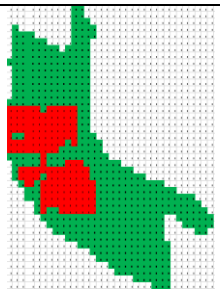
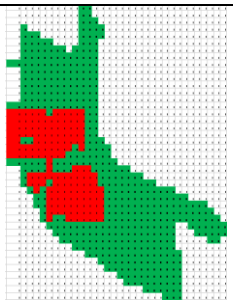
The simulation is carried out for a fixed gas model and a fixed cell model. The fixed cell model means a total of 140 cells are developed within four different periods of time: 1 year (all 140 cells are developed in the first year), 5 Year (each year 28 cells are developed to reach 140 cells at the fifth year), 10 year (each year 14 cells are developed), and 20 year (each year seven cells are developed). Each scenario mentioned above are further divided into gas production with one well per pad, five well per pad, and ten well per pad. In the fixed gas model, 639MCFG is the fixed amount of gas produced, while the number of cells is varied. Cells are added to achieve and maintain a constant level of gas production in the same ways as the fixed cell strategy. The production of 639MCFG is the total gas produced during the simulation period in the fixed cell model with a 1-year development plan having five wells per pad and five pads per square mile, which is the maximum amount of gas that can be produced under this strategy. It means there are 24 scenarios for the price without uncertainties. There are another 24 scenarios with

price uncertainties. Major variables that will be analyzed are total gas production, net social benefit, and mule deer population.

4.5. Results and Discussion

Simulation in this study starts by selecting which cells are to be developed over time. Figure 4-12[41] shows how cells were selected to generate results for this study. Developed cells are indicated by the red color, and green cells mean they are not developed. However, an external user seeking to develop different cells using the model of this study can do so selecting different cells. In the sytem dynamics model, there are 588 variables corresponding to each cell. A cell can be selected to develop by assigning value 1 to the corresponding variable. Zero value for the variable means the cell is not being developed.

Cells Selection in 1 Year Development Case

Fixed Cell Model	**Fixed Gas Model**
	
The year 2000 (140 cells)	The year 2000 (140 cells)

[41] Maps for 10 year and 20 year development is in appendix D

Cells Selection in 5 Year Development Case

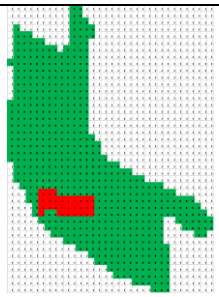
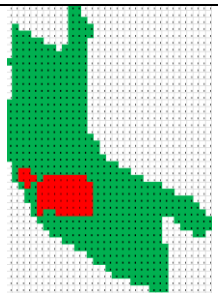
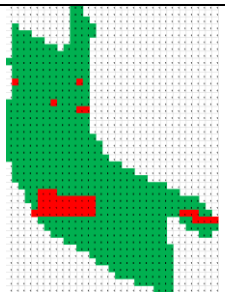
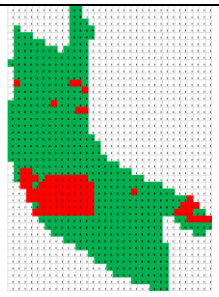
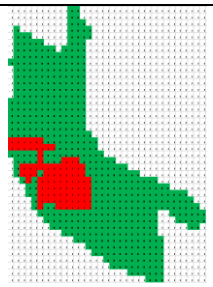
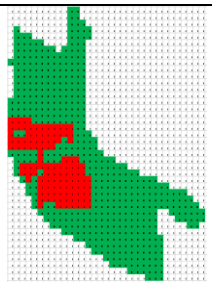
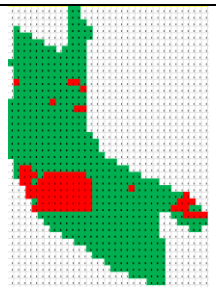
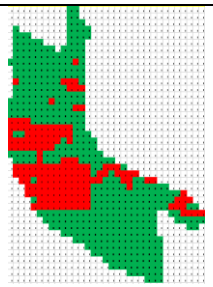
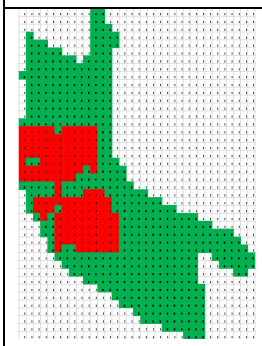
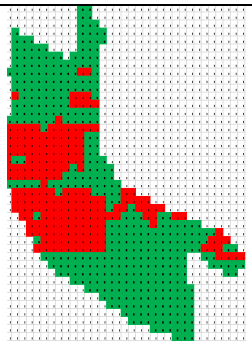
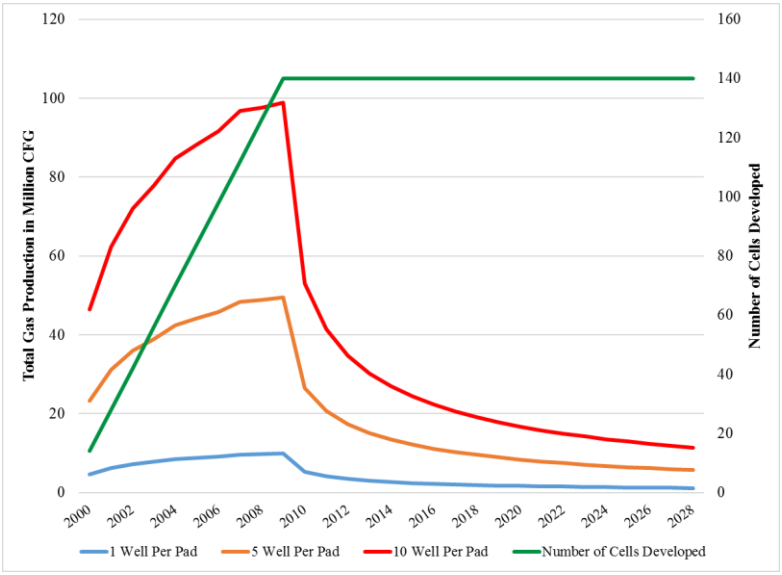
Fixed Cell Model		**Fixed Gas Model**	
			
The year 2000 (28 cells)	The year 2001 (56 Cells)	The year 2000 (40 cells)	The year 2001 (80 Cells)
			
Year 2002 (84 cells)	Year 2003 (112 cells)	Year 2002 (120 cells)	Year 2003 (160 cells)
			
The year 2004 (140 cells)		The year 2004 (199 cells)	

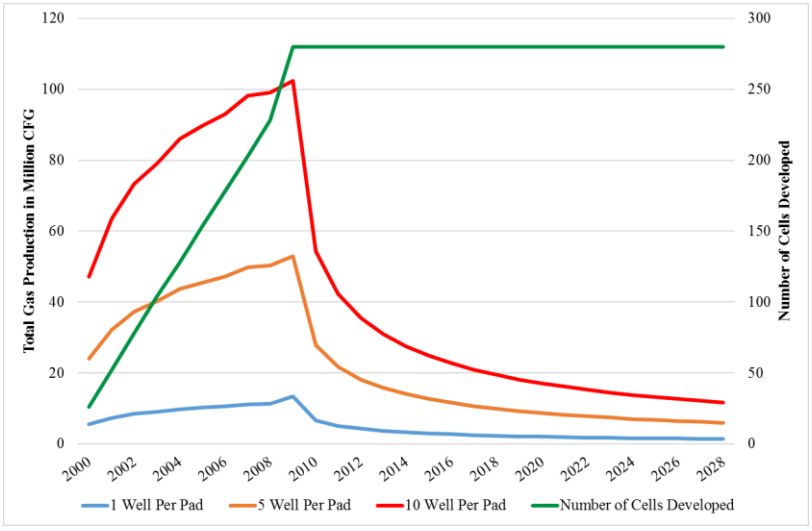
Figure 4-12:Cells Developed Over Time in Two Models

Figure 4-13 shows the level of gas production for several scenarios taking a 10-year development case. Panel A corresponds to fixed cell model, and panel B corresponds to fix gas model. The volume of gas production increases with an increase in

wells per pad. Similar trends are found for other cases too when wells per pad are increased.



A: Fixed Cell Model



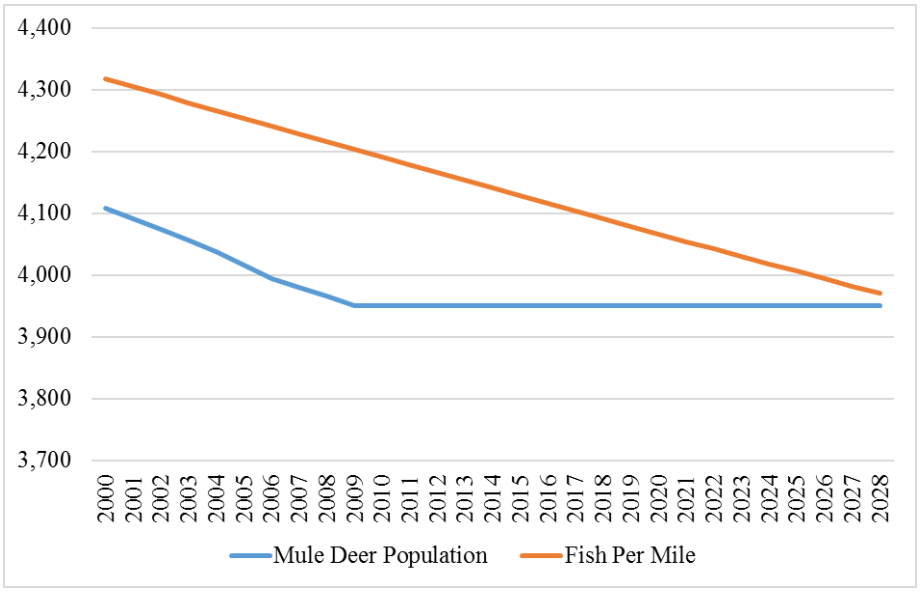
B. Fixed Gas Model

Figure 4-13:Volume of Gas Production with Different Numbers of Wells per Pad

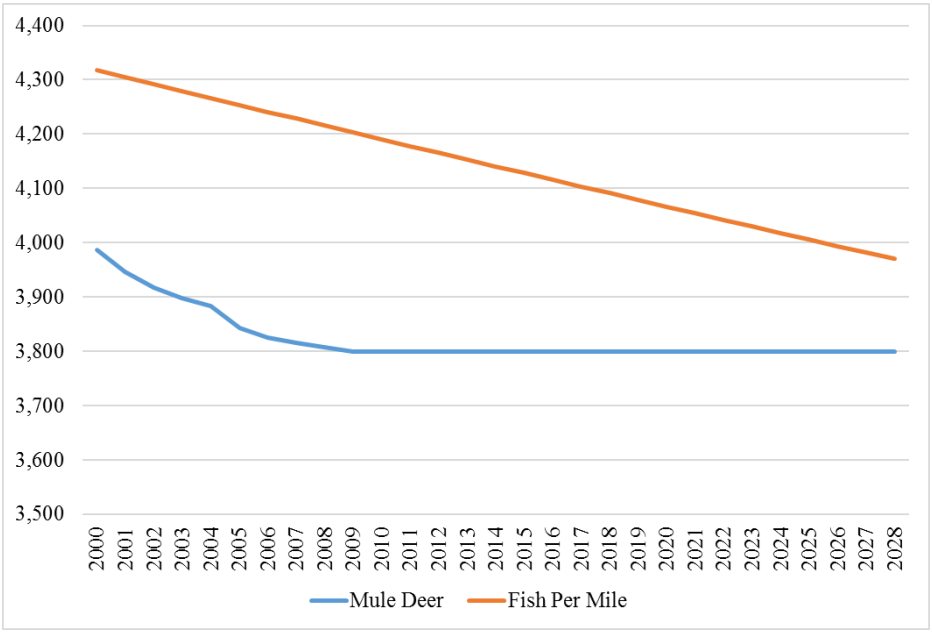
The total volume of gas produced in both, fixed cell and fixed gas, model increases until the tenth year of simulation (The year 2009) because the number of new wells are continuously added until 10th year in the 10-year development case. After the

tenth year, the volume of gas starts to decline because of the decline curve equation (4.1). Total volume of gas in both cases increase proportionately with numbers of wells per pad. For example; in fixed cell case, the maximum volume of gas with 1, 5 and ten wells per pad is 9.89 MCFG, 49.44 MCFG, and 98.89 MCFG. A similar trend is seen in the fixed gas case. However, the level of gas production in fixed gas case for a year and a number of wells per pad is higher than in the fixed cell case. For example; total gas production in fixed gas case with one well per pad in the year 2009 is 13.3 MCFG which is about 3 MCFG more than the volume of gas produced in the same period with same numbers of wells per pad in fixed cell case. The difference is due to more cells developed in fixed gas model to keep the volume of a gas constant in 5-year development case. Figure 15 tells that more gas can be produced disturbing less area by increasing wells per pad.

Figure 4-14 shows the mule deer population and fish population with different numbers of wells per pad. It is important to note here that the number of wells per pad, in the model, does not affect the population of mule deer and fish. These population depends on number of pad and road area. While panel A of the figure corresponds to fixed cell case, panel B represents the fixed gas case. Fish per mile in fixed cell case (fixed gas case) declines from 4,318 fish/mile in the year 2000 to 3,970 fish/mile (3,799 fish per mile) at the end of the simulation period. There will be less fish per mile in fixed gas case because in this case more cells are developed that results in more erosion and more sedimentation load in the river. However, fish per mile is not affected by increasing wells per pad. This is because the assumption of the model is that the erosion is altered by increasing number of the well pad, not by numbers of wells.



A: Fixed Cell Model



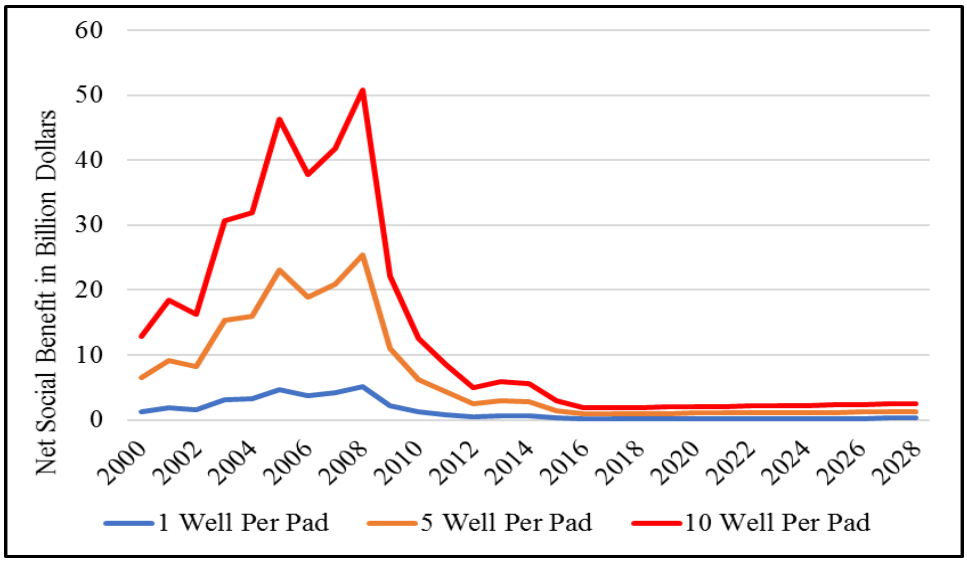
B: Fixed Gas Model

Figure 4-14:Mule Deer and Fish Population with Different Numbers of Wells per Pad

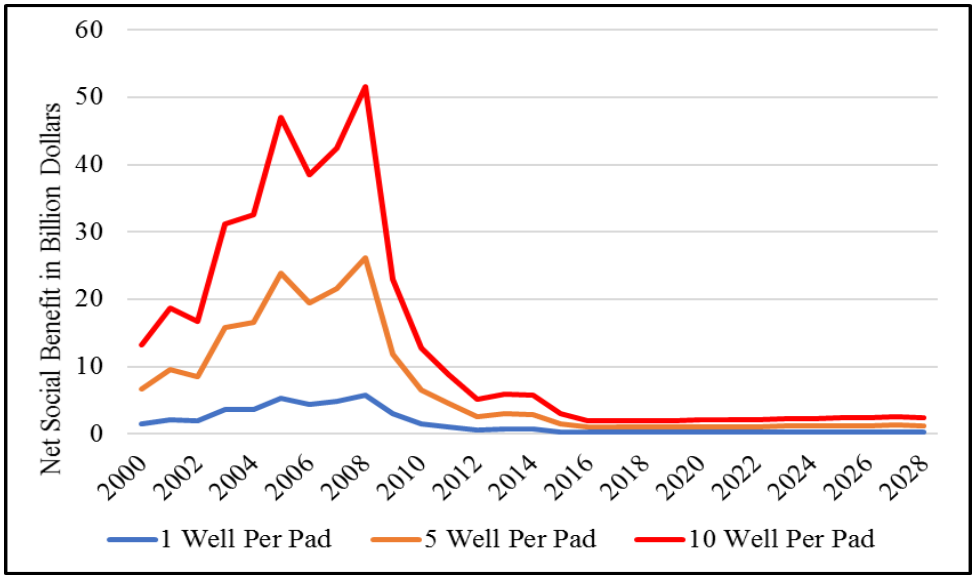
Like the fish population, the mule deer population also declines as development expands and reaches to minimum at 3,950 mule deer (3,799 mule deer) in fixed cell case (fixed gas case) in the year 2009. After the year 2009, the mule deer population remains unchanged because no more cells are developed. As explained earlier, the mule deer

population is determined by number of cells developed and number of well pads but not by wells per pad. This is the reason, the mule deer population in all 3 cases, 1, 5, and 10 wells per pad, are the same.

