ECONOMIC ESSAYS ON WATER RESOURCES MANAGEMENT OF THE TEXAS LOWER RIO GRANDE VALLEY

A Dissertation

by

ANDREW JOHN LEIDNER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2012

Major Subject: Agricultural Economics

Economic Essays on Water Resources Management

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Approved by:

Co-Chairs of Committee,	M. Edward Rister
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ABSTRACT

Economic Essays on Water Resources Management

of the Texas Lower Rio Grande Valley. (May 2012)

Andrew John Leidner, B.A., University of Georgia

Co-Chairs of Advisory Committee: Dr. M. Edward Rister
Dr. Ronald D. Lacewell

The study area for this dissertation is the Texas Lower Rio Grande Valley (Valley). The overarching theme is water and includes regional water management, water management institutions, and water supply decision-making as it relates to community well-being and public health.

The first essay provides a description of a control model developed for the management of a municipal water supply system in the context of public health and waterborne illnesses issues. The most beneficial disease-management strategy is found to depend on the community's levels of infected population, water services, and budget. The model is numerically parameterized using data drawn from Hidalgo County in the Valley. Greater capital depreciation rates and shorter planning horizons contribute to lower levels of community well-being, which is measured as the present value of damages from disease infection levels. Reductions in community well-being are greatest when greater capital depreciation rates are combined with shorter planning horizons.

The second essay provides an overview of the organizations, institutions, policies, and geographic particulars of the region's water management system and the

region's water market. Demand growth for potable water and a relatively-fixed supply of raw water are reflected in increasing prices for domestic, municipal, and industrial (DMI) water rights. The market is characterized by rising prices and the transfer of water from lower-value to higher-value uses. Some reasons for the market's functionality are due to minimal return flows to the Rio Grande (River) occurring throughout the Valley, and the monitoring and enforcement efforts of the Rio Grande Watermaster Program.

The final essay is a presentation of a hydroeconomic model to study regional allocation of water resources across the municipal and agricultural sectors of several counties in the Valley. Results indicate that anticipated population growth will increase demand for municipal water and will motivate the transfer of water from the agricultural sector to the municipal sector and the further development of brackish desalination of groundwater. Population density scenarios indicate greater population density is associated with a greater level of agricultural production and reduced revenue to agriculture from land and water-right sales. On balance, climate change scenarios with population increases to 2060 are associated with fewer acres farmed, cropping pattern shifts to higher-value crops, and increasing irrigation requirements.

Since the study area for this dissertation is encountering a variety of challenges that are related to environmental conditions, institutions, demographics, and health, this dissertation may provide guidance to the broader water-management community and to other locations, where these challenges are also occurring.

DEDICATION

To the memory of Robert W. Leidner, Jr.

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Many people who are, or who have been, associated with Texas AgriLife Extension, Texas AgriLife Research and the Texas A&M University Agricultural Economics department also deserve my gratitude, for without their help, this dissertation would not have been possible. A very big thanks goes to Allen Sturdivant, former Extension Agricultural Economist of the Texas A&M Research Center in Weslaco, Texas. Mr. Sturdivant served as a source of information on Valley water issues as well as the initial point of contact for other water managers and water experts in the Valley, many of whom are listed below. Drs. John Jifon, Kevin Crosby, Luis Ribera, and Guy Fipps provided information on Valley water infrastructure, land conversion capacities and costs, and water requirements of various crops. Folks located at the Texas A&M campus in College Station who helped me along the way include: Michele Zinn, Tracy Davis, Vicki Heard, Dr. Shelly Peacock, Cindy Fazzino, Jennifer Braziel, Toni Merchant, Melissa Kindell, and Kari Moore. Several previous and current students affiliated with the Rister-Lacewell economics research team also deserve thanks. Their research work, their friendship, and often both, contributed positively to this dissertation: Naveen Adusumili, Ann Conrad, Lindsi Dutton, Brant Wilburn, Edgar Alarcon, Will McLaughlin, Thomas Becker, Megan Armenti, Callie Hamilton, Emily Seawright, and Chris Boyer.

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NOMENCLATURE

af	Acre Foot
BPUB	Brownsville Public Utilities Board
CM	Centralized-municipal
DMI	Domestic, Municipal, and Industrial
ENSO	El Niño Southern Oscillation
FA	Falcon-Amistad
IBWC	International Boundary and Water Commission
NAWSC	North Alamo Water Supply Corporation
NRS	NRS Consulting Engineers
POU	Point-of-use
Region M	Rio Grande Regional Water Planning Group
River	Rio Grande
SIS	Susceptible-infected-susceptible
SRWA	Southmost Regional Water Authority
TCEQ	Texas Commission on Environmental Quality
TCM	Thousand Cubic Meters
TWDB	Texas Water Development Board
USGS	United States Geological Survey
Valley	Texas Lower Rio Grande River Valley
yr	Year

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CHAPTER I

INTRODUCTION

The Texas Lower Rio Grande Valley (Valley) (Figure 1-1) poses a number of water resource management issues. It is located on an international border, sharing the Rio Grande (River) with the Mexican state of Tamaulipas. Due in part to the proximity to Mexico, immigration-fueled population growth in the Valley has resulted in rapidly-expanding municipalities. Relative to the rest of the United States, the growing municipalities of the Valley are characterized by high rates of poverty, exhibiting many issues encountered in international economically-developing areas. This rapid urban expansion is occurring into the Valley's longstanding, vast and vigorous agricultural sector, which currently owns the majority of Rio Grande surface water rights.

Climatically extreme, portions of the Valley can be generally characterized as semi-arid, but due to the proximity of the Gulf of Mexico, the entire Valley can be periodically inundated with extreme rainfall events from tropical storm systems. The unique and diverse economic, demographic, and climatic circumstances make the Valley a complex and worthy location for the study of water resource economics and related management strategies.

This dissertation follows the style of the *American Journal of Agricultural Economics.*

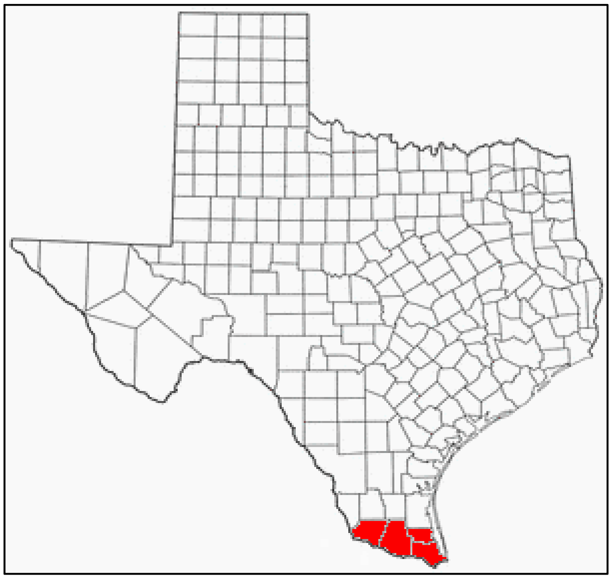

Figure 1-1. Map of the State of Texas with the Lower Rio Grande Valley as the shaded region, 2011.
Source(s): Google Images (2011).

The institutional environment of the Valley is also complex. Water resource management is subject to authorities at all levels of government, including for example: local (e.g., municipal and county governments, irrigation districts), regional (e.g., Rio Grande Watermaster Program), state (e.g., Texas Commission on Environmental Quality), national (e.g., Environmental Protection Agency), and international (e.g., International Boundary and Water Commission). A water market operates across the region, but water rights transactions are complex and highly regulated. The Valley is home to many immigrant communities, known as colonias, which are often hastily-built residential neighborhoods that may not have access to water services considered to be standard in many parts of the United States.

Hydrologically, the Valley has access to one major river, the Rio Grande, which has been extensively developed, meaning a large network of river diversion and water distribution infrastructure exists to serve the demands of municipal and agricultural interests across the Valley. Adjudication of water rights occurred in a period of above average rainfall and resulted in over allocation of expected available supply (Stubbs et al. 2003). During periods of drought, the Valley experiences ongoing environmental concerns. In addition to relying on the River, municipal water suppliers have diversified their portfolio of water supply alternatives to include brackish groundwater desalination. Currently, municipalities in coastal Cameron County are also exploring the potential of seawater desalination.

Given the characteristics outlined above, water resource management in the region is challenging. In recent years, a water market has emerged as a potential solution to urban water scarcity through water rights reallocations from agricultural interests to urban and municipal interests. The water market operating in the Valley has worked well to achieve some water management goals (for example agricultural-to-municipal reallocation), but has arguably left environmental and instream demands unmet. The viability and utility of modifications to the market or potential non-market mechanisms to increase environmental flows are ongoing issues for the Valley. And finally, long-run water resource management planning in the Valley is expected to encounter a variety of issues ranging from environmental, to rapid increases in population and related water demands, to shortfalls in water supplies as a result of climate variability and changing structure of the region.

The overarching objective of this dissertation is to generate information and analyses along with decision-making tools that will assist Valley water resource planners and managers as they confront water-related issues. Included is an evaluation of several facets of regional water management, with a particular focus on municipal water decision-making. The dissertation is divided into three sections, with each section composed of a stand-alone academic paper. The common themes occurring throughout the three papers include water management institutions and policy, water management objectives, and water service costs and benefits. More specifically, the focus includes the interaction of water-supply systems and public health, in the context of water-borne and sanitation-related illnesses; water reallocation from agricultural use to municipal use, in the context of a water market; and long-term region-wide optimal water management for both municipal and agricultural sectors, taking into account demographic changes, institutional changes, and potential climate change.

The three essays that comprise this dissertation are as follows:

1. Drinking Water Supply System Management for Public Health;
2. The Water Market of the Texas Lower Rio Grande Valley; and,
3. Hydroeconomic Analysis of the Texas Lower Rio Grande Valley Water Supplies under Urbanization and Climate Change.

These three papers use three different methodologies to study inter-related water management issues. Essay 1 or Chapter II, “Drinking Water Supply System Management for Public Health,” employs optimal control techniques, and computational methods to model and better understand the decision-making process of municipal water-suppliers and city managers in the context of health-related water and medical services, which affect poorer areas in Hidalgo County. Essay 2 or Chapter III, "The Water Market of the Texas Lower Rio Grande Valley," is a structural and qualitative performance assessment of water-market policies and agents in the Texas Lower Rio Grande Valley regional water management system. Essay 3 or Chapter IV, "Hydroeconomic Analysis of the Texas Lower Rio Grande Valley Water Supplies under Urbanization and Climate Change," includes the development of an optimization model, integrating hydrologic, economic, and institutional characteristics. The hydroeconomic model is applied to evaluate a variety of municipal water-supply options and agricultural water-use, as a function of cropping choice. The response of modeled municipal and agricultural agents to population growth and climate change are explored.

Together, these three papers are designed to provide insight and analyses that can be used by water managers in the region as they look forward to encounter future challenges and opportunities. These challenges will likely come from substantial population growth, which brings with it urban consumer demands, potential health issues, and urban land-use expansion; continued climate variability, with the variability potentially intensifying as climate change takes hold; competitiveness over water between urban and agricultural sectors, and possibly between nations as both the United States and Mexico continue to utilize the shared resource of the Rio Grande. The consequences of these challenges will motivate solutions in the manner of technological and institutional innovations.

CHAPTER II

DRINKING WATER SUPPLY SYSTEM MANAGEMENT FOR PUBLIC HEALTH

2.1 Introduction

The relationship between water supply systems and public health is explored in this essay. Water-related health issues are pervasive throughout both the developed and the developing world. Due to the importance of physical health and the role health plays in productive labor in developing impoverished regions, the relationship between water, health, and economic productivity is especially significant. As of 2010, over 800 million individuals lacked access to “improved sources of drinking-water,” and over 2.5 billion lacked access to “improved sanitation” (WHO and UNICEF 2010). For many years, water systems, public health, economic development, and the interactions and effects connecting them have been the focus of researchers from a wide variety of fields; see Hoddinott (1997) for a review. As examples, diarrheal illnesses kill more than 2 million children annually, mostly in developing countries (Kosek et al. 2003). And, arsenic contamination of groundwater wells in rural Bangladesh reduces household labor supplies by as much as 8% (Carson et al. 2011). A recent willingness-to-pay study for the Bangladeshi arsenic issue, which evaluated decentralized and centralized water treatment solutions, concludes, “the arsenic problem is not merely a problem of technology but is as much, if not more, an issue of institutions – private and public – that influence the financing and delivery of safe water” (Ahmad et al. 2003).