Figure 4-15 depicts the net social benefit for two cases- fixed cell case in panel A and fixed gas case in panel B. Net social benefit is the difference between total revenue generated from the produced gas and total cost. Total cost is the sum of private cost and social cost due to decreased numbers of mule deer and fish.



A. Fixed Cell Model- 10 Year Development Case



B. Fixed Gas Model- 10 Year Development Case

Figure 4-15:Net Social Benefit with Different Numbers of Wells per Pad

In both the fixed cell and fixed gas, cases, net social benefit is positive in all scenarios. The graph shows that the net social benefit increases in proportion to the wells per pad. For example, the net social benefit with 1 well per pad in the year 2000 was $1.2 billion for fixed cell case. This value increased to $12 billion when wells per pad increased to 10. The proportionate increase in the net social benefit with wells per pad is due to the assumption that increasing wells per pad neither affect fish population nor mule deer.

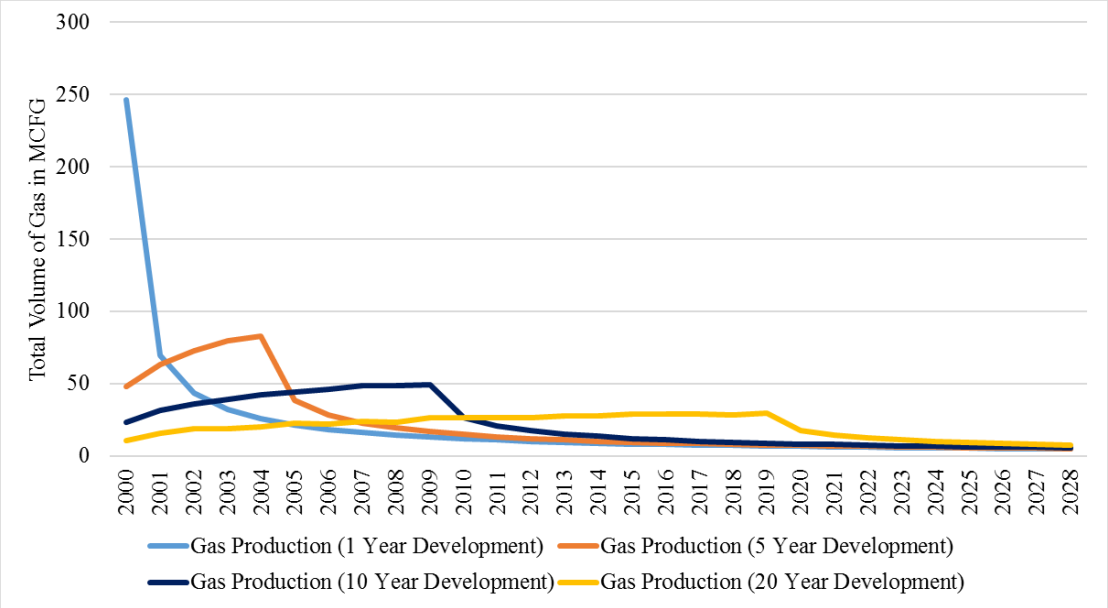
4.5.1 Impact of Development Duration

The net social benefit is the difference between private benefit and cost that is a sum of private cost and social cost. The natural gas market provides information about price that is the value of natural gas production to the society. However, the value associated with public goods i.e. ecosystem services is difficult to assess. The common approach to assess the value of such public goods is to estimate the consumer surplus.

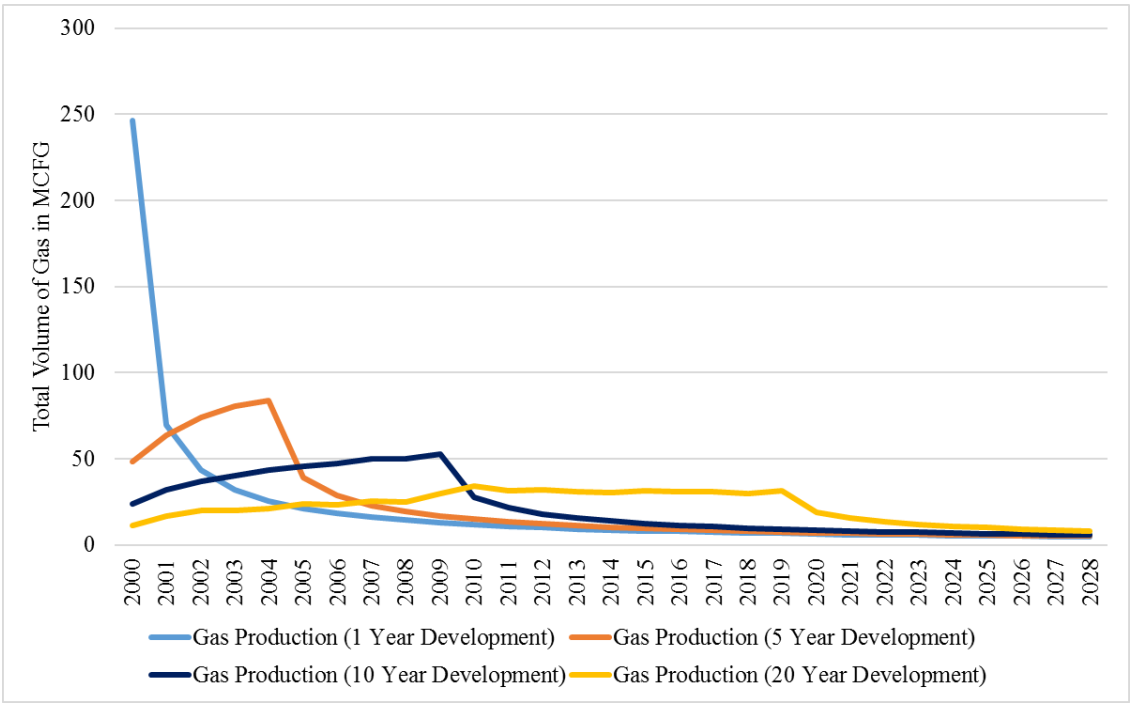
The feature of ecosystem services is that they provide ongoing flow of services. It means a loss of ecological endpoints (mule deer and aquatic species) is a perpetual loss and society pays for it forever.

How the net social benefit and other variables will be affected if the given numbers of cells are developed in different duration of time. There are two major effects. First, the given ecological cost will be spread over a longer period so that a society will have less burden due to discounting factor and perpetual nature of social cost. For example, if two cells are developed in first year then loss of mule deer will take place in the first year. The cost of mule deer loss, a social cost, which is perpetual in nature, will be incurred by a society from the first year. However, if the second cell was developed in the next year, then half of the social cost would be incurred from the second year only, resulting in less total social cost. Second, if the development occurs in later period then fraction of private benefit will be received in later period, which on discounting will give less social benefit. It means discounting factor will affect negatively for the net social benefit if development activity is expanded over longer period.

Figure 4-16 shows the total volume of gas produced for 1-year, 5-year, 10-year, and 20-year development scenario. Panel A corresponds to fixed cell case and fixed gas case is in panel B. All cases are simulated with 5 wells per pad and 5 pads per square mile.



A: Fixed Cell



B: Fixed Gas

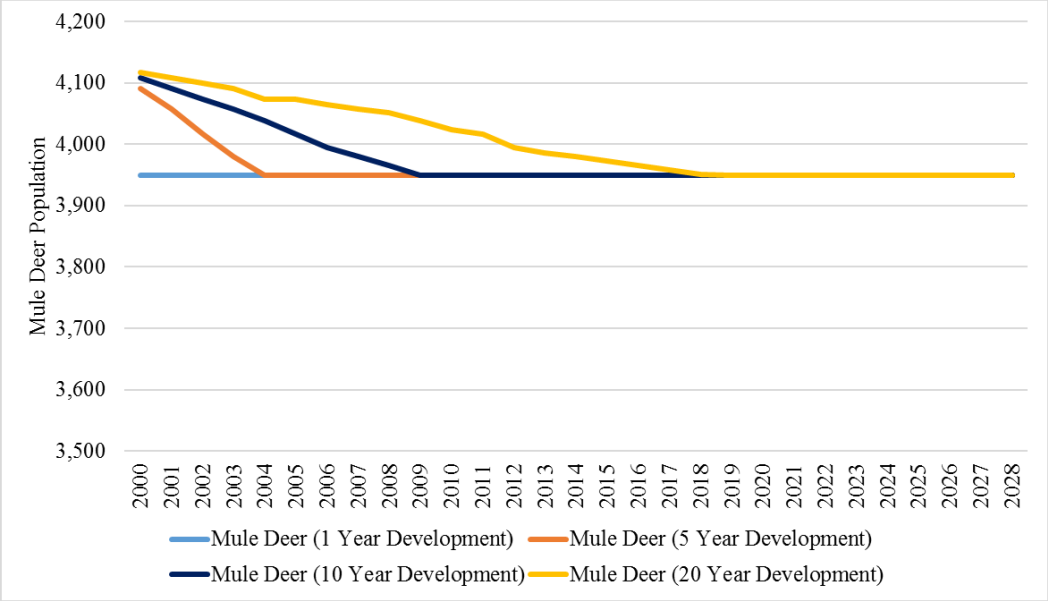
Figure 4-16:Total Volume of Gas Production in Different Scenario

Figure 4-16 shows the gas production increases until development expansion ceases and declines thereafter. Total volume of gas produced during the entire period of simulation in fixed cell case is 639 MCFG, 629 MCFG, 615 MCFG, and 580 MCFG for 1 year, 5 year, 10 year, and 20-year development case respectively. This indicates that given the numbers of cells to be developed, longer horizon of development costs per volume of gas produced. On the other hand, total volume of gas produced during the entire simulation period in fixed gas case is 639 MCFG. But in the fixed gas case the cost is in the form of area developed. More cells are needed to be developed fixed gas case than in fixed cell case for keeping the gas volume constant. This is evident from Figure 14 that the total cells developed in fixed gas case under 5-year development scenario is 199 against 140 cells in fixed cell case. More developed cells mean larger social cost due to decreased population of fish and mule deer.

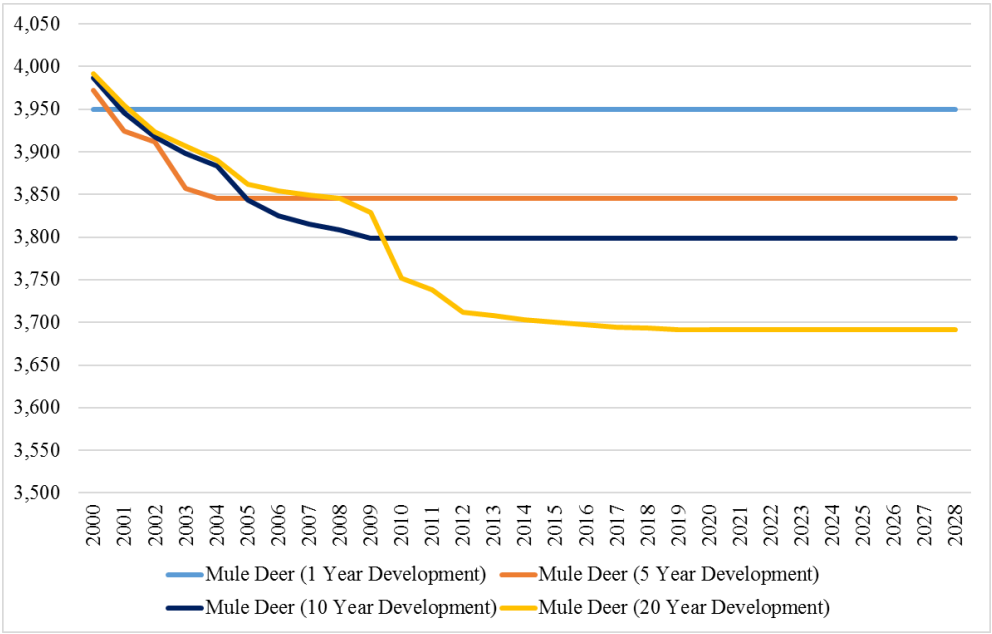
The two panels in Figure 4-16 look similar, but they are not same. For example, total gas production in 2004 for 5-year development case are 82.77 MCFG and 84.15 MCFG respectively. The difference in production at this point is relatively small making it difficult to view in the figures. The similar structure of the graph is due to the increase in new cells being developed in the fixed gas development plan in approximately equal proportion. For example, if 20 new cells need to be developed to keep gas volume constant in the 5-year development case then each year 4 new cells are developed. This strategy produces a similar structure for the two graphs.

The impact of different duration of development on mule deer population is presented in the Figure 4-17. Figure 4-17 shows that the mule deer population declines in proportion of the number of cells developed until development expansion ceases and

remains constant thereafter. In the fixed cell case, mule deer population remains constant at 3,950 at the end of simulation. This number is 3,799 for fixed gas case.

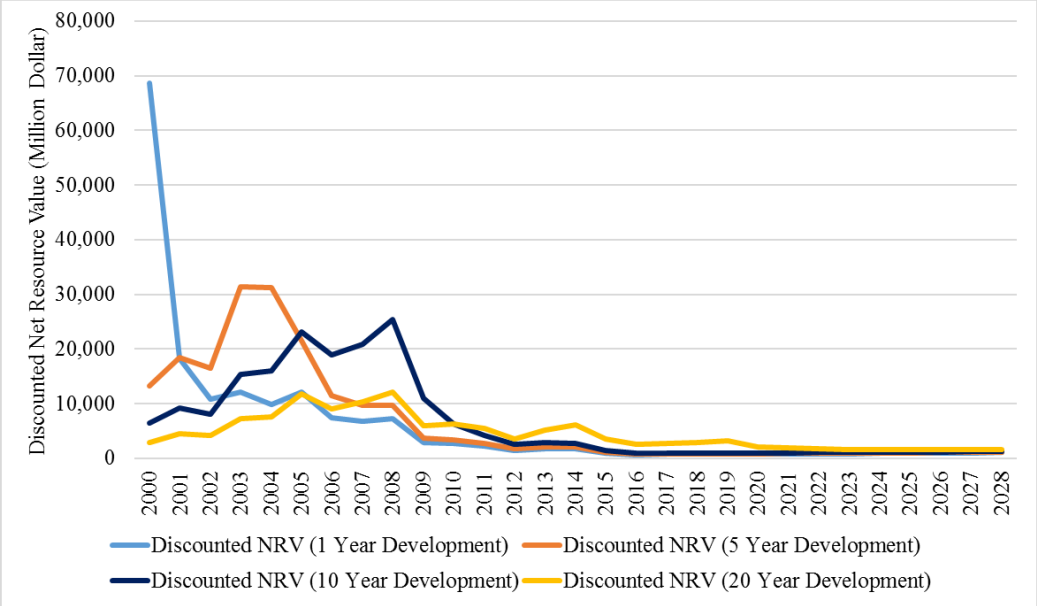


A: Fixed Cell

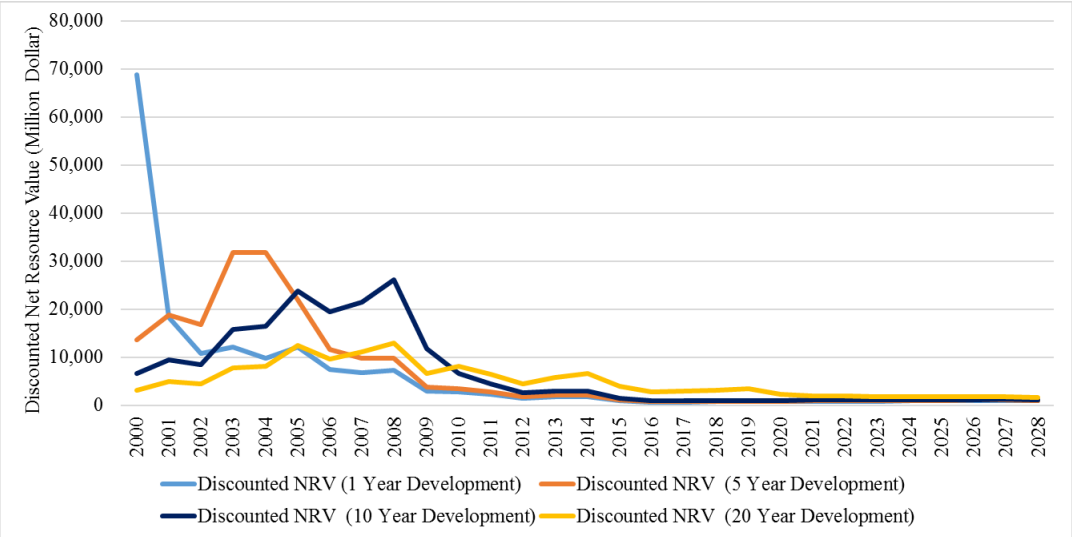


B: Fixed Gas

Figure 4-17:Mule Deer Population in Different Scenario



A: Fixed Cell



B: Fixed Gas

Figure 4-18:Net Social Benefit in Different Scenario

Figure 4-18 shows the net social benefit for two cases. Net social benefit is positive throughout the simulation period for all scenarios. In the beginning, the net social benefit is larger for 1-year development followed by 5, 10, and 20-year development. However, as time elapsed, net social benefit for longer duration

development (e.g. 20-year development) exceeds shorter duration development. This is because of the decline curve equation that governs the flow rate of the gas. In the beginning, more wells are operated for shorter duration development resulting in larger volume of gas. But as time elapses the flow rate in those older wells decline resulting in less revenue and less net social benefit.

Figure 4-19 shows the total net social benefit for the entire simulation period. From the figure, it is seen that total net social benefit is larger for fixed gas case and the difference in net social benefit between fixed cell and fixed gas is increasing as the development period increases.

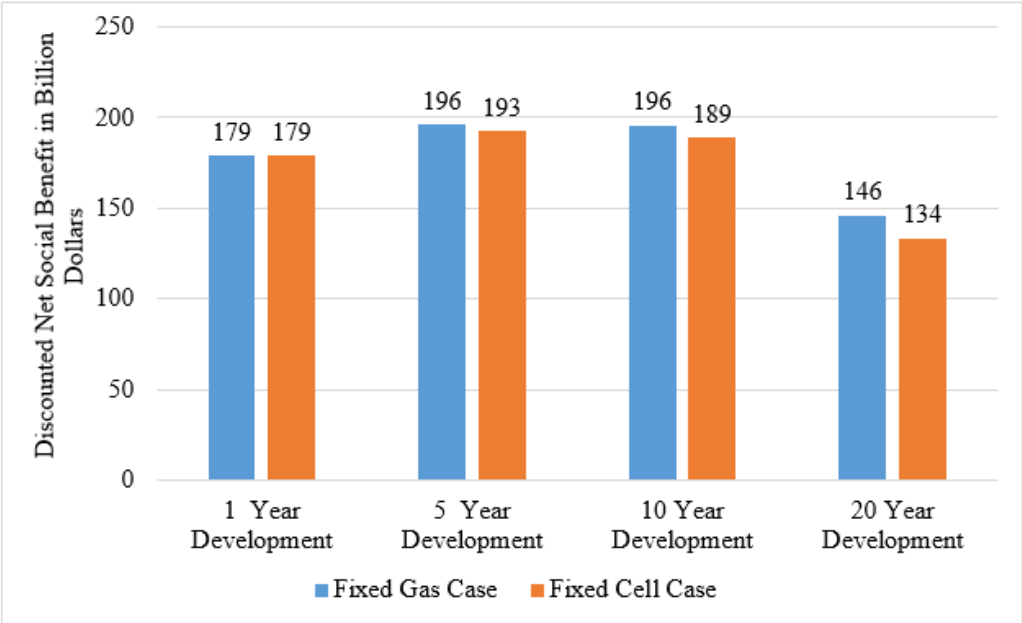


Figure 4-19:Total Net Social Benefit

Figure 4-20 shows how a change in mule deer population (change= Muledeer in year 1 – Mule deer in year 10) spread spatially. A series of similar maps can be created but this specific map shows a change in mule deer population from year 1 to year 10 for fixed gas case. The map shows how the Mule Deer are affected as developed area

increased from 26 cells (75 square miles) to 280 cells (812 square miles) while the number of wells per pad and pad density remain constant.

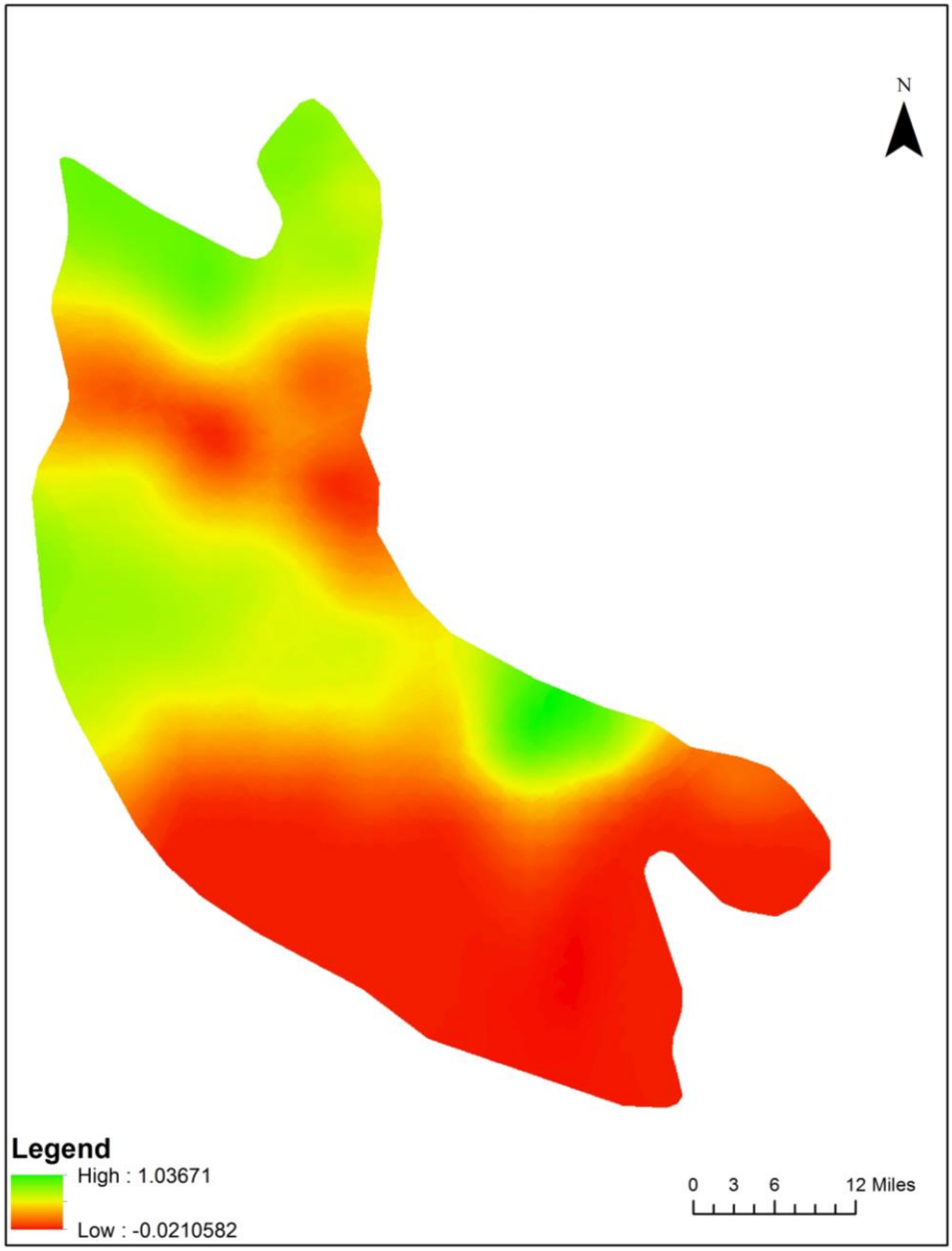


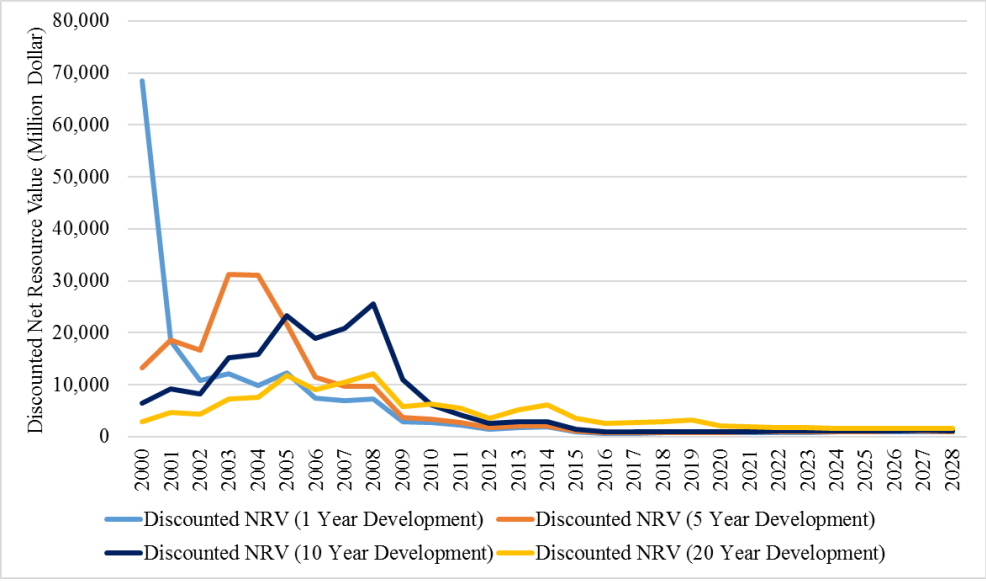
Figure 4-20:Change in Mule Deer Population from Year 1 to Year 10

In the map, a smaller change is represented by the red color and the color changes to green as an increase in mule deer in a cell becomes larger and larger. If the change in mule deer population in the map is compared with the cells developed (map in Appendix

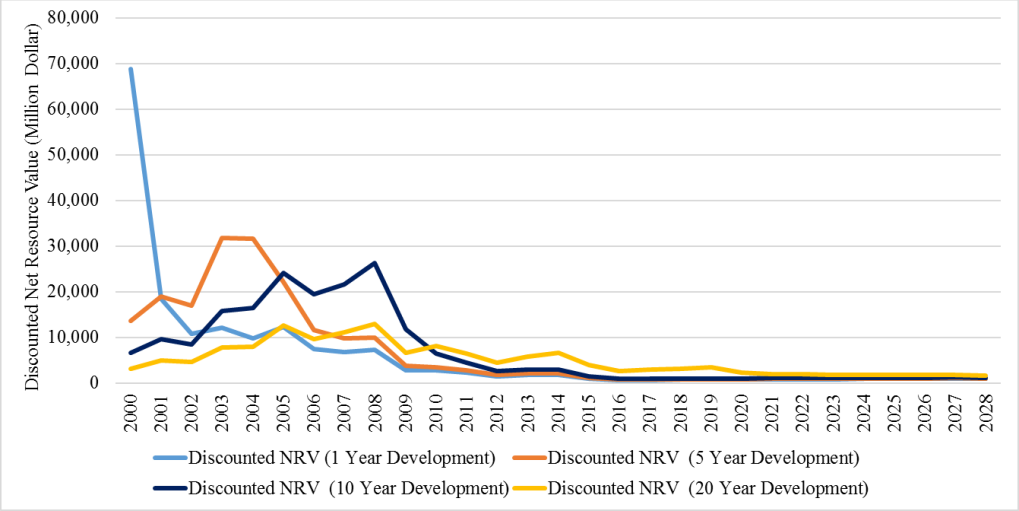
D) then it is seen that mule deer population decreases in the area where cells are developed and population over time increases in those cells where development never took place.

5.2 Impact of Uncertainty: Several uncertainties are associated with shale gas production. This study considers only price uncertainty. Geological uncertainty, as mentioned in Schiozer et al (2004), such as porosity, permeability etc. are assumed to be constant in this study. Price uncertainty affects net social benefit through revenue but does not affect social cost. Social cost in this study is affected by fish and mule deer population, which are affected by number of cells developed and geophysical characteristics of the cell. Figure 4-21 shows the impact of price uncertainty on net social benefit for both, fixed cell and fixed gas cases.

Figure 22: Discounted Net Social Benefit Under Price Uncertainty



A. Fixed Cell



B. Fixed Gas

Figure 4-21:Discounted Net Social Benefit Under Price Uncertainty

Trends and magnitude of discounted net social benefit, as seen in the Figure 22, are not very different in trend and magnitude of that under actual price (Figure 4-18). This may be due to small difference in price under two cases (uncertain and actual price as seen in Figure 4-10). Small difference in two prices may be due to the assumption on mean and variance while carrying out Monte Carlo Simulation. If actual magnitude of discounted net social benefit under two price scenarios are compared then it is larger in the price uncertainty case. Although this study does not develop any theory to support this finding of larger net social benefit in price uncertainty case, this result is in line with Abel (1983) which showed that greater price uncertainty increases the expected marginal uncertainty. Figure 23 shows the total discounted net social benefit for the entire simulation period for two price scenarios. The figure shows that the magnitude of the total discounted net social benefit is larger for uncertain price.

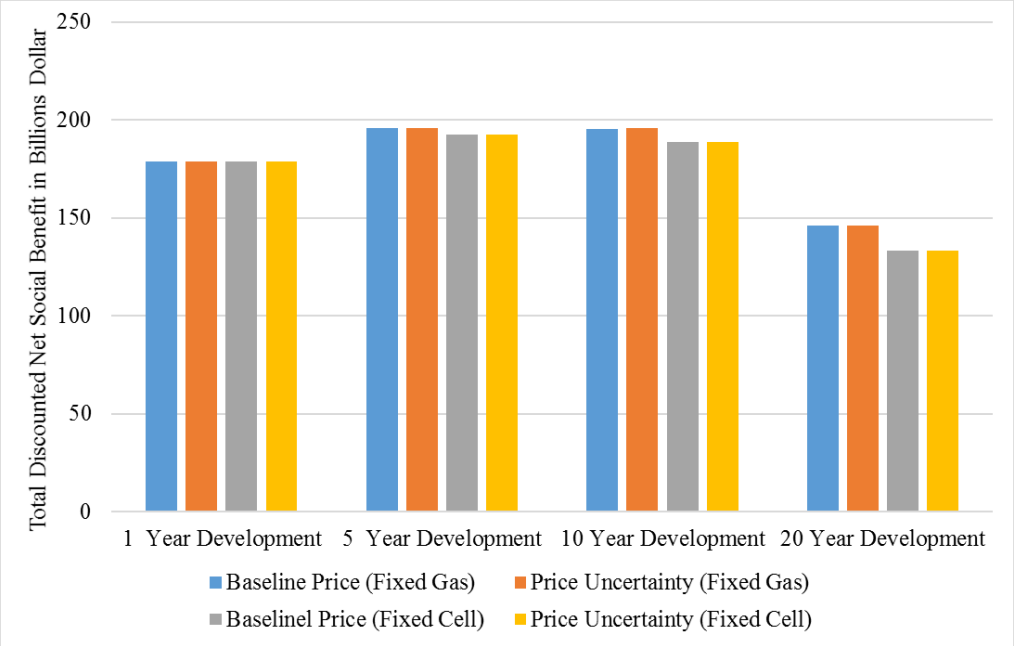


Figure 4-22:Total Discounted Net Social Benefit Under Two Price Scenarios

5. Conclusion

Hydrocarbon development dominated by hydraulic fracturing in the USA is predicted to be increasing in the future resulting in significant land use change. A change in land use results in, among other things, disturbance to an ecological system through land fragmentation and altered form and function of spatial pattern. The disturbed ecological system manifests itself as a. reduction in the mule deer population and creates a social cost. The objective of this study was to develop a method to analyze such an impact by developing a spatiotemporal system dynamics model. This study is in the form of a proof of concept in which results are not representative of actual government decisions. Results are descriptive instead of prospective.

This study has the potential to provide inputs for developing a balanced land management strategy to many stakeholders. Federal land management is the responsibility of the US Department of Interior Bureau of Land Management (BLM). A

BLM resource manager has control over a landscape that contains a wide range of natural resources in a geographic region. Land use plans and planning decisions are the basis for every on-the-ground action the BLM undertakes. Land use plans include both resource management plans (RMPs) and management framework plans (MFPs). Land use plans ensure that the public lands are managed in accordance with the intent of Congress as stated in FLPMA (43 U.S.C. 1701 et seq.), under the principles of multiple use and sustained yield. As required by FLPMA and BLM policy, the public lands must be managed in a manner that protects the quality of scientific, scenic, historical, ecological, environmental, air and atmospheric, water resource, and archaeological values; that, where appropriate, will preserve and protect certain public lands in their natural condition; that will provide food and habitat for fish and wildlife and domestic animals; that will provide for outdoor recreation and human occupancy and use; and that recognizes the Nation's need for domestic sources of minerals, food, timber, and fiber from the public lands by encouraging collaboration and public participation throughout the planning process. Land use plans are one of the primary mechanisms for guiding BLM activities to achieve the mission and goals outlined in the Department of the Interior (DOI) Strategic Plan (BLM 2005).

This study found that production of natural gas cannot be considered in isolation because it has social cost. If social cost is considered then for a given area of land, it is more beneficial to develop the land in longer period (5-10 years) than in shorter period (1-2 years). Very long period can also be detrimental due to the discounting factor. Furthermore, price uncertainty plays an important role to determine revenue and net social benefit. Price uncertainty increases net social benefit through increased revenue.

Although not considered in this study, increased revenue may induce producers to develop more land leading to an increase in social cost. Finally, calculation of net social benefit for each grid cell in this study enables the resource manager to rank different cells of an area in terms of the net social benefit. This feature of the model can help a resource manager to decide to lease the land.

This paper developed a theoretical model to find an analytical solution to the problem. However, the problem with this analytical approach is that it is difficult to solve and find an exact solution. This was evident in the theoretical model. The simulation method on the other hand is able to produce various outcomes that can be compared with each other easily and can be chosen as per the objectives of different policies. The major benefit of the current approach (simulation approach) is that different policies can be tested and the outcome can be visualized using different media. This is not the case of an analytical solution.

Finally, Simultaneous use of ArcGIS, Powersim, and EXCEL software enabled the development and implementation of spatiotemporal system dynamics model. However, the limitation of the software was a major obstacle for making the result more representative and realistic. This study can be expanded and developed to make it a decision support tool by developing a software that features both simulation and spatial analysis software.