The Rio Grande Valley in Texas has experienced substantial population growth in recent years (Leidner et al. 2011b). This population growth has fueled the rapid development of quasi-urban settlements, known as colonias, which are not always connected to utility infrastructure which would be considered standard in most parts of the United States. The struggles of the colonias to attain standard levels of water, wastewater, and other civil infrastructure are well documented in the research literature (Olmstead 2003; Perkins et al. 2001; Reed, Stowe, and Yanke, LLC 2001; U.S. Federal Reserve Bank of Dallas 1996; and Williams 2006) as well as in the popular media (Ramshaw 2011). A survey completed by the United States Geological Survey (USGS) reported in 2007 that as many as 34,924 colonia residents (or 18% of all colonia residents in the Valley) in Cameron, Hidalgo, and Willacy counties did not have access to standard levels of either potable water or wastewater services (USGS 2010b).

The lack of universal access to water services may contribute to health concerns in the area. Suggestive evidence is reflected in the infection rates of water and sanitation-related diseases, which in Hidalgo county exceed the state average over several years (Figure 2-1). In Table 2-1, infection levels from 1999 for Hidalgo and Cameron counties can be compared to average levels in Texas and the United States. In particular, the high rates of hepatitis A and shigelleosis provide suggestive evidence that water and sanitation-related health concerns are more important in Valley counties with significant colonia populations.

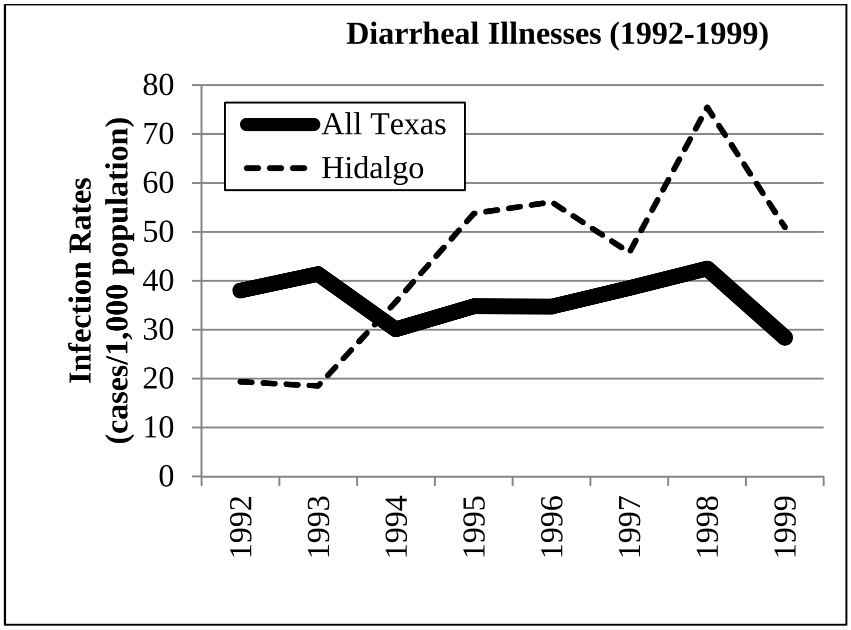

Figure 2-1. Reported infection rates of various diarrheal illnesses for Hidalgo County and for all of Texas from 1992 to 1999. Reported diseases include: Amebiasis, Campylobacteriosis, Salmonellosis, Shigellosis.
Source(s): USGS (2010a) and TXDHS (2007).

Table 2-1. Infection rates (per 100,000 population) of water and sanitation related diseases in two Valley counties (Cameron and Hidalgo) with substantial colonia populations, Texas, and the U.S., 1999.

	Hepatitis A	Salmonellosis	Shigellosis
Cameron County	56.1	14.6	23.5
Hidalgo County	38.0	20.6	19.3
Texas	12.6	11.0	11.4
U.S.	6.3	14.9	6.4

Source(s): Warner and Jahnke (2003), citing TXDHS (1999) and CDC (1999).

The influence of certain institutional and environmental circumstances on optimal water-supply systems and public health management are investigated herein. Some of the circumstances include: the public health manager’s planning horizon, the size of the public health budget, and the rate of capital depreciation of water-service infrastructure; all of which affect public-health and water-service decision-making. An overarching theme of this dissertation is to better understand and to offer suggestions for improving water management institutions. Laws such as the Safe Drinking Water Act (1974), and, closer to the study area, recent legal efforts (Office of the Attorney General 2011) and financial efforts (TWDB 2011) by the Texas government constitute institutions designed to improve living-standards, water-access, and, ultimately, public health of impoverished communities.

These issues are investigated by developing a conceptual, optimal-management model. A case study using data from Hidalgo County is developed to explore the implications of the theoretical model. First, a description of the general model is presented, followed by a discussion of theoretical findings in several special cases. Finally, numerical results are generated and discussed for a case study of Hidalgo County.

2.2 Water and Health Background

Poor drinking water, lack of sanitation infrastructure, and medical institutions contribute to public health issues which can take many forms, including all varieties of waterborne and water-related illnesses such as cholera, dysentery, and malaria. In the early 1900s, cases and mortalities of waterborne illnesses began to decline as drinking water chlorination and antibiotic use become more common (Morris and Levin 1995). But even in the present day, in the wealthiest and most technologically-advanced regions of the world, water-related health issues are not entirely avoidable (Yoder et al. 2008).

For example, in the United States, water-health issues range from arsenic-contamination hotspots (Jakus et al. 2009), to cancer-causing water-treatment byproducts (Adamowicz et al. 2011), to the absence of rudimentary water and sanitation services in certain rural and impoverished locations like areas of the Valley (Olmstead 2004).

Regions of Brazil studied by Feler and Henderson (2011) exhibit similarly rooted urban development and water-sanitation issues as the Valley. They find that municipalities are strategically manipulating their water-supply management institutions to manage the migration-fueled growth of quasi-urban settlements. In the Valley, utility services and management of quasi-urban settlements have been a persistent issue since immigration levels dramatically increased in the past decades (U.S. Federal Reserve Bank of Dallas 1996). Competing institutions' (i.e., private versus public) provision of water services impacts costs as well as water service coverage in the Valley (Olmstead 2004) and associated public health outcomes. Private versus public institutional competition has been shown to have an especially important impact on child health (Galiani 2005).

While many regard access to clean drinking water as a basic human right, in the presence of a constrained budget such a policy may not be operational. Budgetary considerations for water projects and water-related investments, particularly in developing regions where project financing is not local, are quite common (e.g., Easter and Liu 2005; Iyer et al. 2005; and van den Berg and Katakura 1999). Under a limited budget, the model developed here is applied to investigate the tradeoffs between the provision of preventative public health by way of clean drinking water and the provision of therapeutic public health by way of medical treatment, *ex post* an infection. In addition to the more general tradeoff between preventative and therapeutic public health, application of the model allows for consideration of the attributes of two different types of water services: centralized-municipal services (CM) and point-of-use services (POU).

Of interest in this study are the economic tradeoffs between these two types of water services. CM services may be more expensive in the short term, but are more durable through time. POU may be less expensive in the short term, but likely requires more frequent replacement. Not only do the benefits of different water service types vary through time, but at any given point in time the activities' marginal effectiveness, or the ability for either CM or POU to prevent illness, may also vary. For simplicity, assumed in this model is that both CM and POU are, on the margin, equally effective at preventing illness. The more durable nature of CM suggests a dynamic resource allocation structure whereby CM services are conceptualized as stock resources. In this setting, the longer-term net benefits of additional investments into CM stock are weighed against the instantaneous net benefits of nondurable POU services.

Introduced in this paper is an optimal management framework to address public health with preventative water services and remedial medical treatment. Treating a preventative activity (CM) as a stock variable in context of water-borne diseases is new contribution to the water-health literature. This essay contributes to the literature on spatial-dynamic processes and renewable resource models (Smith et al. 2009) as well as to the literature on water-related public health issues (Galiani et al. 2005). Diseases in a population can be conceptualized as a renewable resource management problem where the resource of interest is the disease, which yields costs to the manager rather than benefits (Ceddia 2010). While human and animal diseases have been studied using optimal control methods (e.g., Goldman and Lightwood 2002; Horan and Wolf 2005; Gersovitz and Hammer 2004), this study is one of a few that applies such methods to consider waterborne diseases, another being Wiemer (1987) who considers schistosomiasis in China. Other disease mitigation strategies could also be modeled in a similar fashion, including health care infrastructure (e.g., hospital or clinical networks, public health, or hygiene education levels).

2.3 Model Description

The management model developed in this section is based on a model from the ecology of diseases. The ecological model, called the susceptible-infected-susceptible (SIS) disease model (Hethcote 1976), represents the movement of pathogens through a host population. This is a compartmental model, meaning that the host population is compartmentalized into either the "susceptible" class or the "infected" class. If a pathogen invades a host, the host moves from the susceptible class to the infected class. When an infected host recovers from illness, that host is moved back into the susceptible class. Many variants of disease models exist to accommodate modeling of the diverse array of host-pathogen systems. The SIS model is adapted for use here by making population movements between the susceptible and infected classes a function of the intensity of the economic controls (e.g., the intensity of POU water services or medical treatment) that are of interest to water-service and public health managers.

In the context of waterborne diseases, water services primarily serve as preventive activities. Optimal management of water services for public health would account for the tradeoff between these preventive activities and any available therapeutic activities, such as the treatment of the ill by medical professionals in the community. Modeling these therapeutic activities requires partitioning the community's population into those who are susceptible (or healthy) and those who are infected (or ill). These population dynamics are captured by considering a susceptible-infected-susceptible (SIS) disease model (Hethcote 1976). Similar disease models have been used by economists in previous studies (Goldman and Lightwood 2002; Horan and Wolf 2005; Zaric and Brandeau 2001; and Brandeau et al. 2003).

The model is presented in three parts, consisting of the nature of the two methods of water services, followed by an explanation of the disease model, modified by the inclusion of water services. The final sub-section of the model presentation describes more thoroughly the cost structures faced by the model's decision-making agent.

Water Services

Water services systems in a community can be conceptualized as being composed of three population classes. One class has access to CM water services; the size of this class is denoted by A_t^{cm}. The second class has access to POU water services, such as in-home drinking water filters and home or local septic systems, and is denoted a_t^{pou}. The final class receives no water services. With the total customer pool normalized to one, the size of the final class is $1 - A_t^{cm} - a_t^{pou}$. The management decision considered is how large, if at all, the optimal size of each water-service infrastructure class, given a fixed budget for the community's public health-related services.

Disease Dynamics

This section contains details of the disease model and how the basic SIS model is augmented with controls, such as the intensity of either type of water service and the intensity of medical treatment. These controls adjust the rate of movement between the susceptible and infected classes in the population. The disease model used in this paper is the SIS model with a population size normalized to one:

$$S_t + I_t = N_t = 1, \tag{2.1}$$

where S_t is the population portion of susceptible individuals, I_t is the portion of population infected, and N_t is the total population level, at time t. The dynamics of the disease through the portions of the populations are represented by the derivatives of S or I with respect to time. The time-derivative of the susceptible portion is as follows:

$$\frac{dS}{dt} = \dot{S}_t = a(S_t + I_t) - bS_t - \beta\left(A_t^{cm}, a_t^{pou}\right)S_t + \delta(a_t^m)I_t, \tag{2.2}$$

where a is the population birth rate and is assumed to not be affected by the proportion of people who are infected. This is a reasonable assumption for many waterborne diseases in human populations, i.e., most waterborne diarrheal illnesses are symptomatic for a relatively short period of time, those infected remain fertile and, hence, do not reduce an individual's reproductive ability. For other host organisms, such as those in the cattle industry, such an assumption is more tenuous. Leptospirosis, a waterborne cattle disease, is linked to reproduction losses (Grooms 2006; Dhaliwal et al. 1996).