Chapter 5 : Conclusion- Evaluating the Spatial Externality of Natural Resource Use

Although temporal aspects of natural resource use have long been recognized, spatial aspects are a recent phenomenon. There is growing concern recently over spatial externality of resource management decision-making. Failure to internalize spatial externality produces an inefficient outcome. Furthermore, the issue of spatial externality is complicated due to the intrinsic links between economic, environmental, and ecological systems. A better evaluation of spatial externalities thus calls for theoretical and empirical models that consider interactions of these systems (Wang and Nijkamp 2005). Chapter 1 introduces spatial externality with various examples and argues that natural resource use produces spatial externality that needs to be internalized through various policy measures. It is necessary to consider interactions between various systems before designing such policies. Throughout the preceding chapters, several types of spatial externalities associated with different types of resource use have been examined to show the consequences of such externalities, followed by policy prescription.

Water resources have strategic importance in semi-arid regions like the American West. Climate change and droughts are looming threats for sustainable use of such precious resources. Past records show that droughts are responsible for huge costs in the U.S. economy, mainly through water resources. The second chapter explores the impact of drought of different lengths and times on surface and groundwater resources. The result suggests that later and longer drought are costlier in terms of reduced quantity of water resources compared with earlier and shorter drought. Increasing prices, raising awareness, and controlling population levels were found to be appropriate policy

measures to minimize drought impact. These findings imply that water resource managers need to focus on awareness programs to combat drought and promote sustainable use of water resources.

An important finding of chapter 2 is that the policy options to curb drought's impact have a spatial impact. If awareness programs motivate people to consume less water and less groundwater is pumped in one city, then the aquifer volume underneath other cities increases. The increased aquifer volume in the downstream city means reduced pumping costs for that city. Oppositely, increased population in an upstream city creates a negative externality (i.e., groundwater volume in the downstream city decreases, resulting in increased pumping costs).

These spatial externalities have policy implications. For example, funding for environmental conservation programs is always a big issue. In this context, if a city implements an awareness program for conserving water, then another city can be made liable for contributing to the program based on the saved pumping cost. Similarly, if the population of a city increases, then some water tax can be charged to compensate for the increased pumping cost of another city. Such compensatory money can be earmarked for water conservation programs.

The above findings of spatial impact are directly related with the city of Albuquerque, Rio Rancho, and Santa Fe. While Rio Rancho is relying solely on groundwater, Albuquerque aims to save groundwater for extreme events such as drought in future and plans to meet the water demand using surface water as far as possible. In the future, it is quite possible that the Rio Rancho population may grow rapidly such that the city pumps more groundwater reducing the water level for Albuquerque. Although, New

Mexico is a prior appropriation state and the Albuquerque may go into the litigation process, it can be a win-win situation for two cities to coordinate for mutual benefit. An examination of if Albuquerque Bernalillo County Water Utility Authority should be merged with Rio Rancho for mutual benefit can be a good future research work.

Wildfire risk in the United States is increasing for several reasons, including climate change. The direct and indirect costs of wildfire have become a serious concern for stakeholders. One of the cost-generating impacts of wildfire is that it disturbs watershed and water quality conditions. Reducing the risk of high-severity wildfires through forest restoration is thus an important measure for the sustainability of watersheds and securing safe drinking water. However, generating funds to cover the costs of forest restoration is an important issue.

Wildfire impact is spatial in nature. Post-wildfire rain produces ash and debris that flows into surrounding canyons that drain to the river supplying water for people living far from the forest area. Chapter 3 examines whether water users residing in a distant municipal area are willing to pay for forest restoration activities. Using a double hurdle model and survey-based contingent valuation data, this chapter finds that people who receive the benefit of the restoration of the watershed that impacts their water supply but who are spatially removed from the forest area are willing to pay for the restoration activities.

Willingness to pay is determined by several factors. Rich people are willing to pay more. People who think that the water supply and forest fires are serious problems are willing to pay more for forest restoration activities. Oppositely, people who think water rates are a serious problem are willing to pay less. In addition, people who are

relatively more certain about their preference and the outcome of forest restoration programs are willing to pay more than those who are uncertain. This means that policy makers need to focus on awareness-increasing activities to incentivize people to support forest restoration activities.

Chapter 4 examines another area of spatial impact of natural resource use. Hydrocarbon development is considered to be one of the most important factors for changing land use patterns. A change in land use and land cover substantially affects ecological resources via a change in form and function of landscape interaction. This chapter uses a spatiotemporal system dynamics model to demonstrate that shale gas production in the Unita Piceance Basin in Colorado affects the population of mule deer and fish via habitat destruction and water quality deterioration. Degradation of ecological resources is a social cost because people put different values on these resources. This shows that the use of a natural resource in one place generates costs in another place – a spatial externality. This chapter also demonstrates that gas price uncertainty further increases the social cost of shale gas production.

Chapter 4 is in the form of proof of concept. The results reported should be considered only as descriptive but not prescriptive. The results show that leasing out a given area of land for hydrocarbon development for a short term or very long term is less beneficial than leasing the land for a medium term (i.e., 10 to 15 years). In the very short term, the social cost increases due to perpetual loss of ecological resources in the very beginning of the time horizon. In the very long term lease, net social benefit decreases due to the reduced present value of money. Finally, this chapter provides a method of

analyzing the impact of hydrocarbon development on net social benefit for resource manager and stakeholders.

Appendices

Appenidx A: Supplementary Tables for Chapter 2

Table A1: Description of Variables Used to Estimate Demand Equation

Variable	Categories	Description	Mean Water Use	No. of observation
Risk	Risk Averse	1 if risk averse, 0 otherwise	12.33*	901
	Risk Lover	1 if risk lover, 0 otherwise	11.79	242
	Risk Idiosyncratic	1 if risk idiosyncratic, 0 otherwise	13.07*	352
Experiment	Experiment 2	1 if experiment no.2, 0 otherwise	9.27*	286
	Experiment 3	1 if experiment no.3, 0 otherwise	16.35*	187
	Experiment 4	1 if experiment no.4, 0 otherwise	13.77*	132
	Experiment 5	1 if experiment no.5, 0 otherwise	8.71*	132
	Experiment 6	1 if experiment no.6, 0 otherwise	13.27*	352
	Experiment 7	1 if experiment no.7, 0 otherwise	12.32	121
	Experiment 8	1 if experiment no.8, 0 otherwise	8.6*	231
	Experiment 9	1 if experiment no.9, 0 otherwise	11.93	256
Home ownership	Own Home	1 if owns home, 0 otherwise	12.15*	1815
xeriscape	Xeriscaping	1 if has xeriscaping, 0 otherwise	10.88*	1584
Location in Albuquerque	North West	1 if lives in North West of Albuquerque, 0 otherwise	12.53*	550
	North East	1 if lives in North East of Albuquerque, 0 otherwise	11.48*	804
	South West	1 if lives in South West of Albuquerque, 0 otherwise	11.36	285
Gender	Male	1 if male, 0 otherwise	13.41*	704
	Female	1 if female, 0 otherwise	11.22	1199
Native New Mexican	Native NM	1 if native NM, 0 otherwise	11.91	660
Political Belief	Republican	1 if republican, 0 otherwise	12.92*	539
	Independent	1 if independent, 0 otherwise	11.43	275
	No PB reported	1 if political belief is not reported, 0 otherwise	8.4*	110
	Other Politics	1 if has other political belief, 0 otherwise	8.84*	110
Race	White	1 if white, 0 otherwise	12.16*	1320
	Latino	1 if Latino, 0 otherwise	11.31	418

Table A1(Continued)

Variable	Categories	Description	Mean Water Use	Numbers of observation
Religious Belief	Atheist	1 if atheist, 0 otherwise	10*	484
	Catholic	1 if catholic, 0 otherwise	13.05*	253
	Protestant	1 if protestant, 0 otherwise	13.15*	330
	Don't Report Church	1 if don't report church, 0 otherwise	11.2	165
	Other Church	1 of other church, 0 otherwise	10.74*	209
Education	Technical and Associate	1 if technical and associate degree, 0 otherwise	12.84	187
	Bachelor and Master	1 if bachelor or master's degree, 0 otherwise	12.58*	1287
	Doctors and Professional	1 if doctorate and professional degree, 0 otherwise	9.63*	110
Expectation about Albuquerque	ABQ Good for 20 Years	1 if the respondent think that there will be no water problem in the Albuquerque for next 20 years, 0 otherwise	14.38*	418
Water Problem	ABQ will Experience Problem Soon	1 if the respondent think that Albuquerque will experience water problem soon, 0 otherwise	11.07*	726
	ABQ has Problem Now	1 if the respondent think that the Albuquerque has water problem now, 0 otherwise	10.97*	616
Outdoor Use Variables	Outdoor Change	1 if outdoor water use has changed, 0 otherwise	13.2*	664
	Outdoor Use	1 if the respondent use water for outdoor	13.23*	1605
Indoor Use Variables	Indoor Change	1 if indoor water use has changed, 0 otherwise	12.02	922
	Low Flow Indoor Use	1 if the responded uses low flow devices, 0 otherwise.	11.34*	1690

* Significantly different from zero

Table A2: Demographic Characteristics by Age Cohort, Albuquerque

Age Cohorts	Initial Population	Fertility Rate (*per thousand)*	Mortality Rate (*per 100000)*	Migration
0-4	30214	0	157.6	0.052
5-9	31567	0	14.5	0.065
10-14	37899	1.4	19	0.065
15-19	40288	64.2	74.4	0.065
20-24	37600	118.7	120.7	0.12
25-29	34100	120.0	123.2	0.153
30-34	26142	85.6	153.4	0.086
35-39	20907	39.2	192.6	0.066
40-44	19478	7.9	266.3	0.059
45-49	19490	0.5	373.9	0.07
50-54	19088	0	487.8	0.055
55-59	15947	0	699	0.045
60-64	12704	0	1026.5	0.018
65-69	10139	0	1457	0.021
70-74	6906	0	2129.2	0.02
75-79	4667	0	3466.4	0.014
80-84	2795	0	5751.8	0.013
85plus	1787	0	100000	0.013

Table A3: Demographic Characteristics by Age Cohort, Rio Rancho

Age Cohorts	Initial Population	Fertility Rate (*per thousand)*	Mortality Rate (*per 100000)*	Migration
0-4	2,703	0	123.4	0.080
5-9	2,697	0	11.5	0.067
10-14	3,109	0.6	14.8	0.067
15-19	2,878	109.2	72.2	0.067
20-24	2,136	136.7	132.7	0.079
25-29	1,974	126.7	130.8	0.137
30-34	1,696	81.2	123.4	0.098
35-39	1,381	35	140.8	0.092
40-44	1,339	8.1	221.9	0.055
45-49	1,157	0.5	299	0.059
50-54	1,277	0	422.6	0.051
55-59	1,072	0	586.8	0.038
60-64	1,186	0	859	0.041
65-69	921	0	1,237.10	0.026
70-74	596	0	2,124	0.016
75-79	348	0	3,545.20	0.008
80-84	212	0	6,636.60	0.008
85plus	127	0	12,938.40	0.008

Table A4: Demographic Characteristics by Age Cohort, Santa Fe

Age Cohorts	Initial Population	Fertility Rate (*per thousand)*	Mortality Rate (*per 100000)*	Migration
0-4	5356	0	73.2	0.053
5-9	5886	0	24.1	0.044
10-14	7274	0.2	23.3	0.044
15-19	6617	48.7	154.6	0.044
20-24	5561	47.1	119.9	0.149
25-29	5688	48.6	124.1	0.131
30-34	4836	35.2	139.5	0.092
35-39	4224	22.4	233.3	0.070
40-44	3528	8.3	273.8	0.084
45-49	3367	0.1	342.7	0.078
50-54	3143	0.1	346.6	0.054
55-59	2602	0	486.9	0.038
60-64	2342	0	561.4	0.053
65-69	2066	0	751.2	0.031
70-74	1476	0	1,345.10	0.010
75-79	931	0	2,491.30	0.009
80-84	640	0	4,509.50	0.009
85plus	396	0	13,317.50	0.009

Table A5: Value of Proportion of Labor Force Entering and Exiting the Cities.

	$\zeta_{i(entering)}$	$\zeta_{i(exiting)}$
Albuquerque	0.047	0.1339
Rio Rancho	$If\ year < 1985, \zeta_{i(entering)} = 0.73$ $1986-1995, \zeta_{i(entering)} = 0.75$ $1996-2000, \zeta_{i(entering)} = 0.73$ $2001-2005, \zeta_{i(entering)} = 0.69$ $2006-2007, \zeta_{i(entering)} = 0.68$ $2008-2010, \zeta_{i(entering)} = 0.56$ $\text{Year} > 2010, \zeta_{i(entering)} = 0.64$	$If\ year < 1985, \zeta_{i(entering)} = 0.51$ $1986-1995, \zeta_{i(entering)} = 0.54$ $1996-2000, \zeta_{i(entering)} = 0.56$ $2001-2005, \zeta_{i(entering)} = 0.56$ $2006-2007, \zeta_{i(entering)} = 0.46$ $2008-2010, \zeta_{i(entering)} = 0.51$ $\text{Year} > 2010, \zeta_{i(entering)} = 0.59$
Santa Fe	$If\ year < 2001, \zeta_{i(entering)} = 0.21$ $If\ year \geq 2001, \zeta_{i(entering)} = 0.206$	$If\ year < 2001, \zeta_{i(entering)} = 0.203$ $If\ year \geq 2001, \zeta_{i(entering)} = 0.209$

Table A6: Albuquerque Water Rate*

Service Size	Meter Size	Residential	Commercial	Industrial	Institutional	Multifamily
1	$\frac{5}{8}\times\frac{3}{4}$	$9.77	$10.23	$19.17	$10.53	$12.00
2	1	20.17	20.6	40.21	20.97	24.52
3	1.5	56.47	58.68	120.02	61.27	71.82
4	2	121.05	125.46	261.82	131.42	155.25
5	3	231.69	240.78	496.7	251.55	295.79
6	4	523.28	541.71	1140.54	568.36	673.57
7	6	887.7	899.33	1846.13	938.54	1101.35
8	8 and over	1859.16	1928.45	4026.25	2190.91	2385.26

Source: ABCWUA Water Rate Ordinance, Available at: https://www.abcwua.org/uploads/files/waterrate.pdf

* Table shows monthly fixed charge. Beside the monthly fixed charge, a customer has to pay following charges:

- Commodity charge: $2.018 per unit (1 unit = 748 gallons or 100 cubic feet) of water used
- State surcharge: $ 0.024 per unit of water
- Water credit: Customers who are enrolled in water credit program receive a credit of $10.31 per month.
- Franchise fee: Charge of 4% on the total sales of water and sewer services.
- Electric fuel cost adjustment: If the quarterly analysis of power cost related to water pumping shows that costs are increasing or decreasing, the executive director is authorized to adjust the water commodity charge. An adjustment in the commodity charge will only be made if the needed commodity charge adjustment is $0.01 or greater and shall be in $0.01 increments.

Table A7: Rio Rancho and Santa Fe Water Rate

Rio Rancho		**Santa Fe**		
Fixed Charge	**Volume Charge**	**Meter Size**	**Fixed Charge**	**Volume Charge**
For 5/8" meter $11.53 For 1" meter $13.17	***A. Single Family*** 1-6000 gallons: $5.32/1,000 gallons 7000-10000 gallons:$5.76/1,000 gallons Over 10000 Gallons:$6.21/1,000 gallons Multi Family ***B. Multi Family*** $5.42/1000 gallons ***C. Commercial*** $5.64/1000 gallons ***C. City*** $5.91/1000 gallons	$\frac{5}{8}\times\frac{3}{4}$	$18.42	**<u>For all sizes</u>** **September-April**: 06.06/1,000 gallons for first 7,000 gallons 21.72/1,000 gallons thereafter **May-August**: $06.06/1,000 gallons for first 10,000 gallons $21.72/1,000 gallons thereafter
		1	$36.83	
		1.5	$73.67	
		2	$147.36	
		3	$294.70	
		4	$534.14	
		6	$1,178.78	
		8 and over	$2,099.72	

Source: For Santa Fe: http://www.santafenm.gov/document_center/document/3869

For Rio Rancho: http://www.ci.rio-rancho.nm.us/DocumentCenter/View/66841

Table A8: Growth Rate of Industrial and Commercial Sector

Year	Growth Rate		
	Albuquerque	Santa Fe	Rio Rancho
Up to 1990	0.0166	0.01	0.0072
1991-1995	0.034	0.009	0.029
1996-2000	0.014	0.009	0.064
2001-2005	0.0065	0.009	0.087
2006-2010	-0.0065	0.009	0.022
After 2010	0.014	0.009	0.017

Table A9: NAICS Sectors and Water Use in Gallons Per Employee Per Day

Industrial and Commercial Sectors	Gallons/Employee/Day
Ag & forestry & fishing & hunting	115
Mining	0
Utilities	0
Construction	70
Manufacturing	88
Wholesale trade	42
Transportation & warehousing	50
Retail trade	110
Information	100
Finance & insurance	150
Real estate	100
Professional & technical services	100
Management of companies	100
Administration & waste services	55
Education	100
Health & social services	124
Arts & entertainment & recreational services	100
Accommodations and food services	250
Other services	500
Government & public administration & non-NAICS	136

Source: Gleick et al. (2003)

Table A 10 : Variables and Source of their Values Calibration, Validation, and Scenario Evaluation Period

Variable	Symbol	Data and Modeling Technique During		
		Calibration	**Validation**	**Scenario Evaluation**
Mainstream inflow	$Q^{j}_{m\sin}$	Historic data	Historic data	Inflows from upstream reach
Open water evaporation losses	Q^{j}_{evap}	Equation (2.10c)	Equation (2.19c)	Equation (2.19c)
Groundwater exchange	Q^{j}_{gwsw}	Equation 2.19	Equation 2.28	Equation 2.28
Surface water	Q^{j}_{sw}	Historic data	Historic data	User input
Crop ET	Q^{j}_{cropET}	Equation 2.10b	Equation 2.19b	Equation 2.19b
Gaged surface water inflow	$Q^{j}_{swgaged}$	Historic data	Historic data	Reshuffle of historic data
Ungagged surface water inflow	$Q^{j}_{swungaged}$	Adjusted to satisfy equation	Adjusted to satisfy equation 2.11	Adjusted to satisfy equation
Flow from the conveyance	$Q^{j}_{swdiversion}$	Historic diversion data	Agricultural demand and historic diversion	Similar to validation period
Surface water flows out of the conveyance system	Q^{j}_{convtf}	Historic flow data	Partitioned based on reach specific historic	Similar to validation period
Surface water flows into the conveyance system	Q^{i}_{convtf}	Historic flow data	Partitioned based on reach specific historic	Similar to validation period
Surface water flows out of the conveyance system to	$Q^{i}_{swreturn}$	Residual in equation 2.11	Residual in equation 2.11	Residual in equation 2.11
gaged and ungagged surface water inflows in	Q^{r}_{sw}	Historic data	Historic data	User input
Precipitation falling on the reservoir	Q^{r}_{precip}	Equation 2.21	Equation 2.21	Equation 2.21
Groundwater leakage from the reservoir	Q^{r}_{gw}	Equation 2.28. Reservoir bed thickness and conductivity was adjusted to achieve MODFLOW outcome in calibration period		
Evaporation from the reservoir	Q^{r}_{evap}	Equation 2.19a	Equation 2.19a	Equation 2.19a
Reservoir release	$Q^{r}_{release}$	Historic data	Reservoir operation rule	Reservoir operation rule
Reservoir evaporation rate	$E^{r,m}$	Equation 2.15	Equation 2.15	Equation 2.15
Average daily maximum temperature	$T^{r,m}_{\max}$	Historical data	Historical data	User input
Average daily minimum temperature	$T^{r,m}_{\min}$	Historical data	Historical data	User input
Coefficient of Proportionality	$k^{r,m}$			

Table A10 (continued)

Variable	Symbol	Data and Modeling Technique During		Scenario Evaluation
		Calibration	Validation	
Pan Evaporation	$E_{pan}^{r,m}$	Historic data	Historic data	User input
Reference ET rate	ET_{ref}	Equation 2.16	Equation 2.16	Equation 2.16
Vapor pressure/ temperature gradient	Δ	$33.8639\left[0.05904\left(0.00738T_{avrg}+0.8072\right)^{7}-0.0000342\right]$		
Mean Temperature	T_{avrg}	$\frac{T_{\max}+T_{\min}}{2}$		
Psychrometric constant	γ	$\frac{c_p P}{\varepsilon LHV}$		
Specific heat	c_p	0.242	0.242	0.242
Atmospheric Pressure	P	$1013-0.1055z$		
Weather station elevation	z	ArcGIS map	ArcGIS map	ArcGIS map
ratio molecular weight of water vapor	ε	0.622	0.622	0.622
Net solar radiation	SR	Historic data	Historic data	User input
Wind speed function	U	$15.36\left(1+0.0062U2m\right)$		
Wind speed	$U2m$	Historic data	Historic data	User input
Vapor pressure deficit	D	$e_{sat}-e_{act}$		
Saturated vapor pressure at mean temperature	e_{sat}	$\frac{e_{t\max}+e_{t\min}}{2}$		
Saturated vapor pressure at T_{max}	$e_{t\max}$	$0.611\exp\left[\frac{17.27T_{\max}}{T_{\max}+273}\right]$		
Saturated vapor pressure at T_{min}	$e_{t\min}$	$0.611\exp\left[\frac{17.27T_{\min}}{T_{\min}+273}\right]$		
Actual vapor pressure at mean temperature	e_{act}	$\left(e_{t\max}RH_{\min}+e_{t\min}RH_{\max}\right)/2$		
Maximum relative humidity	$RH_{\max}$	Historical data	Historic data	User input
Minimum relative humidity	$RH_{\min}$	Historical data	Historic data	User input
Latent heat of vaporization for water	LHV	$595-0.51T_{avrg}$		
Water density	ρ_w	1		
Growing degrees in month m for plant	$GD^{m,p}$	Equation 2.17		

Table A10 (continued)

Variable	Symbol	Data and Modeling Technique During		
		Calibration	**Validation**	**Scenario**
Average maximum monthly temperature	$T_{\max}^{m,p}$	Historical data	Historical data	User input
Average minimum monthly temperature	$T_{\min}^{m,p}$	Historical data	Historical data	User input
Base temperature parameter for plant	$T_{base}^{m,p}$	5, 7, 10, 15.5 [for detail see Roach and Tidwell (2006a), pp 41]		
Implied open water coefficient associated	$C_{ow}^{r,m}$	Equation 2.18	Equation 2.18	Equation 2.18
Pan evaporation measured at reservoir	$E_{pan}^{r,m}$	Historical data	Historical data	User input
Reference ET in reach *j* immediately	$ET_{ref}^{j,m}$	Equation 2.16	Equation 2.16	Equation 2.16
Riparian ET in reach *j* for groundwater	Q_{ripET}^{j}	Equation 2.19d	Equation 2.19d	Equation 2.19d
ET coefficient in reach *j* during month	$C^{j,m,c}$	Relationship between GDD and plant ET as explained in Brower (2004)		
Open water evaporation	C_{ow}^{m}	Equation 2.18		
surface area of reservoir *r* during	$A^{r,m}$	Elevation Area Capacity relationship	Elevation Area Capacity relationship	Elevation Area
crop area in reach *j* during month *m* for	$A^{j,m,c}$	Historical data from 1975-1999	1999 crop acreage area for validation.	User input
open water area in reach *j* during month	$A^{j,m,w}$	$\left[\left(\alpha Q^{\delta} \times slope\right) + w_b\right] L_R$	open water area in reach *j* during month	$A^{j,m,w}$
Open water area parameter	α, δ	See Table 2.10 in Roach and Tidwell (2006a) for the	Open water area parameter	α, δ
Fitted bank slope parameter	*slope*	See Table 2.10 in Roach and Tidwell (2006a) for the	Fitted bank slope parameter	*slope*
Fitted base width parameter	w_b	See Table 2.10 in Roach and Tidwell (2006a) for the	Fitted base width parameter	w_b
Reach length	L_R	See Table 2.4 in Roach and Tidwell (2006a) for the	Reach length	L_R
Flow rate	Q	Average monthly flow rate equal to $Q_{m\sin}^{j}$	Flow rate	Q
riparian vegetation area in reach *j* during	$A^{j,m,r}$	Historic data	riparian vegetation area in reach *j* during	$A^{j,m,r}$
percent of reservoir r covered by ice during	$\mathrm{cov}^{r,m}$	Historic data	percent of reservoir r covered by ice during	$\mathrm{cov}^{r,m}$
precipitation rate measured at reservoir	$P^{r,m}$	Historic data	precipitation rate measured at reservoir	$P^{r,m}$
Flow matrix	$\mathbf{Q_{ij}^{t}}$	Equation 1.24	Equation 1.24	Equation 1.24
Compartment head	h_i^t	Initial head from MODFLOW and then Equation 1.27 $h_i = zbot_i + \frac{S_i}{F_i sy_i}$		

Table A10 (continued)

		Data and Modeling Technique During		
Variable	**Symbol**	**Calibration**	**Validation**	**Scenario**
Symmetric conductance (or	α_{ij}	Equation 1.26	Equation 1.26	Equation 1.26
Storage vector	S_i^t	Equation 1.27	Equation 1.27	Equation 1.27
Bottom elevation	$zbot$	MODFLOW	MODFLOW	MODFLOW
horizontal area of compartment	F	Sum of MODFLOW cell times 1 km^2	Sum of MODFLOW cell times 1 km^2	Sum of MODFLOW cell times 1 km^2
Specific yield of unconfined	sy	0.2	0.2	Consistent with McAda and Barroll
Surface water elevation	z_{sw}	Iterative solution of Manning equation	Iterative solution of Manning equation	Equation 1.30 Equation 1.29
Thickness of the flow limiting bed	b_{bed}	5 feet	5 feet	Consistent with McAda and Barroll
Hydraulic conductivity of the	K_{bed}	0.5 feet/day	0.5 feet/day	Consistent with McAda and Barroll
Horizontal area of the river channel	F_{bed}	Sum of MODFLOW cell times 1 km^2	Sum of MODFLOW cell times 1 km^2	Sum of MODFLOW cell km^2
Elevation of the top of the bed sediments	z_{bed}	Adjusted to calibrate river leakages from	Calibrated value (5 ft)	Calibrated value (5 ft)
Groundwater flow to the agricultural	Q_{DUP}	Equation 1.29	Equation 1.29	Equation 1.29
Hydraulic conductivity of the	K_{i-a}	Adjusted to calibrate flow to the drains	Calibrated value (5 ft/day)	Calibrated value (5 ft/day)
Length of drain	L_i			
Characteristic distance beyond	x_i	Adjusted to calibrate flow to the drains	Calibrated value (varies between 0.0005 mile to 1.7 mile for shallow aquifer zone	
Discharge in liters per second	Q_{MAN}	Equation 1.30	Equation 1.30	Equation 1.30
Drain slope	S	Assumed to be equal to river slope		
Manning coefficient of roughness	n	0.028	0.028	0.028
Cross-sectional area of flow	A	Equation 1.31	Equation 1.31	Equation 1.31
Hydraulic radius	R	Equation 1.32	Equation 1.32	Equation 1.32

Table A10 (continued)

		Data and Modeling Technique During		
Variable	**Symbol**	**Calibration**	**Validation and Scenario Evaluation**	**Data Source**
Cross-sectional area of flow	A	Equation 1.31	Equation 1.31	Equation 1.31
Hydraulic radius	R	Equation 1.32	Equation 1.32	Equation 1.32
Volume of water lost through ET from compartment i	Q_{i-ET}	Equation 1.33	Equation 1.33	Equation 1.33
Average vegetation area using groundwater	F_{i-ET}			
Surface elevation of shallow aquifer	z_{i-surf}	Calibrated to estimated ET fluxes from McAda and Barroll (2002). For calibrated values see Tidwell et al. (2006), Table A-5, pp.284		

Table A11: Initial Population (Population for 1975) Used in the Model

Age Cohort	Albuquerque	Santa Fe	Rio Rancho
0-4	24,171	3,669	784
5-9	25,254	4,032	782
10-14	30,319	4,983	902
15-19	32,230	4,533	835
20-24	30,080	3,809	619
25-29	27,280	3,896	572
30-34	20,914	3,313	492
35-39	16,726	2,893	400
40-44	15,582	2,417	388
45-49	15,592	2,306	336
50-54	15,270	2,153	370
55-59	12,758	1,782	311
60-64	10,163	1,604	344
65-69	8,111	1,415	267
70-74	5,525	1,011	173
75-79	3,734	638	101
80-84	2,236	438	61
85plus	1,430	271	37

Table A12: Net Saving of Water in Different Scenario

Scenario	Drought	Population	Awareness	Price	Aquifer Volume (AF)	Compact Balance (AF)	Water Consumption (GPCD)	Net Saving of Water (% of Aquifer Volume)
1	No Drought	Base Population	Constant Awareness	Base Price	1726875410	-704502.7056	154.373659	0.00(0.000)
2	No Drought	Base Population	Constant Awareness	Moderate Price Hike	1727538969	-688335.7758	115.4869649	679,725.74(0.039)
3	No Drought	Base Population	Constant Awareness	Aggressive Price Hike	1727969665	-755660.1922	91.1351061	1,043,098.01(0.06)
4	No Drought	Base Population	Increased Awareness	Base Price	1726963007	-731535.9521	149.9550601	60,563.83(0.003)
5	No Drought	Base Population	Increased Awareness	Moderate Price Hike	1727622931	-717748.4138	111.068366	734,275.35(0.042)
6	No Drought	Base Population	Increased Awareness	Aggressive Price Hike	1728015122	-781715.5096	86.71650723	1,062,499.90(0.061)
7	No Drought	Low Population	Constant Awareness	Base Price	1726871834	-706602.7333	152.8452069	-5,676.06(0)
8	No Drought	Low Population	Constant Awareness	Moderate Price Hike	1727536074	-689045.3533	114.3435296	676,121.89(0.039)
9	No Drought	Low Population	Constant Awareness	Aggressive Price Hike	1727967404	-755961.6731	90.23277832	1,040,535.31(0.06)
10	No Drought	Low Population	Increased Awareness	Base Price	1726959525	-733458.4596	148.4703565	55,159.44(0.003)
11	No Drought	Low Population	Increased Awareness	Moderate Price Hike	1727620083	-718548.4133	109.9686792	730,628.04(0.042)
12	No Drought	Low Population	Increased Awareness	Aggressive Price Hike	1728012903	-781711.1572	85.85792796	1,060,285.31(0.061)
13	No Drought	High Population	Constant Awareness	Base Price	1726857678	-707202.7248	147.0225323	-20,431.31(-0.001)
14	No Drought	High Population	Constant Awareness	Moderate Price Hike	1727524442	-691734.0202	109.9875856	661,800.87(0.038)
15	No Drought	High Population	Constant Awareness	Aggressive Price Hike	1727958465	-756461.9532	86.79533915	1,031,095.75(0.059)
16	No Drought	High Population	Increased Awareness	Base Price	1726945647	-733836.0052	142.8143429	40,904.01(0.002)
17	No Drought	High Population	Increased Awareness	Moderate Price Hike	1727608664	-719348.5388	105.7793962	718,408.39(0.041)
18	No Drought	High Population	Increased Awareness	Aggressive Price Hike	1728004416	-783113.1059	82.58714975	1,050,396.03(0.06)
19	Early Short Drought	Base Population	Constant Awareness	Base Price	1726797463	-609899.5837	154.373659	16,655.97(0)
20	Early Short Drought	Base Population	Constant Awareness	Moderate Price Hike	1727462159	-602435.9832	115.4869649	688,815.83(0.039)
21	Early Short Drought	Base Population	Constant Awareness	Aggressive Price Hike	1727880353	-672395.003	91.1351061	1,037,051.06(0.06)
22	Early Short Drought	Base Population	Increased Awareness	Base Price	1726885059	-650719.1711	149.9550601	63,433.14(0.003)

23	Early Short Drought	Base Population	Increased Awareness	Moderate Price Hike	1727542474	-646968.8066	111.068366	724,597.79(0.041)
24	Early Short Drought	Base Population	Increased Awareness	Aggressive Price Hike	1727929718	-709739.191	86.71650723	1,049,071.91(0.06)
25	Early Short Drought	Low Population	Constant Awareness	Base Price	1726793918	-608598.962	152.8452069	14,412.34(0)
26	Early Short Drought	Low Population	Constant Awareness	Moderate Price Hike	1727459287	-603334.2011	114.3435296	685,045.33(0.039)
27	Early Short Drought	Low Population	Constant Awareness	Aggressive Price Hike	1727878077	-672802.5032	90.23277832	1,034,367.87(0.059)
28	Early Short Drought	Low Population	Increased Awareness	Base Price	1726881543	-651417.2982	148.4703565	59,218.54(0.003)
29	Early Short Drought	Low Population	Increased Awareness	Moderate Price Hike	1727539629	-647269.291	109.9686792	721,452.37(0.041)
30	Early Short Drought	Low Population	Increased Awareness	Aggressive Price Hike	1727927504	-710592.2883	85.85792796	1,046,004.23(0.06)
31	Early Short Drought	High Population	Constant Awareness	Base Price	1726779972	-612612.3556	147.0225323	-3,547.66(0)
32	Early Short Drought	High Population	Constant Awareness	Moderate Price Hike	1727447564	-604256.5779	109.9875856	672,400.03(0.038)
33	Early Short Drought	High Population	Constant Awareness	Aggressive Price Hike	1727869080	-673817.3729	86.79533915	1,024,355.28(0.059)
34	Early Short Drought	High Population	Increased Awareness	Base Price	1726867551	-653295.074	142.8143429	43,349.41(0.002)
35	Early Short Drought	High Population	Increased Awareness	Moderate Price Hike	1727528317	-648647.2346	105.7793962	708,762.86(0.041)
36	Early Short Drought	High Population	Increased Awareness	Aggressive Price Hike	1727918727	-710471.1844	82.58714975	1,037,349.29(0.06)
37	Early Long Drought	Base Population	Constant Awareness	Base Price	1726663277	-826629.5065	154.373659	-334,1259.15(-0.019)
38	Early Long Drought	Base Population	Constant Awareness	Moderate Price Hike	1727330837	-826236.3466	115.4869649	333,694.07(0.019)
39	Early Long Drought	Base Population	Constant Awareness	Aggressive Price Hike	1727749971	-895139.3786	91.1351061	683,924.75(0.039)
40	Early Long Drought	Base Population	Increased Awareness	Base Price	1726750473	-877519.1882	149.9550601	-297,952.93(-0.017)
41	Early Long Drought	Base Population	Increased Awareness	Moderate Price Hike	1727411020	-871317.8787	111.068366	368,795.19(0.021)
42	Early Long Drought	Base Population	Increased Awareness	Aggressive Price Hike	1727797034	-935350.2319	86.71650723	690,777.00(0.039)
43	Early Long Drought	Low Population	Constant Awareness	Base Price	1726659756	-827429.5466	152.8452069	-338,580.63(-0.019)
44	Early Long Drought	Low Population	Constant Awareness	Moderate Price Hike	1727327941	-824236.3228	114.3435296	332,797.98(0.019)
45	Early Long Drought	Low Population	Constant Awareness	Aggressive Price Hike	1727747689	-895647.3155	90.23277832	681,134.68(0.039)
46	Early Long Drought	Low Population	Increased Awareness	Base Price	1726746952	-878319.3316	148.4703565	-302,273.84(-0.017)
47	Early Long Drought	Low Population	Increased Awareness	Moderate Price Hike	1727408153	-871817.7852	109.9686792	365,428.20(0.021)