The rate of movement of population portions from susceptible to infected is determined by the transmission function, denoted as $\beta\left(A_t^{cm}, a_t^{pou}\right)$. It is a function of the size of the water-service neighborhoods represented by A_t^{cm} and a_t^{pou}. In most cases, a reasonable assumption is that increasing levels of A_t^{cm} and a_t^{pou} reduces the population's average transmission rate. One hypothetical exception to this claim could be the case of a biological (or chemical) agent that somehow manages to employ a CM water distribution network as a conduit for new infections (or contaminations). For specific cases, the ability for either CM or POU to reduce transmission depends on the particular disease as well as the particular water-service technology under consideration.

Just as the portion of individuals in the susceptible class is reduced by transmissions, those who are infected and survive rejoin the susceptible class at a recovery rate equal to the function $\delta(a_t^m)$, where a_t^m is the level of medical treatment deployed to the total population. To ensure that healthy people are not given medical treatments, a_t^m is constrained to be less than or equal to the size of the infected portion.

Substituting equation 2.1 into equation 2.2, the time derivative of the susceptible class can be rewritten in terms of only the infected class:

$$\dot{S}_t = a\big((1 - I_t) + I_t\big) - b(1 - I_t) - \beta\left(A_t^{cm}, a_t^{pou}\right)(1 - I_t) + \delta(a_t^m)I_t. \quad (2.3)$$

By assuming that population birth rate is equal to the natural death rate (i.e., $a = b$), further simplification of the susceptible portion's state equation is obtained:

$$\dot{S}_t = bI_t - \beta\left(A_t^{cm}, a_t^{pou}\right)(1 - I_t) + \delta(a_t^m)I_t. \quad (2.4)$$

The $a = b$ assumption imposes a constant population size on the modeled community. This assumption can be relaxed in two directions, one where $a > b$ imposes a growing population and the other where $a < b$ implies a population in decline.

Once again, invoking equation 2.1 can yield the state equation for the infected class from equation 2.4:

$$\begin{aligned} \dot{I}_t = -\dot{S}_t \quad &= (-1)\big(bI_t - \beta\big(A_t^{cm}, a_t^{pou}\big)(1 - I_t) + \delta(a_t^m)I_t\big) \\ &= -bI_t + \beta\big(A_t^{cm}, a_t^{pou}\big)(1 - I_t) - \delta(a_t^m)I_t. \end{aligned} \tag{2.5}$$

Equation 2.5 contains the class (or state) dynamics that are employed later in the setup of the optimal control problem. Next, the transmission and recovery functions are more thoroughly defined to identify more explicit relationships between water services, medical treatment, and the dynamics of the waterborne disease through the population. The transmission function is as follows:

$$\beta\big(A_t^{cm}, a_t^{pou}\big) = \beta^{cm}A_t^{cm} + \beta^{pou}a_t^{pou} + \beta^0\big(1 - A_t^{cm} - a_t^{pou}\big), \tag{2.6}$$

where the natural, or spontaneous, transmission rate β^0 of the disease only affects the portion of the population that receives neither CM or POU water services. Similarly, β^{pou} and β^{cm} are the transmission rates associated with residents receiving CM and POU water services, respectively. Depending on the disease under consideration, the values of the three transmission rates may be different or the same. A typical case where CM and POU do an equally effective job of reducing transmissions (an assumption maintained throughout this essay) can be captured with: $\beta^{cm} = \beta^{pou} = \beta^1$ and $\beta^1 < \beta^0$. In this case, CM and POU water services provide the same level of disease-prevention and, assuming β^1 is quite small, the only portion of the population with significant exposure to the disease are those individuals without any form of water services. Furthermore, if water-service levels are sufficiently high (i.e., $\left(1 - A_t^{cm} - a_t^{pou}\right)$ is sufficiently small), then the population-wide effect of higher, natural transmission rates is, again, small.

The recovery function is defined similarly as a weighted-average of a spontaneous and anthropogenically-altered disease-recovery parameter from the population dynamics of the SIS model:

$$\delta(a_t^m) = \delta^0(I_t - a_t^m) + \delta^m a_t^m, \tag{2.7}$$

where a_t^m is the portion of the total population that receives medical treatment. In this model, administering medical treatment, as it's defined, to individuals who are not infected is not a reasonable policy. Medical treatment only increases the recovery rate and does not impact the transmission (i.e., does not facilitate prevention) of illness. The following constraint is imposed: $a_t^m \leq I_t$. At full treatment of all infected individuals, the following holds: $a_t^m = I_t$. The two recovery coefficients are δ^0, the natural, or spontaneous, rate of recovery, and δ^m, the medically-enhanced recovery rate.

Public Health Expenditures

Introduced in this section are more specifics about the three disease management activities, starting with CM water services (A_t^{cm}). Since CM water services have, relative to POU water services, dynamic properties (i.e. must be constructed, maintained through multiple time periods, and can depreciate), CM water services are represented in the model by a second state variable (the first being the infected portion of the population), which expands and depreciates according to the following equation of motion:

$$\dot{A}_t^{cm} = \frac{(1-A_t^{cm})}{C^w} x_t^w - \gamma A_t^{cm}, \tag{2.8}$$

where A_t^{cm} is the level of build out, with full-infrastructure at $A_t^{cm} = 1$; C^{cm} is a constant component of CM water service cost; x_t^{cm} is a control variable, representing an administrator's expenditures towards CM water services; and γ is a depreciation term used to represent maintenance on existing infrastructure. One of the most important implications for the first term in the CM water-services state equation (i.e., $((1 - A_t^{cm})/C^{cm})x_t^{cm}$) is that expenditures on water supply improvements exhibit decreasing marginal returns. Inverting equation 2.8 yields an expenditure, or cost, function:

$$\begin{aligned} x_t^{cm} &= \left(\dot{A}_t^{cm} + \gamma A_t^{cm}\right)\frac{C^{cm}}{(1-A_t^w)} \\ &= \dot{A}_t^{cm}\left(\frac{C^{cm}}{1-A_t^{cm}}\right) + \gamma A_t^{cm}\left(\frac{C^{cm}}{1-A_t^{cm}}\right). \end{aligned} \tag{2.9}$$

Expenditures to CM (x_t^{cm}) are applied to either new additions (i.e., $\dot{A}_t^{cm}(C^{cm}/(1 - A_t^{cm}))$) or maintenance on existing infrastructure (i.e., $\gamma A_t^{cm}(C^{cm}/(1 - A_t^{cm}))$). Both the new addition and the infrastructure repairs are weighted by a factor (i.e., $C^{cm}/(1 - A_t^{cm})$) that results in increasing marginal costs. With this specification, marginal costs increase to infinity as the level of CM water-service approaches one. This assumption is reasonable for cities with dense central populations and more sparse populations on the outskirts and rural areas, where costs to bring water services to the more rural residents would be increasing with their distance from the city centers; and, ultimately, someone in the population will be so far from the city center that a CM service connection would be prohibitively expensive.

The other two controls in this model, POU and medical treatment, are not represented as state variables, which assumes that POU and medical treatment cannot be stored across time periods. That is, POU water services and medical treatment are completely non-durable, or their annual depreciation rate is set at 100%. This assumption may not be appropriate for all conceivable types of POU devices or household water-treatment systems that are available in the water-treatment marketplace. But in most cases, POU and/or household treatment water systems are less durable than CM water system infrastructure.

The expenditure specifications for POU water services and medical treatment (with 100% annual depreciation rates) are defined as follows:

$$x_t^{pou} = C^{pou} a_t^{pou}, \text{ and} \tag{2.10}$$

$$x_t^{m} = C^{m} a_t^{m}, \tag{2.11}$$

where x_t^{pou} and x_t^{m} are, respectively, the expenditures towards medical treatment of the infected individuals and the expenditures towards POU water service; C^{pou} and C^{m} are constant unit-costs; and a_t^{m}, which was introduced earlier, is the portion of the total population receiving medical treatment and is constrained to be less than the proportion of infected individuals.

For this to be a reasonable method to depict the cost of a medical treatment, the total population must remain constant. A constant total population is assumed when the natural birth and natural death rates are set to be equal. The assumption of constant population is also maintained by the model's omission of disease-induced deaths, or virulence, from consideration. The relaxation of the constant population assumption, in particular, allowing for a growing population is one avenue for future model expansion.

The assumption of negligible virulence, in the context of most developing regions, would not be reasonable. Diarrhea causes an estimated 1.5 million deaths in children under the age of five every year (Wardlaw et al. 2009). But in the context of a highly-developed region, where childhood malnutrition is less severe and where health care institutions are more well-established, a death by waterborne disease is considerably less likely. In the U.S. between 1971 and 2002, there were only 79 recorded deaths from waterborne disease outbreaks associated with drinking water (Reynolds et al. 2008) as compared with millions of deaths worldwide primarily from the countries of Africa and southeast Asia (WHO 2007). A more general model that can accommodate the possibility of virulence is another avenue for future research.

In contrast to the increasing marginal costs of CM water services (equation 2.9), the marginal costs of providing POU water services (equation 2.10) and medical treatment (equation 2.11) are constant across the community. This is a simplifying assumption but provides reasonable outcomes. An argument can be made that either POU or medical services could more accurately be portrayed as a dynamic, stock resource. Cultural familiarity with POU technology and the efficiency of health care institutions can both potentially increase over time. For computational tractability, because additional state variables impose onto models the "curse of dimensionality" (Rust 1997; Woodward, Wui, and Griffin 2005), and because CM water services are considered most appropriate (i.e. more so than the other two), CM is the only disease management strategy to be portrayed with a state variable for the current scope of this study.

2.4 Public Health Manager's Decision

The decision issue formulated by this model does not precisely correspond to the social planner's decision issues as traditionally considered by resource and welfare economists, i.e., including those studied by Goldman and Lightwood (2002) or Gersovitz and Hammer (2004). The agent's decision issue described here may more closely resemble that of a public choice agent in the context of public health management. The deviation from the traditional social planner's decision issues is mainly due to two reasons. First, the social planner's problems consider a more holistic view of social welfare (i.e., inclusive of disease damages as well as income levels and management costs), whereas the objective function here only includes disease damages. Secondly, social planner's decision issues usually are optimized over an infinite time horizon. Here, the time horizon is chosen to bear a closer resemblance to the management decision time-frame likely to be faced by public health and economic development administrators who are appointed, elected, or possess funding for only a limited time. Therefore, the problem is identified as a public health manager's decision with the objective to minimize the damages from waterborne disease over a defined time period subject to a fixed annual budget and the population dynamics of the disease. The damage function could assume a variety of specifications; a simple, linear specification is chosen here:

$$D(I_t) = k_I I_t, \tag{2.12}$$

where the damage from the disease called the morbidity damage ($k_I I_t$); k_I is the per-unit costs of contracting a disease, which is normalized to one. The final equation included in the model is a budget constraint on expenditures, ensuring that the public-health manager spends exactly the full budget:

$$x_t^m + x_t^{pou} + x_t^{cm} = E_t, \tag{2.13}$$

where E_t is the exogenous level of total expenditure. The administrator is tasked with optimally dividing up funds equal to E_t towards the goal of minimizing the damages caused by waterborne disease. The value of E_t, essentially the size of an administrator's budget determined by either a higher-ranking administrator, a local budget board, or some legislative action, can conceivably vary across time periods and can conceivably be considered a stock in the case of some management regimes. For this essay, the issue of fluctuating or storable levels of E_t is not addressed; hence, E_t is considered as a constant through time. Mathematically, the problem of the administrator is:

$$\max_x \int_0^T \left((-1)k_I I_t\right) e^{-rt}\, dt, \tag{2.14}$$

Subject to:

$$\begin{aligned}\dot{I}_t = \quad & -bI_t + \left(\beta^{cm} A_t^{cm} + \beta^{pou} a_t^{pou} + \beta^0\left(1 - A_t^{cm} - a_t^{pou}\right)\right)(1 - I_t) \\ & -(\delta^0 (I_t - a_t^m) + \delta^m a_t^m),\end{aligned} \tag{2.15}$$

$$\dot{A}_t^{cm} = \frac{(1 - A_t^{cm})}{C^{cm}} x_t^{cm} - \gamma A_t^{cm}, \tag{2.16}$$

$$x_t^m = C^m a_t^m, \tag{2.17}$$

$$x_t^{pou} = C^{pou} a_t^{pou}, \tag{2.18}$$

$$x_t^m + x_t^{pou} + x_t^{cm} = E_t, \tag{2.19}$$

$$a_t^m \leq I_t, \tag{2.20}$$

$$a_t^{pou} \leq 1 - A_t^{cm}, \text{ and} \tag{2.21}$$

$$A_t^{cm}, a_t^{pou}, a_t^m \geq 0. \tag{2.22}$$

The objective function and many of the constraints have been discussed previously. Two additional constraints that require further explanation are equations 2.20 and 2.21. Equation 2.20, if binding, suggests medical services are distributed to the entire infected portion of the population. Equation 2.21, if binding, suggests water services, which can be either CM or POU, are distributed to the entire population, both susceptible and infected. Each of these constraints imposes two important conditions on the public health manager's decision issue for the context of many waterborne illnesses. Many cases could be made where such assumptions are reasonably relaxed. Wealthy households that already have access to CM water services may choose to further augment the quality of their household water supply with a POU system that serves to enhance drinking water aesthetics as well as to provide an additional barrier against the transmission of disease. Chemical and biological contaminants are reduced to a target level by a municipal water provider per specific standards set out by the Safe Drinking Water Act (1974). Specific cases may exist where some of these contaminant levels (e.g, arsenic contamination) can be further reduced by POU devices, thereby giving an incentive and reasonable justification for households to adopt both CM and POU services.

The model assumes there is no terminal value on either stock variable, proportion infected, or CM infrastructure. Arguably, a negative value on the stock of those infected and a positive value on the stock of CM would be reasonable assumptions. One expected result from a positive salvage value being placed on terminal CM stock would be to motivate CM investments in later periods compared to results of the model application. Additional modeling considerations are left as avenues for future research.

Hamiltonian and First Order Conditions

Developed in this section is a Hamiltonian for the health manager's decision (equations 2.14-22). From the Hamiltonian, a set of first-order conditions are generated, and the economic implications of several of the first-order conditions are discussed. By first substituting constraints 2.17 and 2.18 directly into the budget constraint (equation 2.19), the problem is shortened, but qualitatively unchanged, and yields the following Hamiltonian:

$$H \equiv (-1)(k_I I_t)$$
$$+\lambda_t^I \left(-bI_t + \left(\beta^{cm} A_t^{cm} + \beta^{pou} a_t^{pou} + \beta^0 \left(1 - A_t^{cm} - a_t^{pou}\right)\right)(1 - I_t)\right.$$
$$\left. -(\delta^0 (I_t - a_t^m) + \delta^m a_t^m)\right)$$
$$+\lambda_t^A \left(\frac{(1-A_t^{cm})}{C^{cm}} x_t^{cm} - \gamma A_t^{cm}\right)$$
$$+\phi_t^E \left(E_t - C^m a_t^m - C^{pou} a_t^{pou} - x_t^{cm}\right)$$
$$+\phi_t^m (I_t - a_t^m)$$
$$+\phi_t^{pou} \left(1 - A_t^{cm} - a_t^{pou}\right). \tag{2.23}$$

The following first-order conditions are generated from this Hamiltonian:

$$\frac{dH}{dx_t^{cm}} \equiv \lambda_t^A \frac{(1-A_t^{cm})}{C^{cm}} - \phi_t^E = 0, \tag{2.24}$$

$$\frac{dH}{da_t^{pou}} \equiv \lambda_t^I\big((\beta^{pou} - \beta^0)(1 - I_t)\big) - \phi_t^E C^{pou} - \phi_t^{pou} = 0, \tag{2.25}$$

$$\frac{dH}{da_t^{m}} \equiv \lambda_t^I(\delta^0 - \delta^m) - \phi_t^E C^m - \phi_t^m = 0, \tag{2.26}$$

$$\frac{dH}{dA_t^{cm}} \equiv \lambda_t^I\big((\beta^{cm} - \beta^0)(1 - I_t)\big) + \lambda_t^A\left(\frac{x_t^{cm}}{C^{cm}} - \gamma\right) - \phi_t^{pou} = \mathrm{r}\lambda_t^A - \dot{\lambda}_t^A, \tag{2.27}$$

$$\frac{dH}{dI_t} \equiv (-1)(k_I)$$

$$+\lambda_t^I\left(-b - \left(\beta^{cm}A_t^{cm} + \beta^{pou}a_t^{pou} + \beta^0\big(1 - A_t^{cm} - a_t^{pou}\big)\right) - \delta^0 I_t\right)$$

$$+\phi_t^m = \mathrm{r}\lambda_t^I - \dot{\lambda}_t^I, \tag{2.28}$$

$$\frac{dH}{d\phi_t^E} \equiv E_t - C^m a_t^m - C^{pou}a_t^{pou} - x_t^{cm} = 0, \tag{2.29}$$

$$\frac{dH}{d\phi_t^m} \equiv I_t - a_t^m = 0, \text{ and} \tag{2.30}$$

$$\frac{dH}{d\phi_t^p} \equiv \big(1 - A_t^{cm} - a_t^{pou}\big) = 0. \tag{2.31}$$

Some basic insights can be gained from an interpretation of this set of first-order conditions. Rearranging equation 2.24 generates:

$$\lambda_t^A = \phi_t^E \frac{C^{cm}}{(1 - A_t^{cm})}, \tag{2.32}$$

where, in optimality, the marginal value to the objective function of another unit of water supply infrastructure (λ_t^A), or the shadow price of water infrastructure, is equal to the shadow price of the budget constraint (ϕ_t^E) weighted by the marginal cost of an additional unit of CM water infrastructure (i.e., $C^{cm}/(1 - A_t^{cm})$). That is, the optimality rule of equating marginal benefits and costs holds. Similar results are found for POU services:

$$\lambda_t^I\big((\beta^{pou} - \beta^0)(1 - I_t)\big) = \phi_t^E C^{pou} + \phi_t^{pou}, \tag{2.33}$$

where the shadow value of an additional infected individual (i.e, λ_t^I) multiplied by the difference in a susceptible individual's infection rate with POU services (i.e., $(\beta^{pou} - \beta^0)(1 - I_t)$) is equal to the shadow price of the budget share multiplied by the unit cost of another unit of POU (i.e., $\phi_t^E C^{pou}$) plus the shadow price of switching an individual from receiving no water service to receiving either CM or POU services (i.e., ϕ_t^{pou}). More intuitively, when considering to deploy a unit of POU to a household, the public health manager must consider ability of the POU device to reduce infections (i.e., $(\beta^{pou} - \beta^0)(1 - I_t)$) and the value of a marginal reduction in infections (i.e., λ_t^I). Together, those values are weighed against the marginal value of the budget change (i.e., $\phi_t^E C^{pou}$), which can be thought of as the POU opportunity costs, i.e., funds spent on POU can no longer be spent on CM or medical services.

Similarly, for medical intervention, the first-order conditions present a comparison of marginal benefits and costs:

$$\lambda_t^I(\delta^0 - \delta^m) = C^m \phi_t^E + \phi_t^m, \tag{2.34}$$

where the shadow value of an additional infected individual (i.e., λ_t^I) multiplied by the difference in that infected individual's recovery rate with medical intervention (i.e., $(\delta^0 - \delta^m)$) is equal to the shadow price of the budget share multiplied by the unit cost of another individual's medical intervention (i.e., $C^m \phi_t^E$) plus the shadow price of providing medical intervention to only infected individuals (i.e., ϕ_t^m). Here, as with CM and POU water services, the rule of setting marginal costs equal to marginal benefits holds.

Switching Points

In the previous section, marginal benefits and marginal costs of system controls are discussed in the context of individual controls in isolation from the other controls. This section takes that concept one step further and discusses the comparison of marginal net benefits across two or more controls. Controls are selected into the optimal management regime based on their relative marginal net contribution to the Hamiltonian. When two controls have equal marginal net benefits, the manager is indifferent as to the use of either control. In the event that two controls do not have equal marginal net benefits, the control with the greatest marginal net benefit is implemented first, with the intensity of that activity limited by either the budget constraint or another system constraint. As examples, some of the other constraints that could be binding are that only infected individuals can be treated with medical care (equation 2.20); water-service coverage cannot be redundant (i.e., households cannot have both CM and POU provided by a utility); and water-service coverage cannot exceed the total population (equation 2.21). If a system constraint is binding and the budget constraint is not, then any remaining funds in the budget are applied to the management activity with the next greatest marginal net benefit.

The term "switching point" refers to the condition of equal marginal net benefits, where on either side of the switching point a different management strategy is preferred (i.e., switching point implies the marginal net benefit curves cross each other, and are not simply tangent). Therefore, upon crossing a switching point, the preferred policy *switches* from one strategy to another.

Case 1: POU and Medical Allowed, CM Not Allowed (i.e., $A_t^{cm} = x_t^{cm} = 0, \forall\, t$)

This section includes a discussion of several special cases of the more general model described above. Starting with the simplest of such cases, consider if CM water services are not feasible (i.e., $A_t^{cm} = 0, \forall\, t$) due to a region's absence of CM know-how or the absence of materials. This reduces the public health manager's decision to a choice between two abatement activities, POU or medical treatment. In optimality, the marginal net benefits of these two activities can be equated as follows:

$MNB_t^{pou} = MNB_t^{m}$, or

$$\lambda_t^I(\beta^{pou} - \beta^s)(1 - I_t) - \phi_t^E C^{pou} - \phi_t^{pou}$$
$$= \lambda_t^I(\delta^0 - \delta^m) - C^m \phi_t^E - \phi_t^m. \quad (2.35)$$

For this case, the marginal net benefits are simply the Hamiltonian first-order conditions (equations 2.25 and 2.26). The Hamiltonian is linear with respect to these two particular controls, which yields a solution whereby the management activity with the greatest marginal net benefit at any given time is implemented to the fullest extent allowed by the system constraints. Assuming that funding levels are insufficient to deploy either POU or medical activities at maximum capacity (i.e. $E_t/C^m \leq I_t$and $E_t/C^{pou} \leq 1$), the following condition exists in optimality for every point in time:

$$\text{If } \frac{MNB_t^{pou}}{MNB_t^m} = \frac{\lambda_t^I\left((\beta^{pou}-\beta^s)(1-I_t)\right)-\phi_t^E C^{pou}-\phi_t^{pou}}{\lambda_t^I(\delta^0-\delta^m)-\phi_t^E C^m-\phi_t^m}\begin{Bmatrix} > \\ = \\ < \end{Bmatrix}1,$$

$$\text{then} \begin{cases} a_t^{pou*} = E_t/C^{pou}, a_t^{m*} = 0 & \text{POU preferred} \\ E_t = C^m a_t^m + C^p a_t^{pou} & \text{Indifferent} \\ a_t^{pou*} = 0, a_t^{m*} = E_t/C^m & \text{Medical prefered} \end{cases} . \quad (2.36)$$

The results described in equation 2.36 imply that the activity yielding the greatest marginal net benefit is deployed until the budget is exhausted. If the budget constraint is relaxed (by supposing that the budget is sufficient to deploy all of the most preferred activity with some amount left over), then the amount left over can be applied to deployment of the 2^{nd} most preferred activity. For a graphical description, consider the numerical example illustrated in Figure 2-2. In the region to the left of s (Figure 2-2), POU is the preferred activity. Since the x-axis represents the infected portion of the community, this is the same region where infection levels are lowest. The intuitive reasoning for this characteristic is that a community with lower infected and higher susceptible portions of the population benefits the most from preventing the larger portion of susceptibles from contracting an illness.