48	Early Long Drought	Low Population	Increased Awareness	Aggressive Price Hike	1727794844	-933907.97	85.85792796	690,028.79(0.039)
49	Early Long Drought	High Population	Constant Awareness	Base Price	1726645468	-828342.8378	147.0225323	-353,782.33(-0.02)
50	Early Long Drought	High Population	Constant Awareness	Moderate Price Hike	1727316123	-825557.1926	109.9875856	319,658.61(0.018)
51	Early Long Drought	High Population	Constant Awareness	Aggressive Price Hike	1727738696	-898160.2032	86.79533915	669,628.94(0.038)
52	Early Long Drought	High Population	Increased Awareness	Base Price	1726733200	-876595.8329	142.8143429	-314,302.59(-0.018)
53	Early Long Drought	High Population	Increased Awareness	Moderate Price Hike	1727396731	-873294.6625	105.7793962	352,529.14(0.02)
54	Early Long Drought	High Population	Increased Awareness	Aggressive Price Hike	1727786037	-936381.826	82.58714975	678,748.37(0.039)
55	Late Short Drought	Base Population	Constant Awareness	Base Price	1726728279	-975190.0602	154.373659	-417,817.93(-0.024)
56	Late Short Drought	Base Population	Constant Awareness	Moderate Price Hike	1727391971	-967594.2618	115.4869649	253,469.99(0.014)
57	Late Short Drought	Base Population	Constant Awareness	Aggressive Price Hike	1727829407	-1048950.79	91.1351061	609,548.77(0.035)
58	Late Short Drought	Base Population	Increased Awareness	Base Price	1726815110	-1012290.756	149.9550601	-368,088.17(-0.021)
59	Late Short Drought	Base Population	Increased Awareness	Moderate Price Hike	1727473890	-1008197.691	111.068366	294,785.54(0.017)
60	Late Short Drought	Base Population	Increased Awareness	Aggressive Price Hike	1727876176	-1078376.58	86.71650723	626,892.22(0.036)
61	Late Short Drought	Low Population	Constant Awareness	Base Price	1726724753	-975690.0723	152.8452069	-421,844.57(-0.024)
62	Late Short Drought	Low Population	Constant Awareness	Moderate Price Hike	1727389002	-968094.2799	114.3435296	250,000.94(0.014)
63	Late Short Drought	Low Population	Constant Awareness	Aggressive Price Hike	1727827156	-1049750.653	90.23277832	606,498.09(0.035)
64	Late Short Drought	Low Population	Increased Awareness	Base Price	1726811659	-1012490.902	148.4703565	-371,739.02(-0.021)
65	Late Short Drought	Low Population	Increased Awareness	Moderate Price Hike	1727471117	-1010797.628	109.9686792	289,412.73(0.016)
66	Late Short Drought	Low Population	Increased Awareness	Aggressive Price Hike	1727873974	-1078386.555	85.85792796	624,680.76(0.036)
67	Late Short Drought	High Population	Constant Awareness	Base Price	1726710603	-976890.1073	147.0225323	-437,194.18(-0.025)
68	Late Short Drought	High Population	Constant Awareness	Moderate Price Hike	1727377572	-970290.5861	109.9875856	236,374.47(0.013)
69	Late Short Drought	High Population	Constant Awareness	Aggressive Price Hike	1727818109	-1050451.176	86.79533915	596,750.32(0.034)
70	Late Short Drought	High Population	Increased Awareness	Base Price	1726797833	-1014790.861	142.8143429	-387,864.89(-0.022)
71	Late Short Drought	High Population	Increased Awareness	Moderate Price Hike	1727459848	-1011097.631	105.7793962	277,843.43(0.016)
72	Late Short Drought	High Population	Increased Awareness	Aggressive Price Hike	1727865229	-1080377.881	82.58714975	613,943.71(0.035)

73	Late Long Drought	Base Population	Constant Awareness	Base Price	1726556900	-1351172.369	154.373659	-965,179.02(-0.055)
74	Late Long Drought	Base Population	Constant Awareness	Moderate Price Hike	1727226270	-1341173.435	115.4869649	-285,810.76(-0.016)
75	Late Long Drought	Base Population	Constant Awareness	Aggressive Price Hike	1727682198	-1419562.584	91.1351061	91,728.55(0.005)
76	Late Long Drought	Base Population	Increased Awareness	Base Price	1726643814	-1387972.729	149.9550601	-915,065.59(-0.052)
77	Late Long Drought	Base Population	Increased Awareness	Moderate Price Hike	1727308539	-1380074.135	111.068366	-242,442.57(-0.014)
78	Late Long Drought	Base Population	Increased Awareness	Aggressive Price Hike	1727749178	-1451233.706	86.71650723	127,037.24(0.007)
79	Late Long Drought	Low Population	Constant Awareness	Base Price	1726553362	-1351472.341	152.8452069	-969,017.49(-0.056)
80	Late Long Drought	Low Population	Constant Awareness	Moderate Price Hike	1727223341	-1341573.396	114.3435296	-289,139.33(-0.016)
81	Late Long Drought	Low Population	Constant Awareness	Aggressive Price Hike	1727679975	-1419462.578	90.23277832	89,605.53(0.005)
82	Late Long Drought	Low Population	Increased Awareness	Base Price	1726640345	-1388172.761	148.4703565	-918,734.94(-0.053)
83	Late Long Drought	Low Population	Increased Awareness	Moderate Price Hike	1727305649	-1380674.141	109.9686792	-245,931.93(-0.014)
84	Late Long Drought	Low Population	Increased Awareness	Aggressive Price Hike	1727746996	-1451731.95	85.85792796	124,356.72(0.007)
85	Late Long Drought	High Population	Constant Awareness	Base Price	1726539362	-1350672.345	147.0225323	-982,217.39(-0.056)
86	Late Long Drought	High Population	Constant Awareness	Moderate Price Hike	1727211931	-1342469.822	109.9875856	-301,445.50(-0.017)
87	Late Long Drought	High Population	Constant Awareness	Aggressive Price Hike	1727671095	-1420662.531	86.79533915	79,525.89(0.004)
88	Late Long Drought	High Population	Increased Awareness	Base Price	1726626427	-1390572.756	142.8143429	-935,052.47(-0.054)
89	Late Long Drought	High Population	Increased Awareness	Moderate Price Hike	1727294390	-1382774.119	105.7793962	-259,291.36(-0.015)
90	Late Long Drought	High Population	Increased Awareness	Aggressive Price Hike	1727738374	-1453934.525	82.58714975	113,532.94(0.006)

Appendix B: GIS Map to Show Spatial Impact

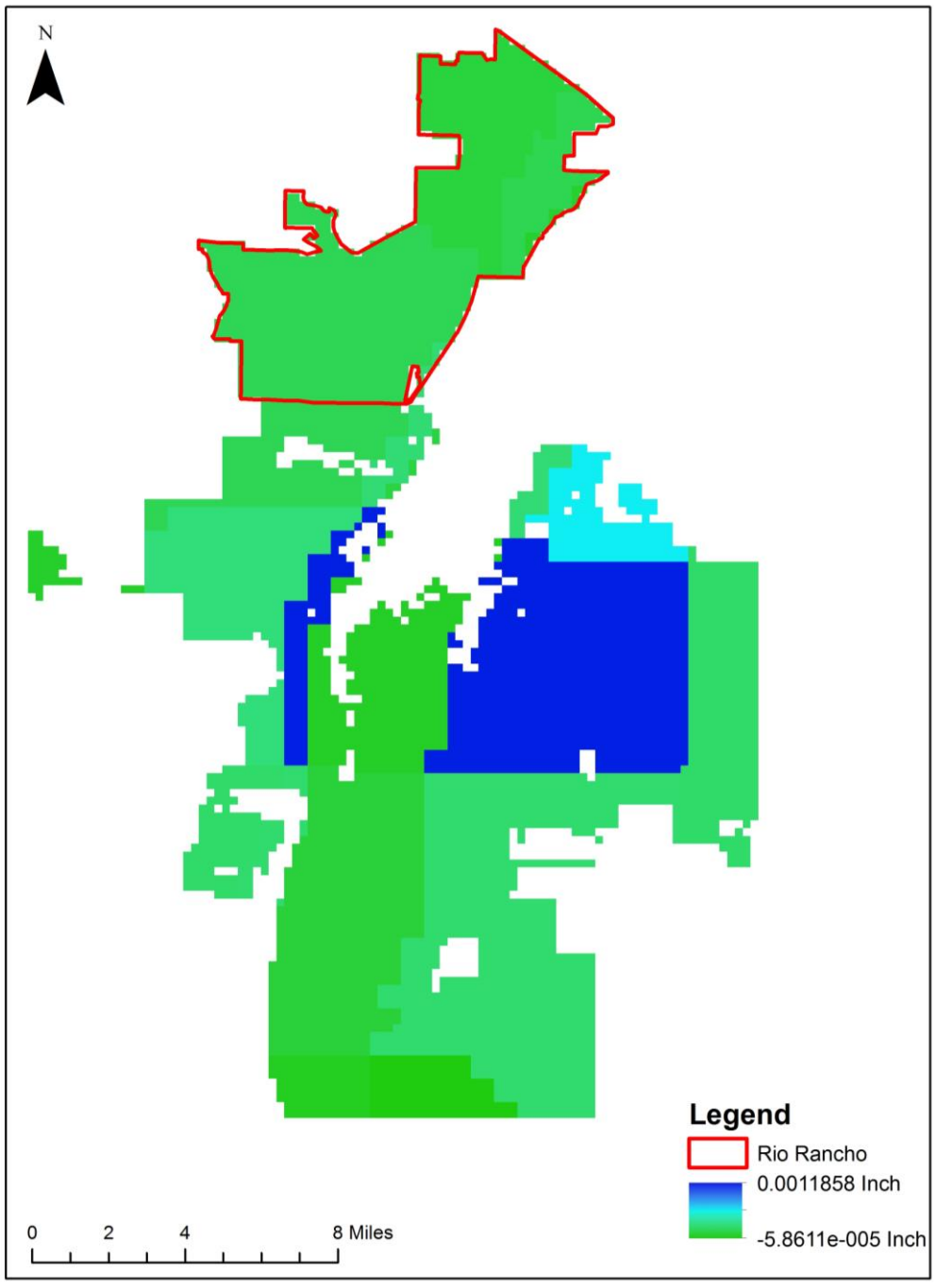


Figure B1: Impact of Awareness Increase in Santa Fe in Water Table Height

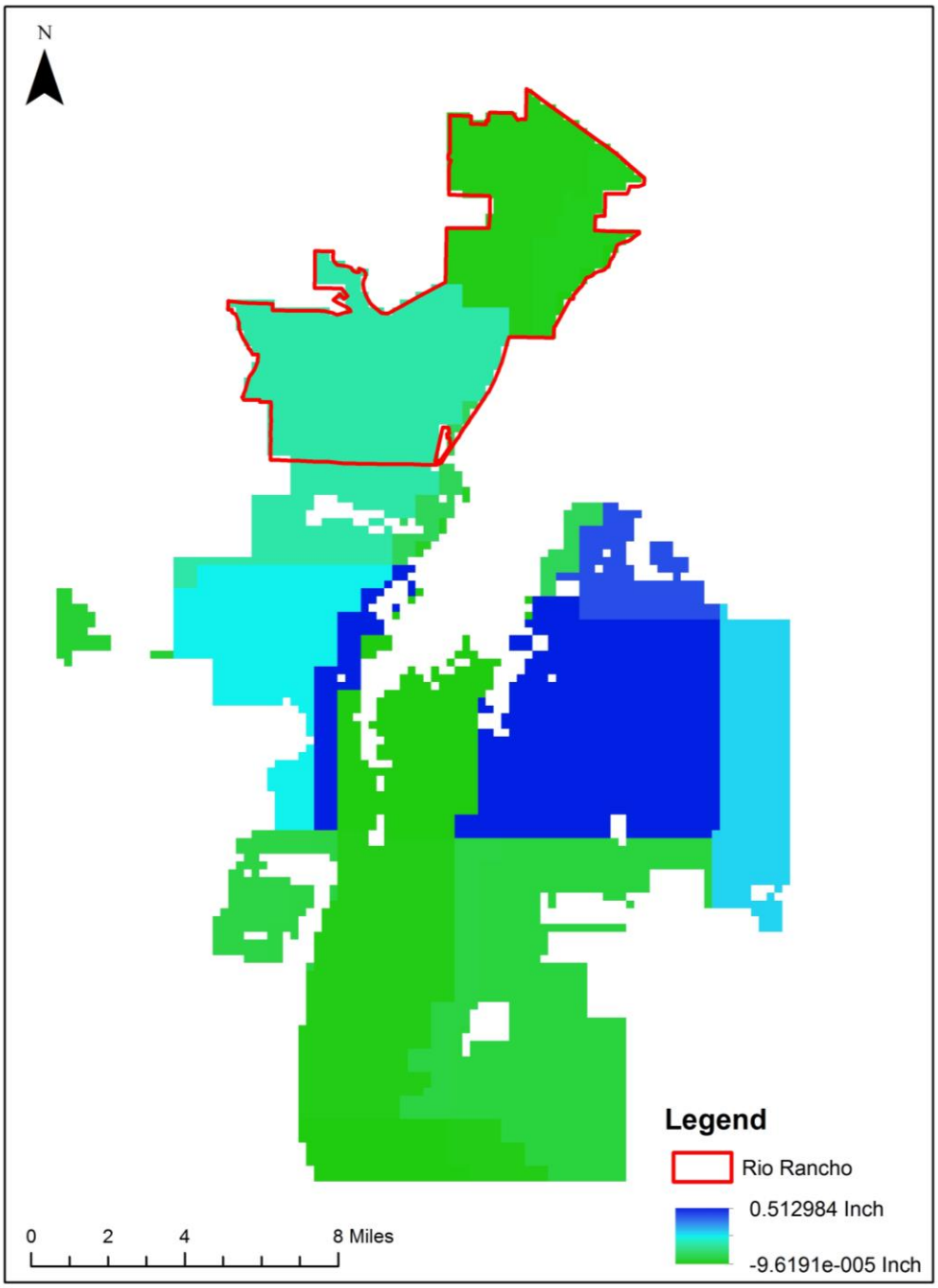


Figure B2: Impact of Awareness Increase in Rio Rancho in Water Table Height

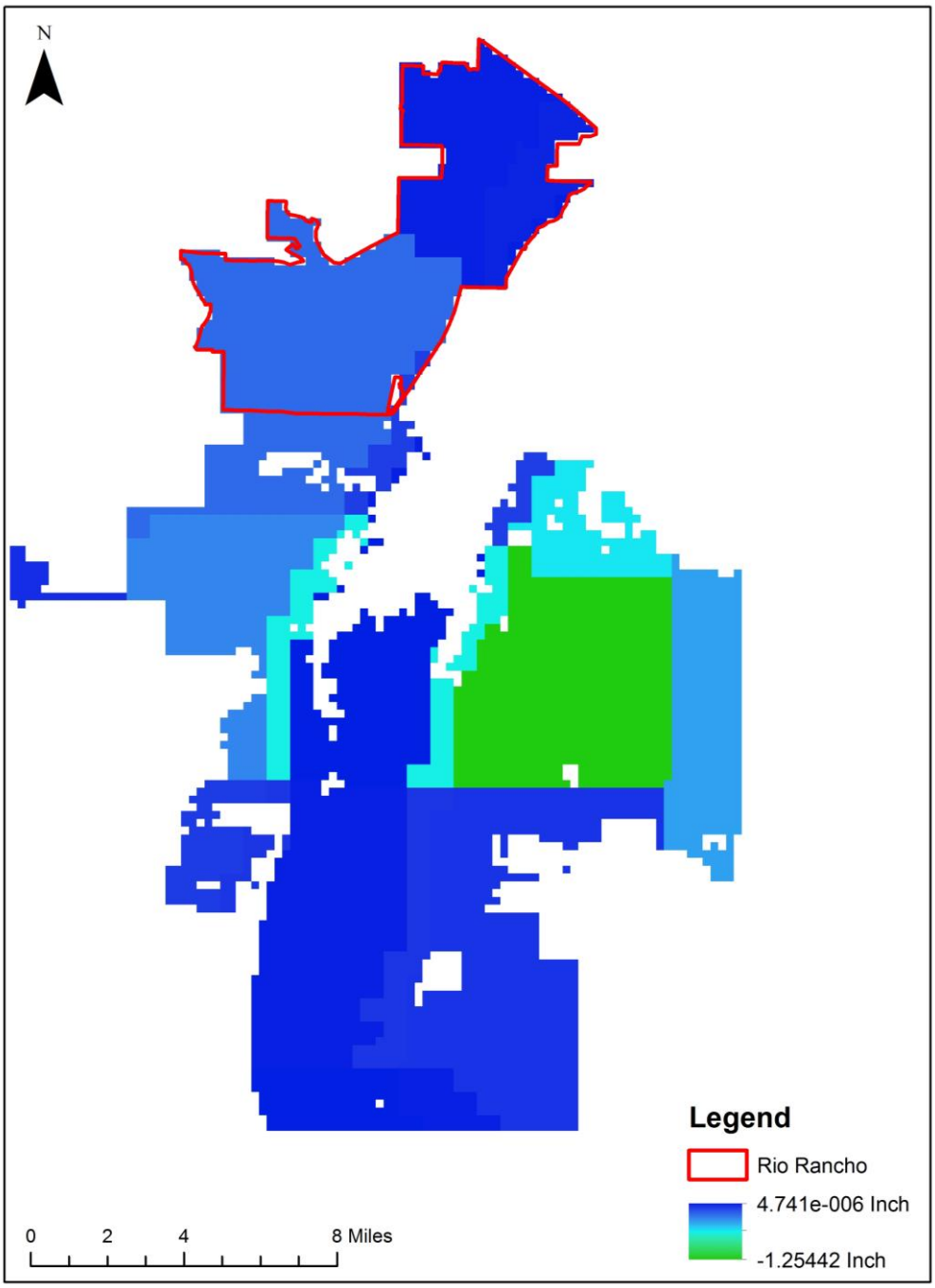


Figure B3: Impact of Population Increase in Rio Rancho in Water Table Height

Appendix C: Summary of the Numerical Model for Surface Water and Groundwater

This section summarizes the numerical model for surface water and groundwater used in this study. This model is borrowed from Roach and Tidwell (2006a).