Additionally, notice the benefits of POU decrease as infected populations increase (i.e., as one moves rightward along the x-axis). Intuitively, this makes sense given that POU is a preventive activity. The additional value of prevention is lower at higher levels of infection because there are fewer susceptible individuals to gain benefit from prevention, and those currently infected gain nothing from further prevention efforts in the short term.

For Figure 2-2, the MNB_t^m curve is assumed to be positive and constant, but in reality, this may not be the case. Suppose the difference between the spontaneous and the medically-enhanced recovery rates are minimal, or non-existent (i.e., $\delta^0 - \delta^m = 0$). This situation explains the policy of industrialized regions providing universal water services. In these regions, individuals who become ill generally take autonomous

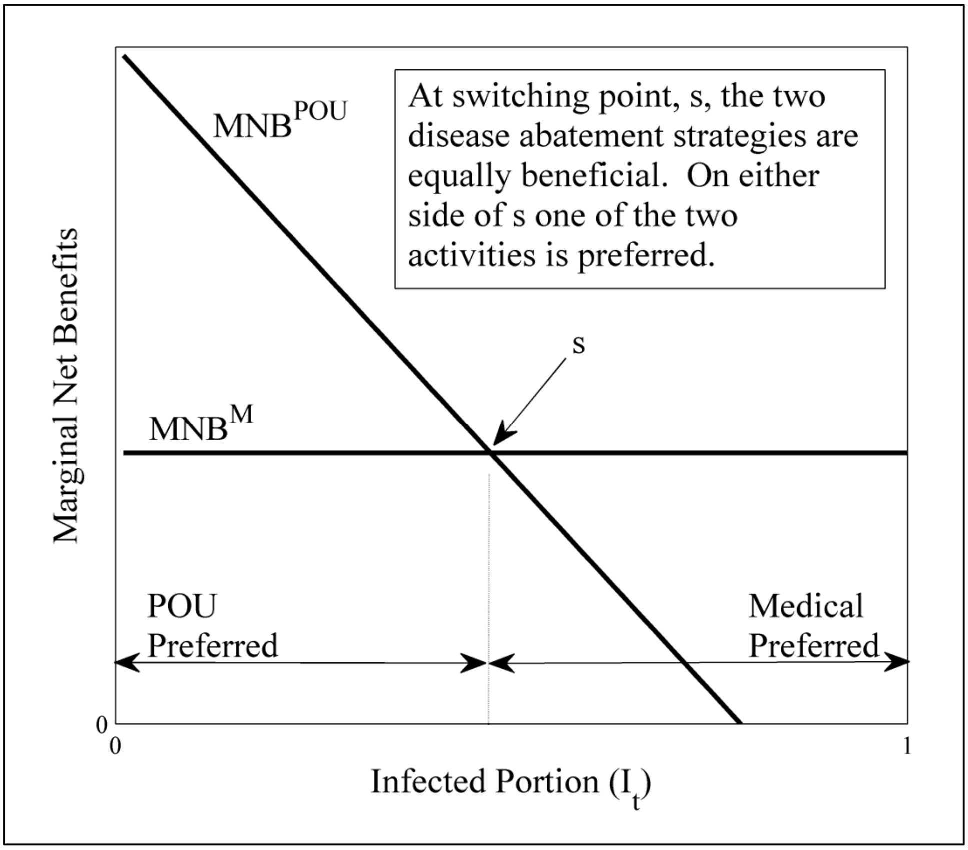

Figure 2-2. Marginal net benefit curves (MNB) and switching point (s) for waterborne disease management system with two abatement activities, point-of-use (MNB^{POU}) water services (equation 2.25) and medical services (MNB^{m}) (equation 2.26).

Note: This illustration uses the following parameter values: $\lambda_t^I = -100$, $\beta^{pou} = 0.01$, $\beta^0 = 0.2$, $\phi_t^E = 1$, $C^{pou} = 3$, $C^m = 6$, $\phi_t^{pou} = 1$, $\delta^0 = 0.5$, and $\delta^m = 1.0$.

measures, i.e., they are wealthy enough to take a day off of work to recover. Due to these individuals' self-imposed convalescence, the medically-enhanced recovery rate stemming from social policies to medicate ill individuals does not greatly improve from the "spontaneous" recovery rate. Therefore, the marginal net benefits of medical coverage that specifically targets common waterborne illnesses is small and, if costs are sufficiently large, may be negative. In either case, whether they are negative or positive, as portrayed in Figure 2-2, the marginal net benefits of medical treatment may be greater than, equal, or less than the marginal net benefits incurred by prevention, depending on the community's portion of infected.

Considering a different scenario, the case could be that all points along the MNB_t^{pou} curve are negative. This might occur as a result of C^{pou} being sufficiently large. This scenario describes many, if not most, incidences of waterborne illness that are incurred during recreation at a natural water body. Certainly, the technological knowledge and ability exists to sufficiently treat water in natural systems to prevent these infections, but doing so is simply, prohibitively costly. The implication is that society has revealed its preference to endure a limited number of infections and treats those individuals that get infected with medical attention. Or, borrowing from the case described in the previous paragraph, those infected individuals are wealthy enough to recover on their own.

The point at which MNB_t^m exceeds MNB_t^{pou} indicates the most beneficial disease management activity switches from POU to medical. This point is denoted by s. In the aforementioned examples discussed, the exact location of the switching point (i.e., the values associated with MNB_t^m and MNB_t^{pou}) can vary greatly across applications, depending on the community being considered, the water source (or sources), and any of the large array of institutional, cultural, and economic factors that contribute to waterborne illness transmission and the coverage of medical and water-service systems.

To serve as an intuitive example, one might consider the relative locations of the marginal net benefit curves for a more specific region or health issue, like those encountered in the Valley. In 1999, two Valley counties with significant populations of colonia residents reported notably higher rates of infection from sanitation and water-related diseases than found in the rest of Texas and the U.S. (Table 2-1).

Warner and Jahnke (2003) suggest that higher incidences of some of these diseases could be driven by sanitation conditions in the colonias. Assuming that greater infection rates in Cameron County are driven by colonia residents, then the infection rates across only the county's colonia residents would be greater still than the rate across all of Cameron County. From the model, greater levels of infected implies that public health managers at the colonia-level accounting stance (i.e., from their specific institutional perspective) perceive a community in which medical treatment is more valuable than preventative water-service activities.

<u>Case 2: All Activities (CM, POU, and Medical) Allowed</u>

CM water services and POU water services confer the same types of benefits into the system; that is, both types of services reduce population transmission rates by factors of their associated transmission rates, respectively, β^{cm} and β^{pou}. As before, the optimality condition of equal marginal net benefits applies, with the MNB_t^{CM} coming from the first-order conditions equation 2.24:

$$MNB_t^{x_t^{cm}} = \lambda_t^A \frac{(1-A_t^{cm})}{C^{cm}} - \phi_t^E \ . \qquad (2.37)$$

The marginal net benefits of CM expenditures are more complex than the other two activities because the benefits of additional spending depend on the stock-level of CM infrastructure. Consider Figure 2-3 for a graphical interpretation.

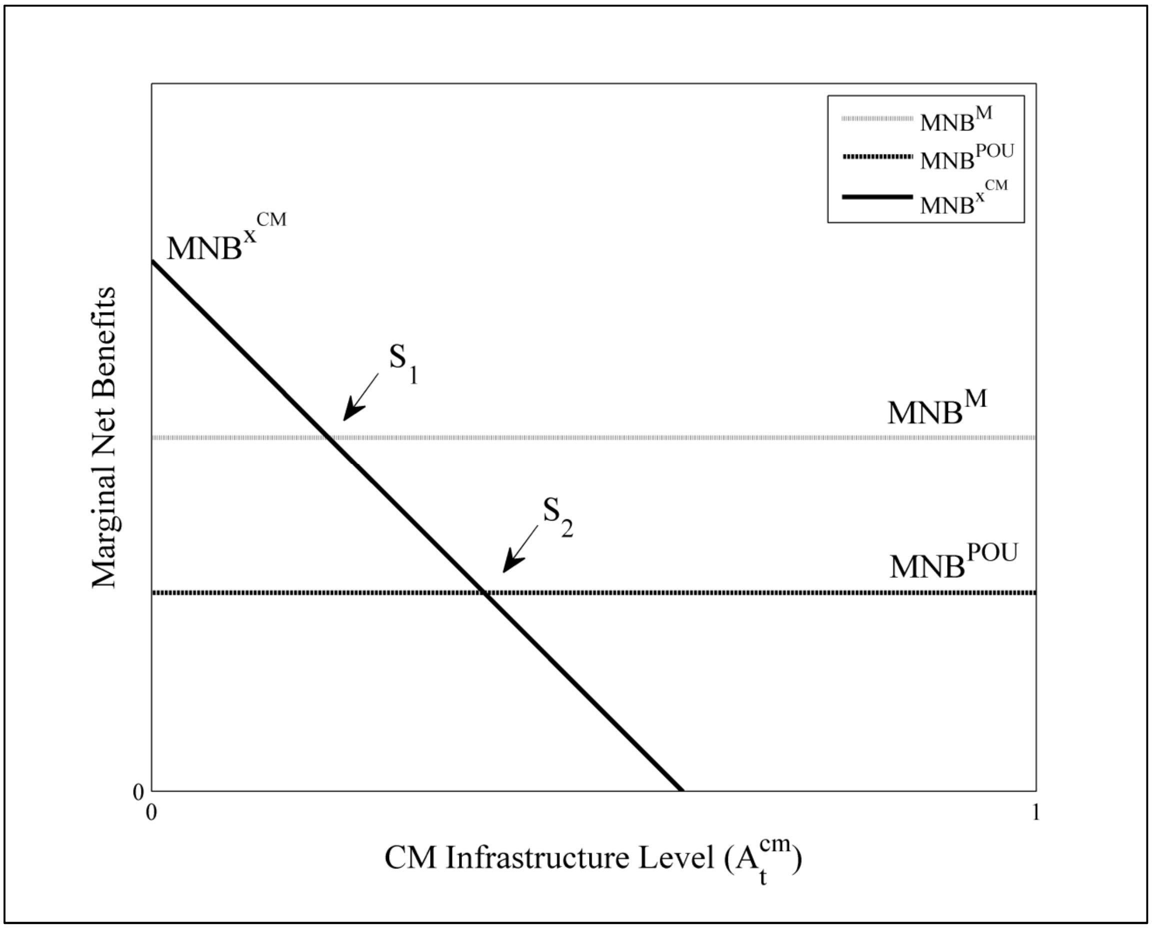

Figure 2-3. Marginal net benefit curves (MNB) and switching points (s_1, s_2) for disease management systems with three management activities, centralized-municipal water services (MNB^{xCM}) (equation 2.24), point-of-use water services (MNB^{POU}) (equation 2.25), and medical services (MNB^{M}) (equation 2.26).
Note: This illustration uses the following parameter values: $\lambda_t^I = -100$, $\beta^{pou} = 0.01$, $\beta^0 = 0.2$, $\phi_t^E = 1$, $C^{pou} = 3$, $C^m = 4$, $\phi_t^{pou} = 1$, $\delta^0 = 0.5$, $\delta^m = 1.0$, $v = 0.0$, $\lambda_t^A = -100$, $C^{cm} = 4$.

Notice in Figure 2-3 at CM levels to the left of s_1, where CM levels are low, the marginal net benefits of CM investment (the solid line) exceed the other two disease management strategies. With additional investment to increase the stock of CM infrastructure (i.e., moving rightward along the x-axis) the marginal net benefit of additional CM investments declines. Intuitively, this makes sense in the context of a centrally-populated community, where to extend CM water services to the outskirts of the community (which could extend into vast and remote locations) becomes increasingly expensive to both deliver services initially and maintain those investments through time. Eventually, the value of CM expansion falls. Then, precisely at s_1, the most socially-beneficial activity becomes the purchase and distribution of POU water services.