***Numerical Model for Surface Water*:** Roach and Tidwell (2006a) adopted a spatial system dynamics approach to model surface water dynamics in the middle Rio Grande by dividing the river system into 17 conceptual spatial units referred to as reaches. The mass balance equation for a reach (j) is given as:

$$Q^j_{msout} = Q^j_{msin} + Q^j_{sw} + Q^j_{gwsw} - Q^j_{evap} \quad \text{(C.2.1)}$$

Where,

$Q^j_{msout} =$ mainstream flow out of the bottom of reach j

$Q^j_{msin} =$ mainstream flow into the reach j

$Q^j_{gwsw} =$ net sum of all interactions between the river and groundwater system in the reach, and is positive for a groundwater gaining, and negative for a groundwater losing reach.

$Q^j_{evap} =$ Open water evaporative losses

Equation (C.2.1) assumes that a change in storage in a river reach with respect to the other flows through the reach and precipitation gains to open water are negligible. If

$Q^j_{sw} =$ net sum of all surface water inflows into and diversion out of the reach then,

$$Q_{sw}^{j} = Q_{swgaged}^{j} + Q_{swungaged}^{j} - Q_{swdiversion}^{j} + Q_{swreturn}^{j} \quad \text{(C.2.2)}$$

Where $Q_{swgaged}^{j}, Q_{swungaged}^{j}, Q_{swdiversion}^{j}, Q_{swreturn}^{j}$ are gaged and ungagged surface water inflows, surface water diversion and returns, respectively.

Mass balance in the conveyance system assuming negligible direct evaporation losses from conveyance features is modeled as in equation (C.2.3)

$$Q_{swdiversion}^{j} + Q_{convtf}^{i} = Q_{cropET}^{j} + Q_{convgw}^{j} + Q_{swreturn}^{j} + Q_{convtf}^{j} \quad \text{(C.2.3)}$$

Where,

$Q_{swdiversion}^{j} =$ diversion from the reach *j*

$Q_{convtf}^{i} =$ flow from the conveyance system immediately upstream

$Q_{convET}^{j} =$ Evapotranspiration from crops

$Q_{convgw}^{j} =$ Conveyance water-groundwater exchange. It is positive if the conveyance system gains water from the groundwater system and vice versa.

$Q_{swreturn}^{j} =$ Surface water flows out of the conveyance system to the river

$Q_{convtf}^{j} =$ Surface water flows out of the conveyance system to the downstream conveyance system

Roach and Tidwell (2006a) included seven reservoirs in their model. The reservoir mass balance is calculated as:

$$\Delta S^{r} = Q_{sw}^{r} + Q_{precip}^{r} - Q_{gw}^{r} - Q_{evap}^{r} - Q_{release}^{r} \quad \text{(C.2.4)}$$

Where

ΔS^r = change in storage for a given time step at reservoir r

Q^r_{sw} = gaged and ungagged surface water inflows

Q^r_{precip} = Precipitation that falls directly on the reservoir surface

Q^r_{gw} = groundwater leakage from the reservoir

Q^r_{evap} = evaporation from the reservoir

$Q^r_{release}$ = release from the reservoir including spills

Equation (C.2.5) is used to estimate the winter evaporation rate for the reservoirs where pan freezes during November through March.

$$E^{r,m} = \frac{T^{r,m}_{\max} + T^{r,m}_{\min}}{2} k^{r,m} \qquad \text{(C.2.5)}$$

Where,

$E^{r,m}$ = evaporation rate from reservoir r during month m

$T^{r,m}_{\max}$ = average daily maximum temperature for reservoir r during month m

$T^{r,m}_{\min}$ = average daily minimum temperature for reservoir r during month m

$k^{r,m}$ = coefficient of proportionality for reservoir r during month m

For Elephant Butte during all months, and for other reservoirs during April through October, the evaporation rate is estimated with equation (C.2.6).

$$E^{r,m} = 0.7 E^{r,m}_{pan} \qquad \text{(C.2.6)}$$

where

$E_{pan}^{r,m}$ = pan evaporation measured at reservoir *r* during month *m.*

Crop and open-water evaporation are estimated using reference evapotranspiration (ET) given by equation (C.2.7),

$$ET_{ref} = \frac{\frac{\Delta}{\Delta+\gamma} SR + \frac{\gamma}{\Delta+\gamma} UD}{\rho_w LHV} \tag{C.2.7}$$

Where

ET_{ref} = reference ET rate

Δ = vapor pressure/temperature

$$\text{gradient} = 33.8639\left[0.05904\left(0.00738\frac{T_{\max}+T_{\min}}{2}+0.8072\right)^7 - 0.0000342\right]$$

γ = psychometric constant = $\frac{c_p P}{\varepsilon\lambda}$

U = wind speed function = $15.36(1+0.0062U2m)$

$U2m$ = wind speed in *km/day* measured in 2 meters

D = vapor pressure deficit

LHV = latent heat of vaporization for water

ρ_w = water density

c_p = specific heat

P = Atmospheric pressure = $1013 - 0.1055z$

z = weather station elevation

$\lambda =$ Latent heat of vaporization $= 595 - 0.51\dfrac{T_{\max} + T_{\min}}{2}$

$\varepsilon =$ ratio of the molecular weight of water vapor to dry air

Reference ET is modified to estimate crop coefficient using either growing degree or monthly average method. The growing degrees are calculated as:

$$GD^{m,p} = \left(\frac{T_{\max}^{m,p} + T_{\min}^{m,p}}{2} - T_{base}^{p} \right) days^{m} \qquad \text{(C.2.8)}$$

Where,

$m =$ month

$p = plant$

$GD^{m,p} =$ growing degrees in month m for plant type p

$T_{\max}^{m,p} =$ the average maximum monthly temperature for month m

$T_{\min}^{m,p} =$ the average minimum monthly temperature for month m, or $T_{base}^{m,p}$, whichever is larger

$T_{base}^{m,p} =$ the base temperature parameter for plant type p

$days^{m} =$ number of days in month m

The hydrological model considers 20 different types of plants grown in the study area. The data and functional relationship between growing degree days, plant ET, and plant species are based on Brower (2004).

Where there is no pan evaporation data, open water evaporation can be estimated using open water coefficient. A product of reference ET and open water coefficient gives the value of open water evaporation for a particular place. For this purpose, Roach and Tidwell (2006a) estimate open water coefficient for reaches immediately upstream of a reservoir using equation (C.2.9).

$$C_{ow}^{r,m} = \frac{0.7E_{pan}^{r,m}}{ET_{ref}^{j,m}} \qquad \text{(C.2.9)}$$

Where,

$C_{ow}^{r,m}$ = implied open water coefficient associated with reservoir *r* in month *m*

$E_{pan}^{r,m}$ = pan evaporation measured at reservoir *r* during month *m*

$ET_{ref}^{j,m}$ = reference ET in reach *j* immediately upstream of reservoir r in month *m*

ET rate for a specific plant type or open water is obtained by multiplying reference ET by a plant or open water coefficient. The result is then multiplied by the area of the plant or water to get volumetric evapotranspiration.

$$\begin{aligned}
Q_{evap}^{r} &= E^{r,m}A^{r,m}\left(1-\text{cov}^{r,m}\right) \text{------(a)} \\
Q_{cropET}^{j} &= ET_{ref}^{j,m}\sum_{p} C^{j,m,c}A^{j,m,c} \text{-----(b)} \\
Q_{evap}^{j} &= ET_{ref}^{j,m}C_{ow}^{m}A^{j,m,w} \text{--------} \ (c) \\
Q_{ripET}^{j} &= ET_{ref}^{j,m}\sum_{p} C^{j,m,r}A^{j,m,r} \text{-----} \ (d)
\end{aligned} \qquad \text{(C.2.10)}$$

Where,

Q_{evap}^{r} = evaporation from reservoir *r* [equation C.2.4]

Q^{j}_{cropET} = crop ET in reach j [equation C.2.3]

Q^{j}_{evap} = open water evaporation in reach j [equation C.2.1]

Q^{j}_{ripET} = riparian ET in reach j for groundwater balance

$E^{r,m}$ = evaporation rate from reservoir r during month m [equation C.2.5]

$ET^{j,m}_{ref}$ = reference ET in reach j during month m [equation C.2.9]

$C^{j,m,c}$ = ET coefficient in reach j during month m for crop c

C^{m}_{ow} = open water evaporation coefficient during month m

$A^{r,m}$ = surface area of reservoir r during month m

$A^{j,m,c}$ = crop area in reach j during month m for agricultural crop c

$A^{j,m,w}$ = open water area in reach j during month m

$A^{j,m,r}$ = riparian vegetation area in reach j during month m for plant r

$\text{cov}^{r,m}$ = percent of reservoir r covered by ice during month m

The interaction between surface water (river-groundwater, and reservoir-groundwater) is modeled using equation (1.20). The details of the interaction modeling mechanism of equation (A.2.11) will be discussed in the groundwater model.

$$Q_{swgw} = \frac{K_{bed} F_{bed}}{b_{bed}} \left(z_{sw} - \beta \right) \times \beta \left(= z_{bed} \text{ if } z_{bed} - b_{bed} \geq h \text{ otherwise } h \right) \qquad \text{(C.2.11)}$$

Where,

z_{sw} = surface water elevation

b_{bed} = thickness of the flow-limiting bed sediments

K_{bed} = hydraulic conductivity of the flow limiting bed sediments

F_{bed} = horizontal area of the river channel

h = groundwater head

Finally, precipitation gain for the reservoir is modeled using equation (C.2.12).

$$Q^{r}_{precip} = P^{r,m} A^{r,m} \left(1 - \text{cov}^{r,m}\right) \tag{C.2.12}$$

Where,

Q^{r}_{precip} = precipitation gains to reservoir *r* [equation C.2.4)

$P^{r,m}$ = precipitation rate measured at reservoir *r* during month *m*

$A^{r,m}$ = area of reservoir *r* during month *m* [equation C.2.10]

$\text{cov}^{r,m}$ = percent of reservoir *r* covered by ice during month *m* [equation C.2.10]

***Numerical Model for Surface Water*:** Change in water storage in any compartment over a period is equal to the sum of flows into the compartment less the sum of the flows out of the compartment. Consider Figure 7, which shows four compartments, *a*, *b*, *c*, and *d*, of a hypothetical aquifer. A change in water storage in compartment *a* is given as:

$$\frac{dS_a}{dt} = Q_{ab} + Q_{ac} + Q_{ad} + Q_{aB} \tag{C.2.13}$$

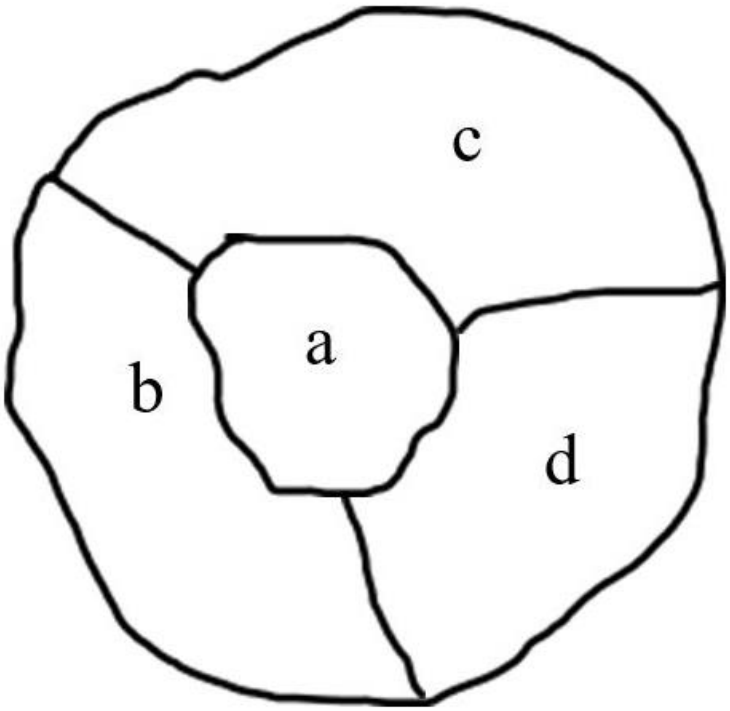


Figure C1: A Hypothetical Aquifer with Four Compartments
Source: Adapted from Roach and Tidwell (2009)

Where,

$\frac{dS_a}{dt}$ = change in storage per unit of time in compartment *a*

Q_{ai} = flows into *a* from *i*, $i \in b, c, d$. It is positive if compartment *a* gains water, and negative for flow out.

Q_{aB} = sum of boundary flows for compartment *a*. Boundary flow includes ET, well extraction and injection, recharge, stream leakage, and drain capture.

Storage in aquifer compartment *i* at time *t+1* is modeled as a function of storage and head values at time *t:*

$$\mathbf{S_i^{t+1}} = \mathbf{S_i^t} + \Delta t \left[\sum_{j=1}^{n} \mathbf{Q_{ij}^t} + \mathbf{Q_{iB}^t} \right] \quad \text{(C.2.14)}$$

Where,

$n =$ total number of aquifer compartments

$\mathbf{S_i^{t+1}}, \mathbf{S_i^t} =$ storage vector for n compartments *at* time $t+1$ and t

$\Delta t =$ timestep duration

$\mathbf{Q_{iB}^t} =$ boundary flow vector for n compartments at time t

$\mathbf{Q_{ij}^t} =$ flow matrix representing flows from i to j at time t $\forall i, j$

Flow matrix is a function of head difference and conductance (and connectivity)

$$\mathbf{Q_{ij}^t} = \boldsymbol{\alpha}_{\mathbf{ij}} \sum_{i=1}^{n} \sum_{j=1}^{n} \Delta h_{ij}^t \quad \text{(C.2.15)}$$

$$\Delta h_{ij}^t = h_j^t - h_i^t \quad \text{(C.2.16)}$$

$$\alpha_{i,j} = \frac{Q_{i,j}}{h_j - h_i} \quad \text{(C.2.17)}$$

Where,

$\boldsymbol{\alpha}_{\mathbf{ij}} =$ a symmetric conductance (and connectivity) matrix

$h_j^t, h_i^t =$ representative heads in compartment j and compartment i

Aquifer storage is calculated using equation (C.2.18)

$$S_i = \left(h_i - zbot_i\right) F_i sy_i \quad \text{(A.2.18)}$$

Where,

$F_i =$ the horizontal area of compartment *i*

$sy_i =$ specific yield of unconfined compartment *i*

$zbot_i =$ bottom elevation of compartment *i*

River-aquifer and reservoir-aquifer interactions, Q_{i-swgw} in each compartment is modeled as in equation (C.2.11), rewritten in equation (C.2.19).

$$Q_{i-swgw} = \frac{K_{i-bed} F_{i-bed}}{b_{i-bed}} \left(z_{i-sw} - \beta \right) \times \beta \left(= z_{i-bed} \text{ if } z_{i-bed} - b_{i-bed} \geq h_i \text{ otherwise } h_i \right) \qquad \text{(C.2.19)}$$

Where,

$z_{sw} =$ surface water elevation

$b_{bed} =$ thickness of the flow-limiting bed sediments

$K_{bed} =$ hydraulic conductivity of the flow limiting bed sediments

$F_{bed} =$ horizontal area of the river channel

$h =$ groundwater head

Groundwater flow to the agricultural drains in the Albuquerque basin is modeled as:

$$Q_{DUP} = \frac{K_{i-a} L_i}{x_i} \left(h_i^2 - z_{i-sw}^2 \right) \qquad \text{(C.2.20)}$$

Where,

$Q_{DUP} =$ groundwater flow to the agricultural drains

K_{i-a} = hydraulic conductivity of the aquifer compartment

L_i = length of drain

x_i = characteristic distance beyond which the drain has negligible effect on groundwater head

Average monthly surface water stage (z_{sw}) is found using iterative method in such a way that it equalizes Q_{DUP} in equation (C.2.21) with Manning equation for open channel flow given as:

$$Q_{MAN} = \frac{AR^{\frac{2}{3}}S^{\frac{1}{2}}}{n} \tag{C.2.21}$$

$$A = (z_{sw} - z_{bed})W \tag{C.2.22}$$

$$R = \frac{A}{2(z_{sw} - z_{bed}) + W} \tag{C.2.23}$$

Where,

Q_{MAN} = discharge in liters per second

S = drain slope

n = Manning coefficient of roughness

A = cross-sectional area of flow

R = hydraulic radius

Finally, ET through shallow aquifer is modeled as a head-dependent flux.