Infected levels are held constant in Figure 2-3. Across the entire range of CM infrastructure levels, the marginal net benefits of POU (dotted line) exceed the marginal net benefits of medical treatment (dashed line). The dominance of POU over medical treatment in this example implies that the infected levels are sufficiently low; recall Figure 2-2, where locations to the left of s are associated with higher marginal net benefits of POU.

As another more practical example, consider that across colonia residents in half of rural households and a fifth of urban households there is incomplete plumbing (Warner and Jahnke 2003). In such an environment, a public health manager with a colonia-level accounting stance perceives a public health situation that is relatively lower in CM (or arguably POU) water services than the situation perceived by a public health manager with a city-wide or county-level accounting stance. A county-level public health manager observes a public health environment with a higher level of CM stock, and, therefore, may prefer to use medical or POU services in lieu of expanding the CM at a marginally increasing cost.

2.5 Numerical Results

A discrete version of the model (Appendix A) is implemented to generate numerical results. The model is parameterized using information from Hidalgo County, Texas (Appendix B) and solved using an evolutionary computation algorithm (Appendix C). This section presents an example application of the model, rather than representing a literal policy recommendation.

The particular context under consideration in the numerical example abstracts away from several important water-related disease aspects. The numerical application assumes disease transmission path occurs through the ingestion of contaminated drinking water. An argument can be made that disease transmissions also occur as a result of a combination of insufficient wastewater and sanitation systems and poor hygiene. In the context of household water use, POU systems and CM systems may not provide equivalent protection from disease. In particular, water used for household hygienic purposes may be treated if the household is apart of a CM system and may not be treated if the household depends on a POU system. In addition to simplifying the dynamics of disease transmission, the model is based on a single public health decision-maker for the Hidalgo County case study. Such an administrative position does not exist in Hidalgo County. Public health management for the county is a product of a variety of agencies and groups at many levels of administration, i.e., state, county, city, and colonia. These realities, and many others, are not explicitly considered in the remainder of this essay and remain avenues for future research and for greater refinement of the model.

Baseline Results

The baseline scenario evaluated numerically employs a planning horizon of six years. Such a planning horizon can be considered too short or too long, depending on the authority and the discipline that is considering the length of a water-health program. Many economic development projects, including those designed to enhance water and sanitation services, have relatively short planning horizons, perhaps three years or less. Water-supply planning, especially at the regional level, typically considers a longer planning horizon. In the context of climate change, such a planning horizon can equal and exceed half a century. For this paper, six years provides a time frame of sufficient length to explore implications of model applications. Later sections investigate the effect of shortening the time horizon from six years to two. Such a comparison may be useful in the context of local, short-term political offices, such as a mayor, city council, or county commissioners' court.

Table 2-2 contains the results from the optimization of the baseline scenario based on Hidalgo county parameters with starting values for the state variables coming from estimated levels of infected population and CM water coverage (Appendix B). In model year one, the budget share is optimally divided between POU and medical activities, with 0.31 going to POU and 0.69 going to medical. This means both POU and medical-services activities have greater marginal net benefit than centralized-municipal services at that point in time in the program since no investment is made in CM. Of POU and medical, POU has the greater marginal net benefit. This is known because the water-services constraint is binding (the portion receiving "none" water services is zero), whereas the medical-services constraint is not (the portion of infected receiving medical treatment is 0.58). In more practical terms, a binding water-services constraint means

Table 2-2. Optimization results for the baseline model in the context of water and health management for Hidalgo County, Texas.

Parameter/Variable description	Model notation	Reference Equations						
Time	t (year)		1	2	3	4	5	6
Budget shares								
Centralized-municipal	x_t^{cm}/E_t	2.8, 2.9, 2.13	0.00	0.00	1.00	1.00	0.00	0.00
Point-of-use	$a_t^{pou}C^p/E_t$	2.6, 2.10, 2.13	0.31	1.00	0.00	0.00	1.00	1.00
Medical	$a_t^m C^m/E_t$	2.7, 2.11, 2.13	0.69	0.00	0.00	0.00	0.00	0.00
Water Services								
Centralized-municipal	A_t^{cm}	2.8, 2.9	0.96	0.86	0.78	0.81	0.82	0.74
Point-of-use	a_t^{pou}	2.6, 2.10	0.04	0.13	0.00	0.00	0.13	0.13
None	$1 - A_t^{cm} - a_t^{pou}$	2.6	0.00	0.01	0.22	0.19	0.05	0.13
Medical Services								
Infected portion of total population	I_t	2.1, 2.5, 2.7, 2.12	0.15	0.09	0.10	0.17	0.16	0.12
Medically-treated portion of total population	a_t^m	2.7, 2.11	0.09	0.00	0.00	0.00	0.00	0.00
Medically-treated portion of infected	a_t^m/I_t	2.7	0.58	0.00	0.00	0.00	0.00	0.00

that POU devices are distributed to every individual in the community who does not already have CM, so that universal water services are achieved; that is, every individual (or household) has either POU or CM.

Expenditures on medical treatment for year one, being the second most preferred strategy, are in the amount of the budget less the expenditures already made on POU. Expenditures on CM are zero, indicating that the marginal net benefit of that strategy in model year one is lower than for the other two strategies. An alternative presentation of selected data from Table 2-2 is illustrated in Figures 2-4 and 2-5, where budget shares and water-service coverage levels are presented graphically.In model year two and for the rest of the years in the baseline scenario, water services are estimated to be more beneficial than medical treatment. Considering Figure 2-5, the influence of capital depreciation is evident. The brick-patterned bar representing stock levels of CM follows a downward trend when considering the entire six year planning horizon. The large re-investment in CM in years three and four (Figure 2-4) is reflected in the temporarily increasing levels of CM stock, portrayed across years three, four, and five (Figure 2-5). The CM investments in the middle years are triggered by the declining CM stock levels in the early years. One assumption of the analysis is that as CM stock declines, investments in CM become marginally less expensive. Therefore, once CM stock declined through years one and two, CM investments became more desirable because the marginal net benefits increased per dollar investment. Recalling Figure 2-3, the CM investment is triggered by leftward movement along the x-axis (declining levels of CM) until a switch point is crossed. CM investment activities cease altogether in years five and six because the decision-maker assumes the community receives no value from CM stock beyond the planning horizon of six years.

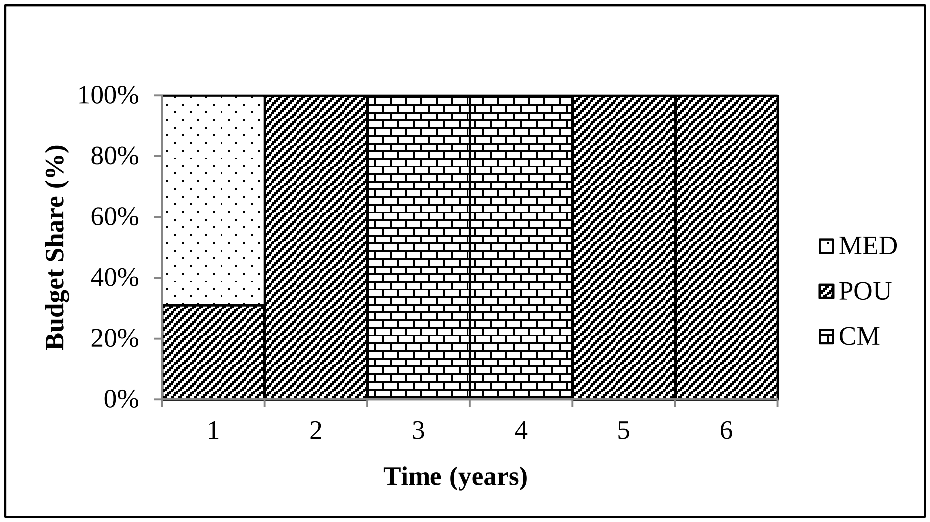

Figure 2-4. Budget shares in the baseline model of three disease management strategies, medical treatment (MED), point of use water systems (POU), and centralized municipal water systems (CM).

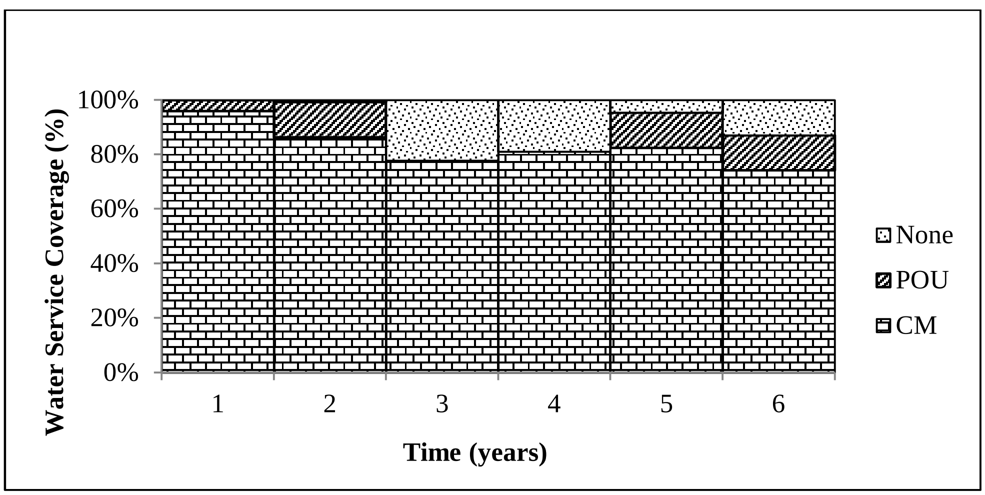

Figure 2-5. Water service coverage levels representing no water service (None), point of use systems (POU), and centralized municipal systems (CM) in the baseline model.

Conceptually, two dynamic forces are at work that dictate investments in CM stock. One force is the depreciation of CM capital stock, which results in investment (or re-investment or maintenance efforts) incur greater marginal net benefits to the community. The other force is the impending end of time for the modeled decision-maker, who gains nothing from CM's durability once time in the model ends. The former force induces CM expenditures in model years three and four, and the latter force reduces (to zero) CM expenditures in model years five and six. This suggests that a longer planning period could favor CM expenditures in years five and six.

The absence of medical care in model years two through six can be explained by diarrheal illnesses being relatively common and pervasive, and frequently mild cases are not addressed with medical care. Moreover, the model abstracts away from disease virulence. If disease virulence were allowed to occur in the model, then the social cost of an infection-induced death would likely increase the marginal net benefits of medical care activities. Medical care, by increasing the infected group's rate of recovery, would thereby reduce the occurrence of disease-induced deaths. But in this essay, the analysis is targeted towards the Valley and Valley colonias which, while impoverished relative to the rest of Texas and the U.S., do not have the problems of child and infant mortality due to waterborne illnesses that exist in the more severely impoverished parts of the globe.