$$Q_{iET} = ET_{i-ref} F_{i-ET} \theta \begin{cases} \theta = 1 \; if \; \left(z_{i-surf} - h_i\right) < 0 \; ft \\ \theta = 1 - \dfrac{2\left(z_{i-surf} - h_i\right)}{30} \quad if \quad 0 \; ft \le \left(z_{i-surf} - h_i\right) \le 9 \; ft \\ \theta = 0.4 - \dfrac{\left(z_{i-surf} - h_i\right) - 9}{28} \quad if \quad 9 \; ft \le \left(z_{i-surf} - h_i\right) \le 16 \; ft \\ \theta = 0.15 - \dfrac{3\left(z_{i-surf} - h_i\right) - 48}{280} \quad if \quad 16 \; ft \le \left(z_{i-surf} - h_i\right) \le 30 \; ft \\ \theta = 0 \quad if \quad \left(z_{i-surf} - h_i\right) \ge 30 \; ft \end{cases} \qquad \text{(C.2.24)}$$

Where,

Q_{iET} = volume of water lost through ET from compartment i

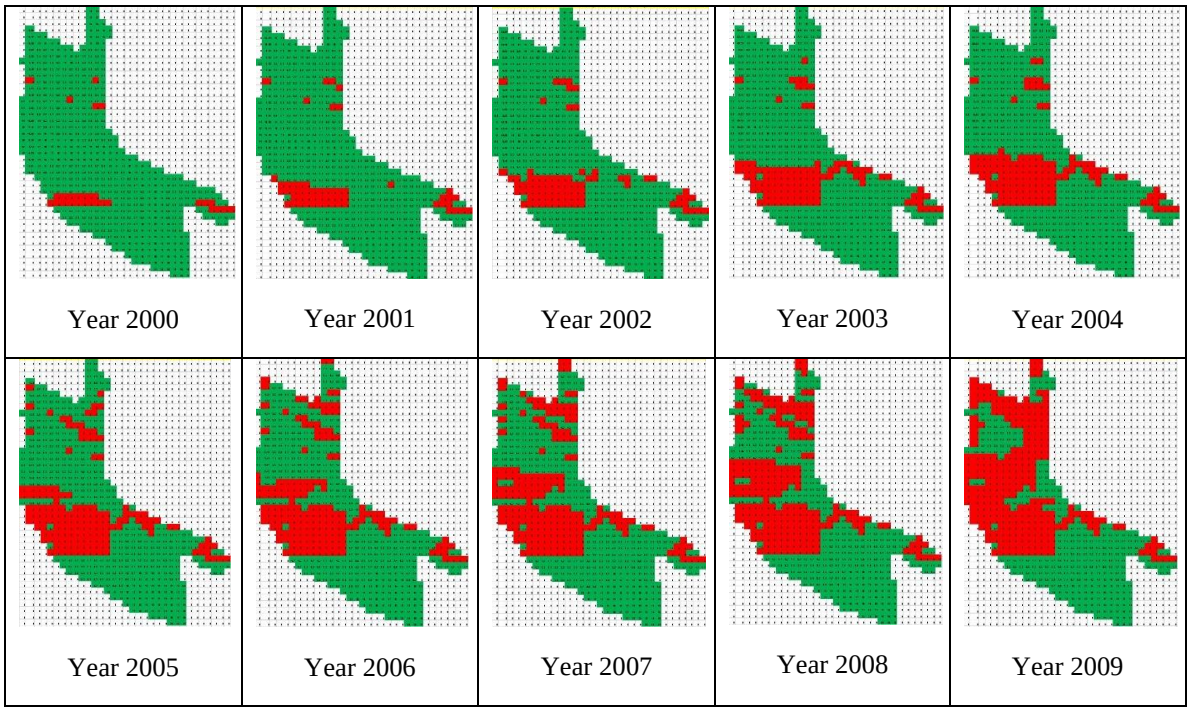
$ET_{i-ref} = -5 \; ft/yr \quad \forall i$

F_{i-ET} = area of vegetation using groundwater

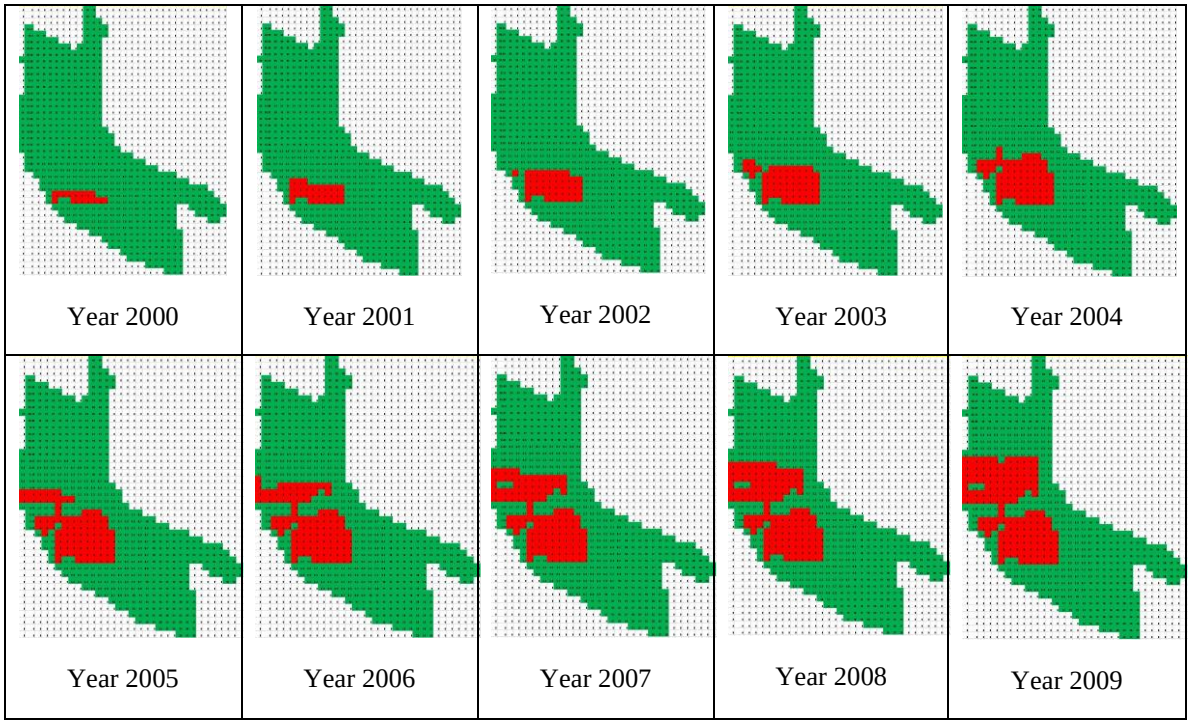
z_{i-surf} = surface elevation of shallow aquifer compartment i

Appendix D: Cells Developed Over Time in Two Models

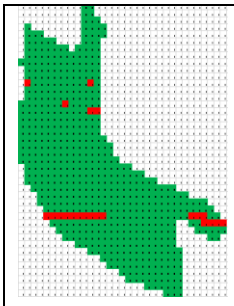
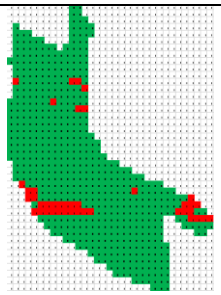
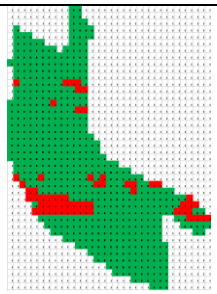
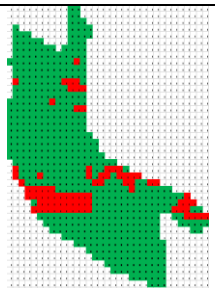
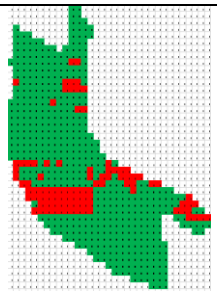
A. Fixed Gas Model: 10 Year Development



B. Fixed Cell Model: 10 Year Development



C. Fixed Gas Model: 20 Year Development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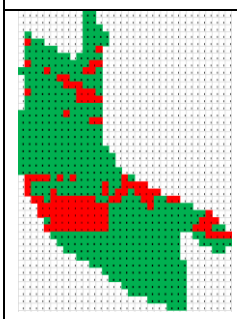	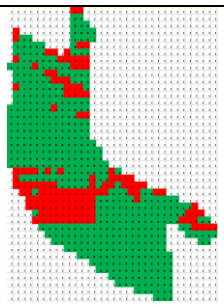	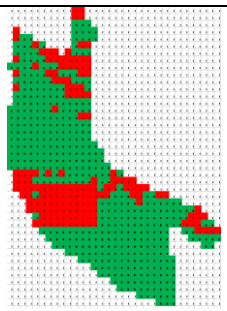	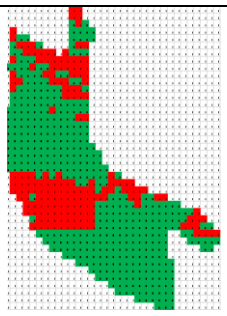	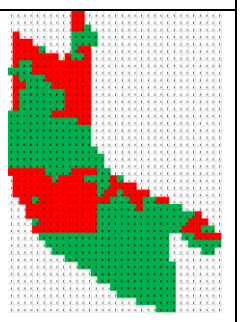
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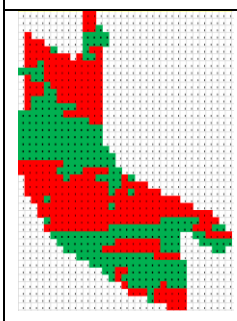	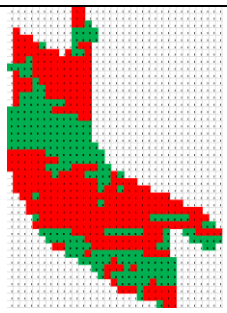	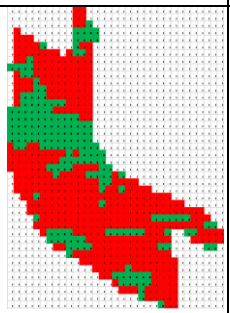	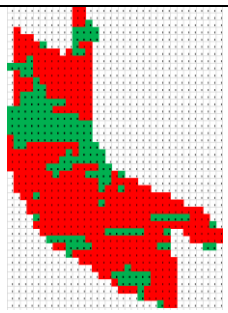	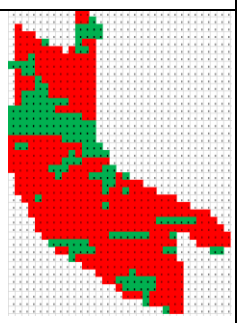
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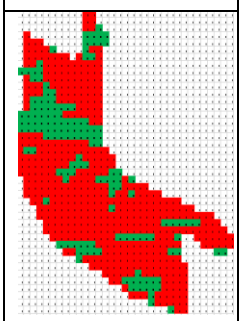
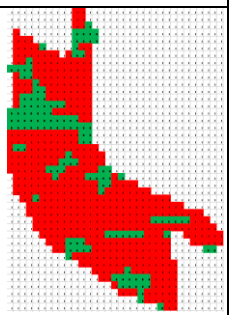
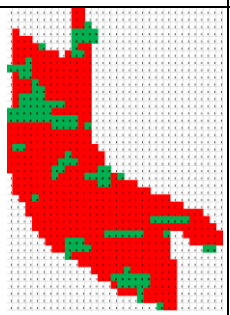
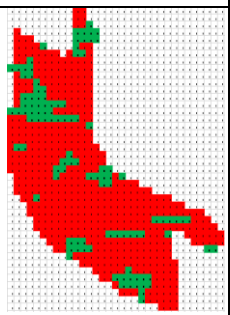
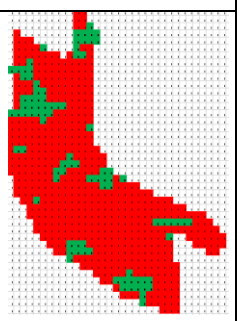
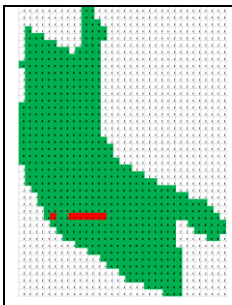
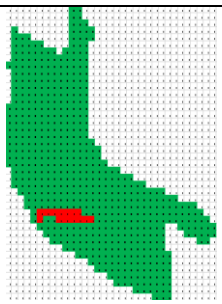
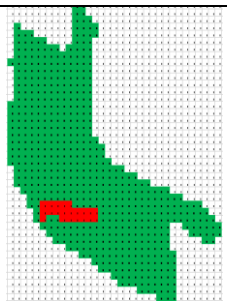
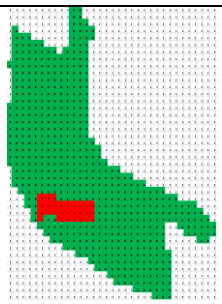
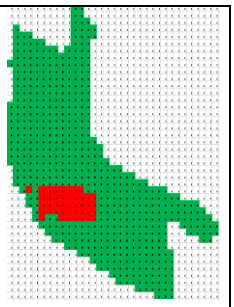
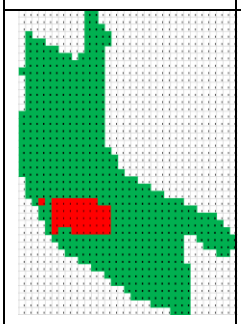
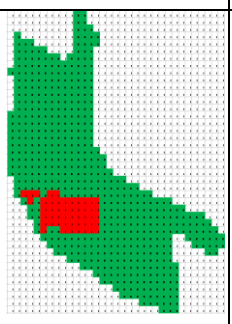
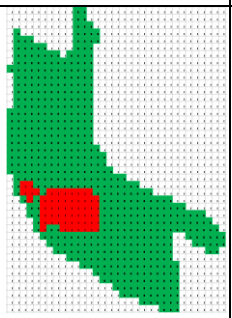
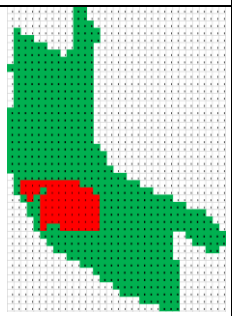
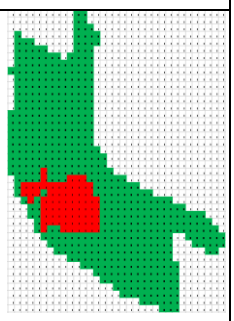
				
Year2015(446cell)	Year2016(460cell)	Year2017(474cell)	Year2018(482cell)	Year2019(497cells)

D. Fixed Cell Model: 20 Year Development

				
Year 2000	Year 2001	Year 2002	Year 2003	Year 2004
				
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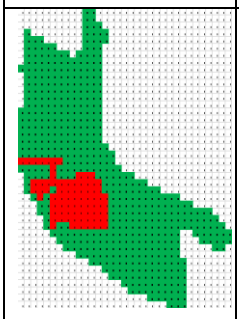	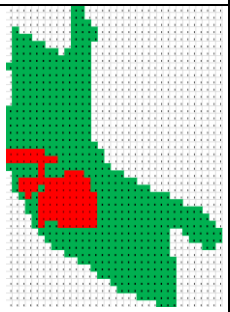	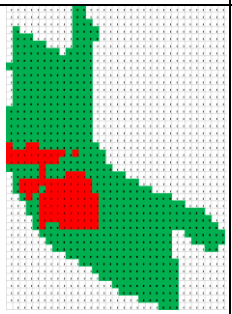	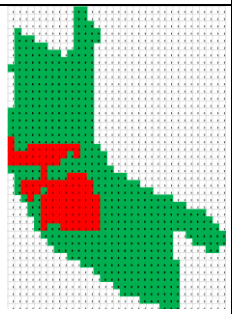	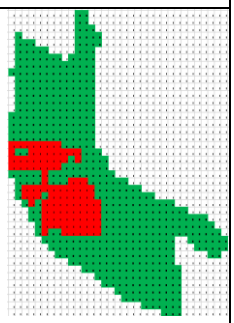
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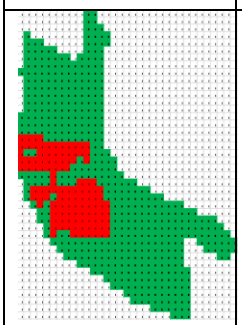	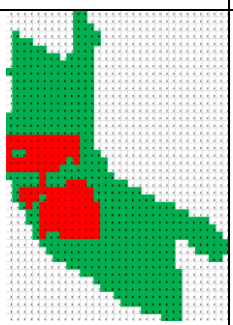	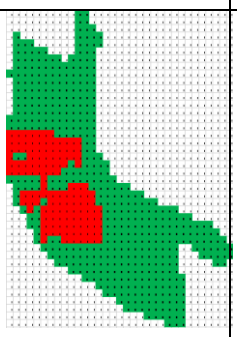	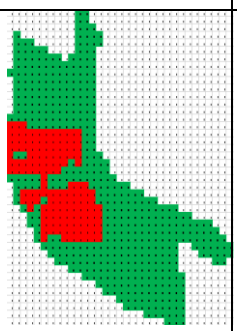	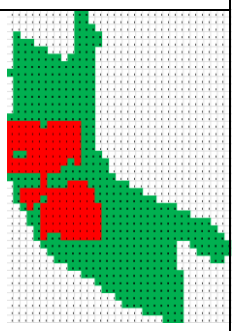
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