Figure 2-6 contains an alternative portrayal of the baseline model results where POU investments are plotted through time in CM stock space. In model year one, the implementation of POU is restricted by the water-services constraint (i.e., the point $t=1$ is located on the water service size constraint). In model year two, POU implementation

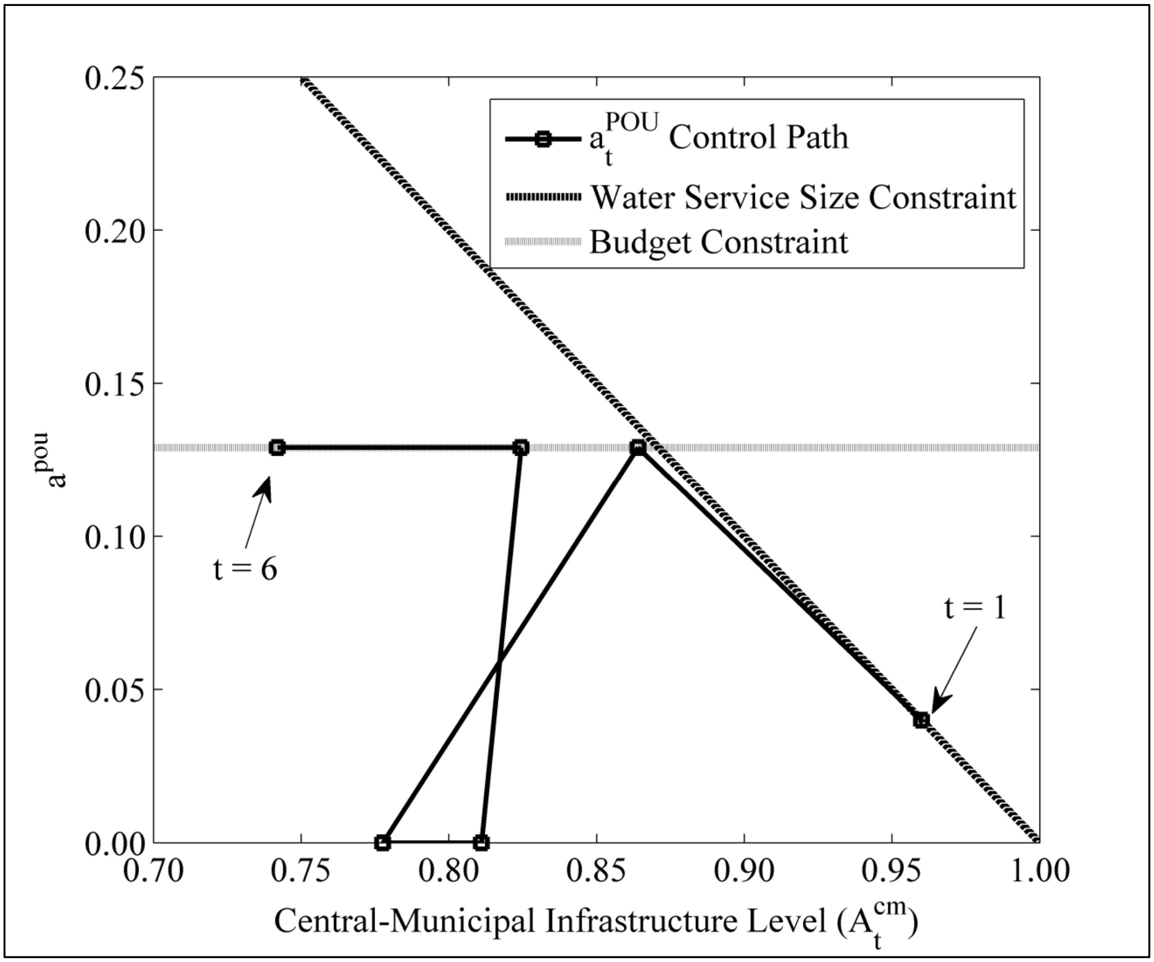

Figure 2-6. Optimal control path for point-of-use (a_t^{pou}) with institutional constraints at different levels of central-municipal infrastructure (A_t^{cm}) using baseline values of a public health manager's problem for Hidalgo County, Texas.

is constrained by the budget as there are insufficient funds to provide the entire population with water services, and population portion of size 0.01 goes without water services (Table 2-2). In model year three and four, no POU is implemented. Public health expenditures in these periods are characterized by full investment of available funds into CM stock, as shown by the rightward movement of the control path between years three and four, and four and five. In the final two model years, once again, POU is the most beneficial management activity and is constrained only by the size of the manager's budget.

Varying the Manager's Budget

One expected result from varying the size of the manager's budget (i.e., E_t) is that damages from the illness fall as expenditures on illness mitigation increase. This is demonstrated to be the case in these sensitivity runs, the full results of which are included as Appendix D. The most interesting result in this permutation of the model is the changes in the temporal-distribution of CM investments.

Budget Set at 50% of the Baseline. Consider Figures 2-7 and 2-8 which represent budget shares and water-service coverage where the budget size is reduced to 50% of the baseline. Relative to the baseline CM investments, in this scenario, CM budget shares are occurring sooner and consume the entirety of the manager's budget for three years instead of two. In the baseline case, the manager has sufficient funds to build CM levels to "acceptable" levels starting in years three and four. With a reduced budget, the manager has incentive to more immediately restore CM, and obtain the benefits of its durability sooner rather than later. CM investments in year one are zero because in year one the CM stock is sufficiently high (i.e., marginally increasing costs so high) that the marginal net benefit to additional CM is lower than the other two activities. Ultimately, beginning in years five and six, the end of time for the manager dominates the management choice and POU expenditures comprise the full budget.

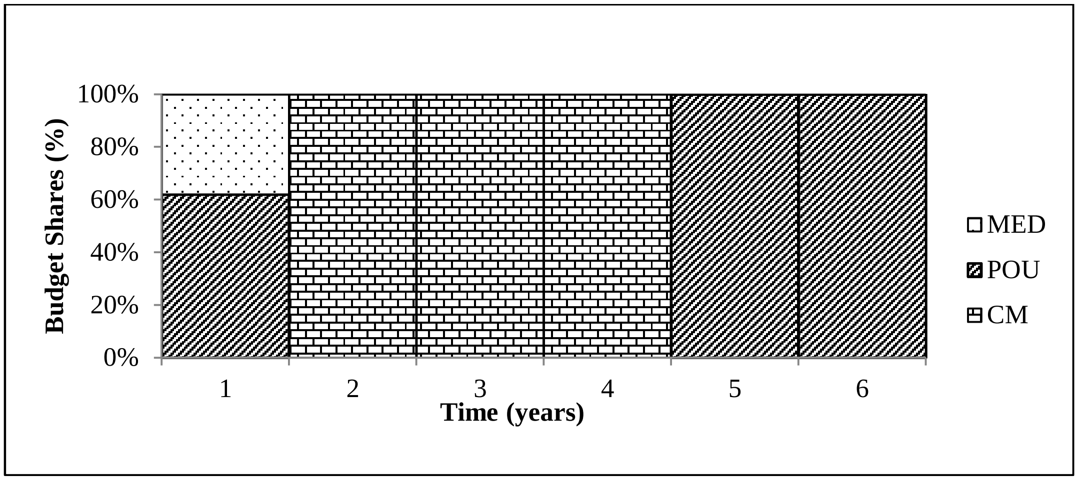

Figure 2-7. Budget shares in the model of three disease management strategies, medical treatment (MED), point of use water systems (POU), and centralized municipal water systems (CM), with the budget size reduced to 50% of the baseline.

The water service coverage representation (Figure 2-8) displays the results of the manager's expenditure decisions. Most notably, notice the depreciation of CM between years one and two and years five and six are more rapid than between years two, three, and four, when the budget shares for CM investment are 100%. Comparing the final level of water services for 50% reduction in budget to the baseline (Figure 2-5), it is clear that the smaller budget has resulted in a modeled community that, at the end of the time horizon, has less CM infrastructure. Specifically, the low budget scenario ends with 68% of the population having CM water service, whereas the baseline scenario ends with 74%.

<u>Budget Set at 200% of the Baseline.</u> As might be anticipated when the budget size doubles, the community's well being improves. This is reflected in cumulative

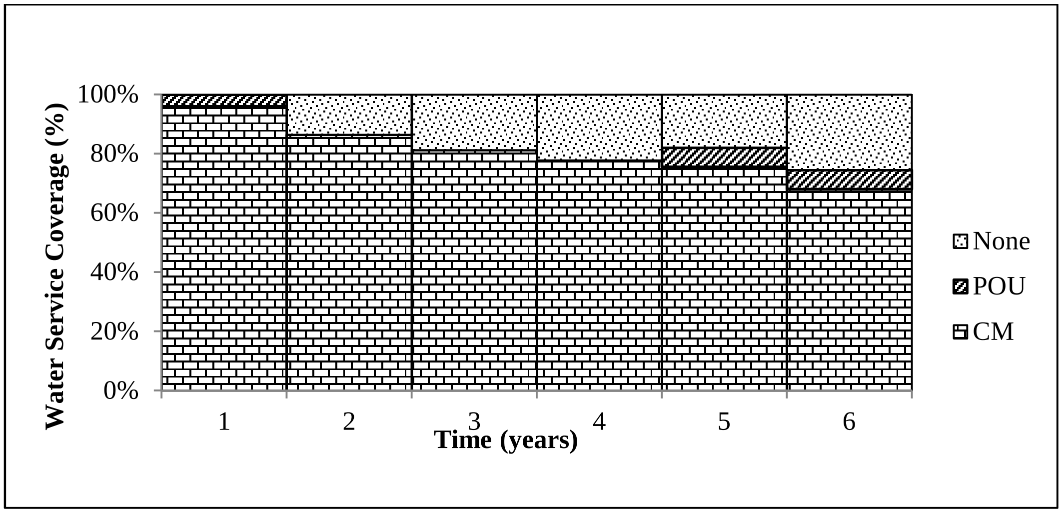

Figure 2-8. Water service coverage levels representing no water service (None), point of use systems (POU), and centralized municipal systems (CM) in the baseline model, with the budget size reduced to 50% of the baseline.

damage levels, respectively 0.54 for the wealthier scenario and 0.68 for the baseline scenario (Table 2-2). Also in the increased budget scenario, the CM investments take on a much different distribution through time than in the baseline scenario (comparing Figure 2-9 to Figure 2-4), and complete water service coverage (via either CM or POU service) is maintained throughout all six years (Figure 2-10). In terms of budget shares, rather than having two or three years where CM investments comprise the entirety of the manager's budget, as was the case in the two previously discussed cases, the manager with the larger budget manager invests in CM in five of six time periods with investments slightly exceeding 50% of the total budget in just one year. The end of time influence on the manager is more evident, visually, in the wealthier scenario's budget

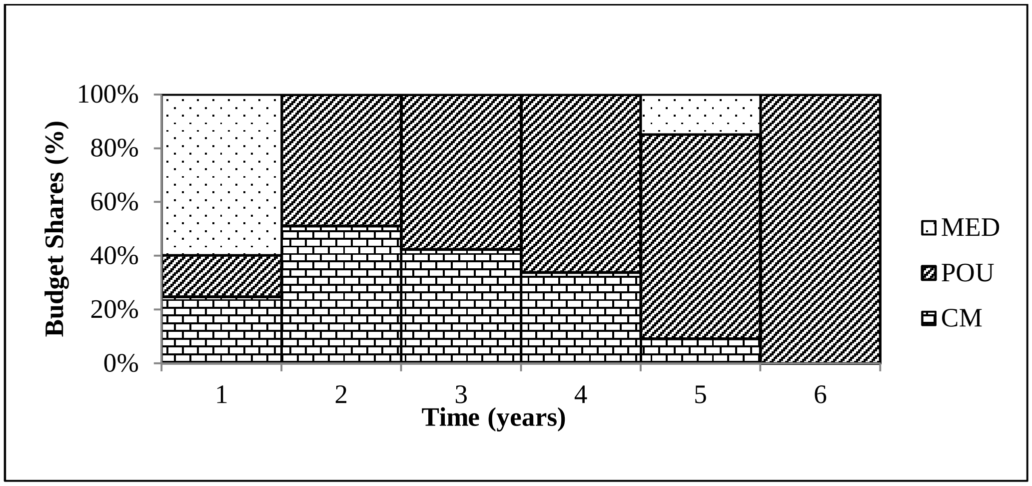

Figure 2-9. Budget shares in the model of three disease management strategies, medical treatment (MED), point of use water systems (POU), and centralized municipal water systems (CM) in a sensitivity scenario with the budget size increased to 200% of the baseline.

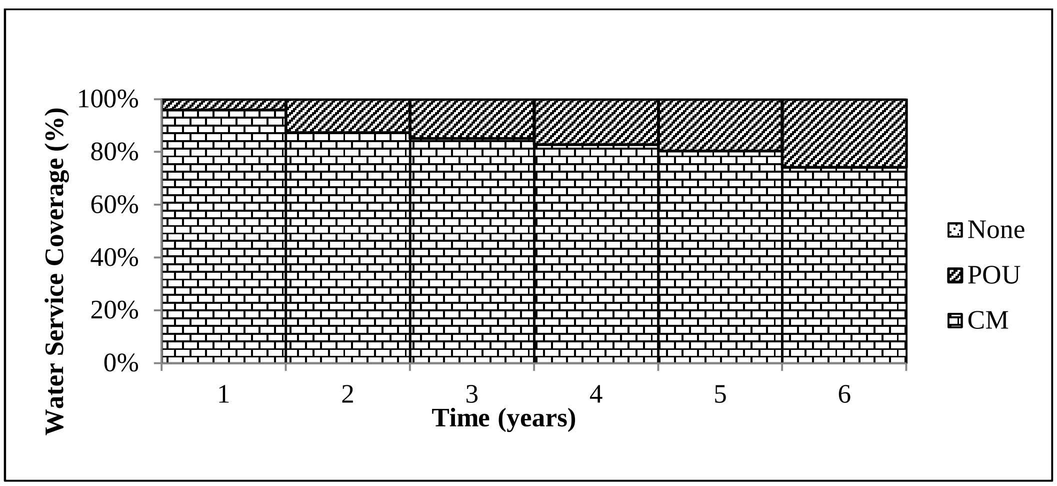

Figure 2-10. Water service coverage levels representing no water service (None), point of use systems (POU), and centralized municipal systems (CM) in a sensitivity scenario with the budget size increased to 200% of the baseline.

shares. In Figure 2-9, CM investment peaks in the second year and then investment levels consistently decline every year thereafter, equaling zero in the final year.

Varying the Capital Depreciation Rate

Reported in this section is the effect of capital depreciation rate. By assumption, a higher capital depreciation rate results in lower levels of CM infrastructure. The reduction in CM stock cannot be overcome by additional CM investments or expenditures in other management activities, and thereby results in higher levels of the portion of infected population persisting through time. Notice in Figure 2-11 that the endpoint (i.e. $t = 6$) of the scenario with the lowest depreciation rate (program A in Figure 2-11) is located at the furthest north and west of the other endpoints (i.e., endpoint of B at $t = 6$ and endpoint of C at $t = 6$). Because capital depreciation rates in scenario A are relatively low compared to B and C, the CM stock is more durable, extending the time that initial CM users can benefit from lower disease transmission rates. On the other end of the spectrum, the endpoint of the program with the greatest capital depreciation rate (C, $t = 6$) is located furthest south and east in the Figure 2-11, indicating that the program is associated with higher disease prevalence and lower CM stock in the final model year.

Varying the Planning Horizon

Another important factor impacting the solution is the planning horizon for the public health manager. For this scenario, the time horizon is varied exogenously. Many development and research related public health projects carry different requirements to funding entities and government bodies. Some of the requirements may explicitly or implicitly limit the planning horizon (or extend, in very rare instances) for a given public health manager. To investigate the effect that a difference in planning

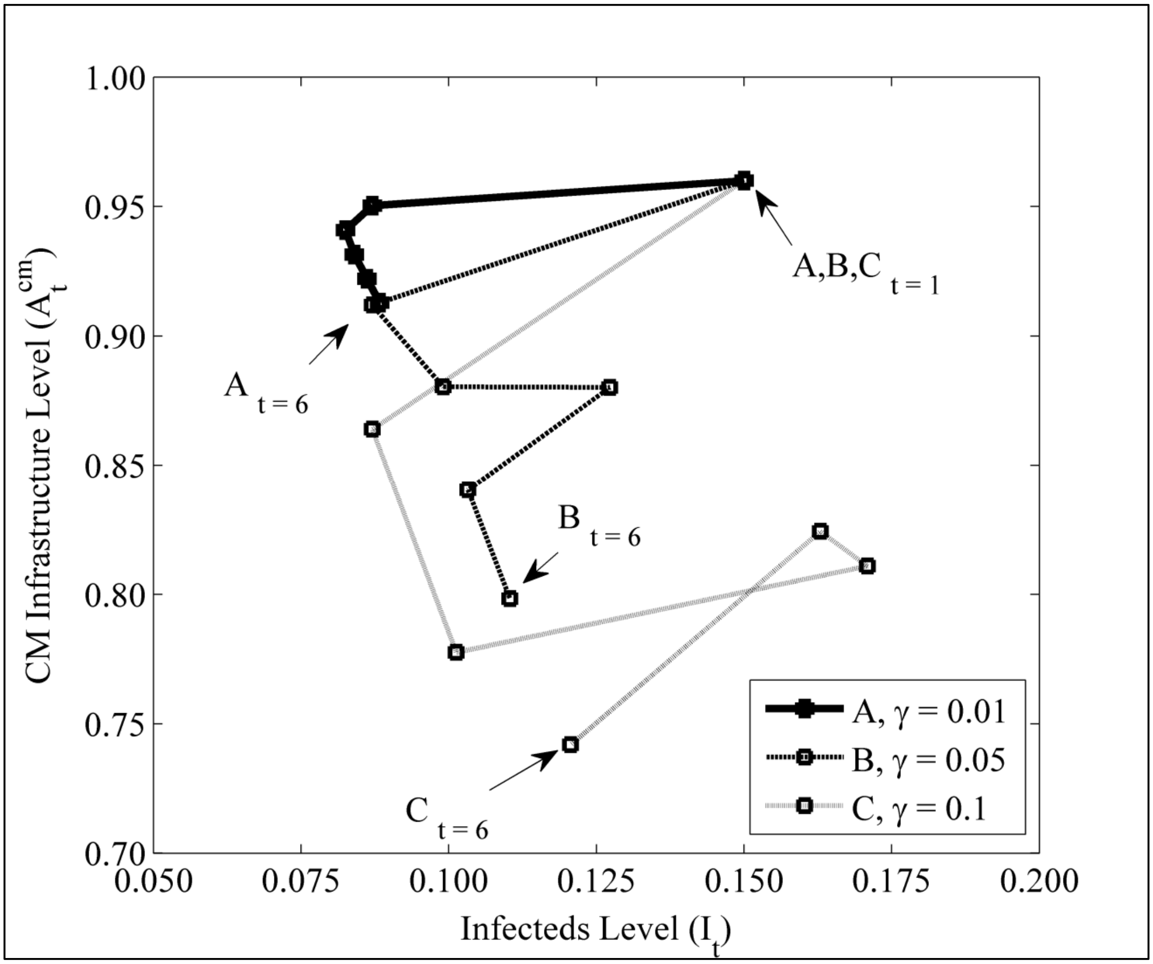

Figure 2- 11. Optimal state-paths for the two stock variables, CM water services and infected population levels, as the capital depreciation rate (A: $\gamma = 0.01$; B: $\gamma = 0.05$; C: $\gamma = 0.10$) is varied in the context of a public health manager's problem for Hidalgo County, Texas.

horizons may have on the measured public health outcome, the model is solved using two different planning horizons, the baseline of six years and a shorter planning horizon of two years.

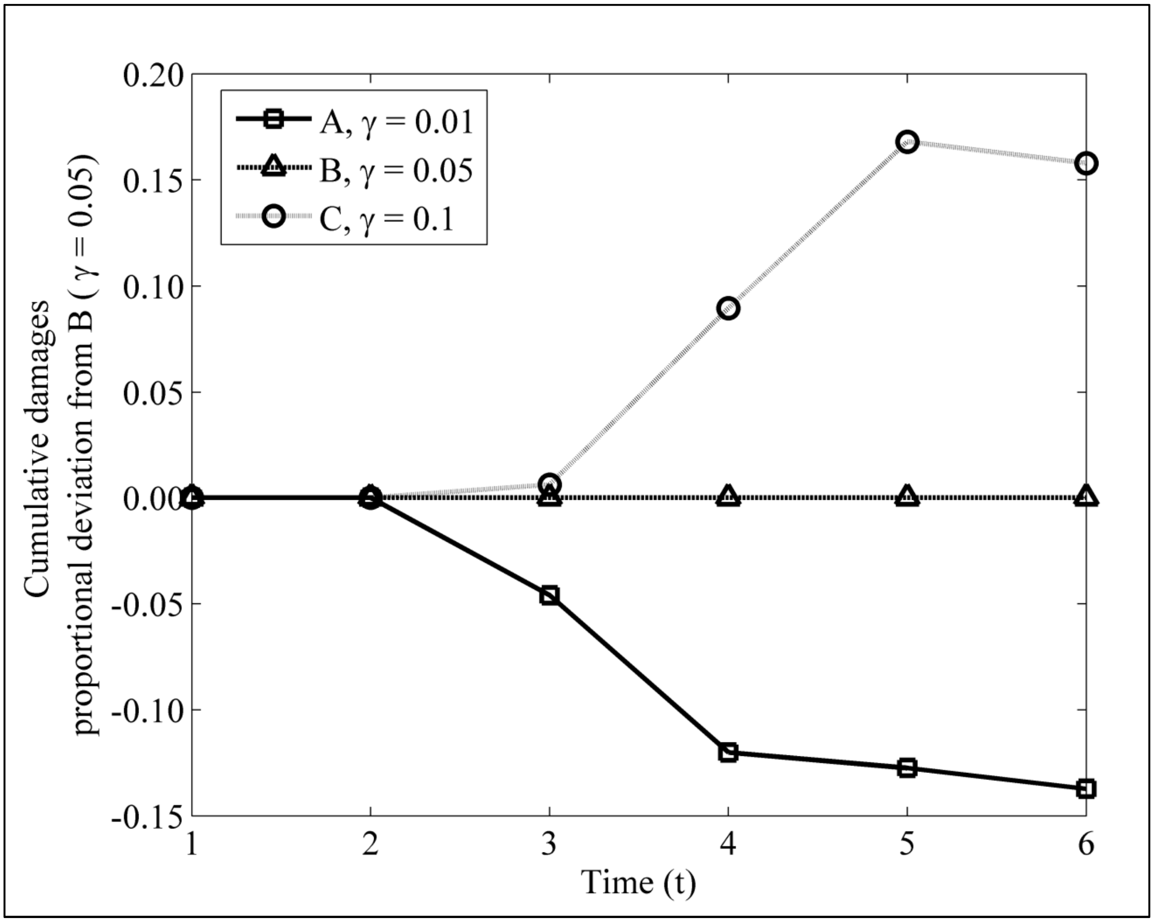

Figure 2-12. Proportional changes in cumulative damages to a community from infections of a waterborne disease as the capital depreciation rate (γ) of central-municipal (CM) infrastructure is varied (A: $\gamma = 0.01$; B: $\gamma = 0.05$; C: $\gamma = 0.10$) in the context of a public health manager's problem for Hidalgo County, Texas.

While the ending points of each program may provide suggestive evidence that scenarios with greater capital depreciation rates leave the community less well off, more conclusive evidence is found by examining the cumulative damages of each scenario. This evidence is depicted in Figure 2-12. The greatest cumulative damages over the 6-year program are found in the scenario with the most rapid depreciation of CM capital stock, the dotted-line representing scenario C.

To reasonably compare results from two scenarios with different planning horizons, the scenario with the shorter time horizon is solved in a sequence, recursively, utilizing outputs from the first run as inputs for the second run, and so on. More explicitly, for the scenario with a two-year planning horizon, results are generated solving the model for two years. Using the final levels of the state variables (CM stock and portion of infected) from the first iteration as starting values in a subsequent iteration, the model is solved again. The final state levels from the second iteration are again used as inputs into a third iteration. Combining the results from all three iterations, each of which was two years, a composite six-year result is compared with the baseline scenario which employs a six-year planning horizon as discussed previously.

One of the more clearly illustrated differences between the two planning horizon scenarios is the difference in CM infrastructure stock accumulation over time. In particular, the CM stock in the two-year program precipitously descends from the starting value of 0.96 to the relatively lower level of 0.74. In the six-year scenario, reinvestment in CM infrastructure during periods three and four slows the decline of CM stock. Also, as illustrated in Figure 2-13, the relative locations of the end points for the two planning horizons suggests that the six-year program is preferred, due to its location further to the north and west, where CM levels are high and infection levels are low. This suggestion is confirmed by examining Figure 2-14, which displays the cumulative damages of both programs, and, indeed, the cumulative damages of the two-year program, while equal or lower than the 6-year program in five of six years, exceeds the six year program in the final year of the comparison.

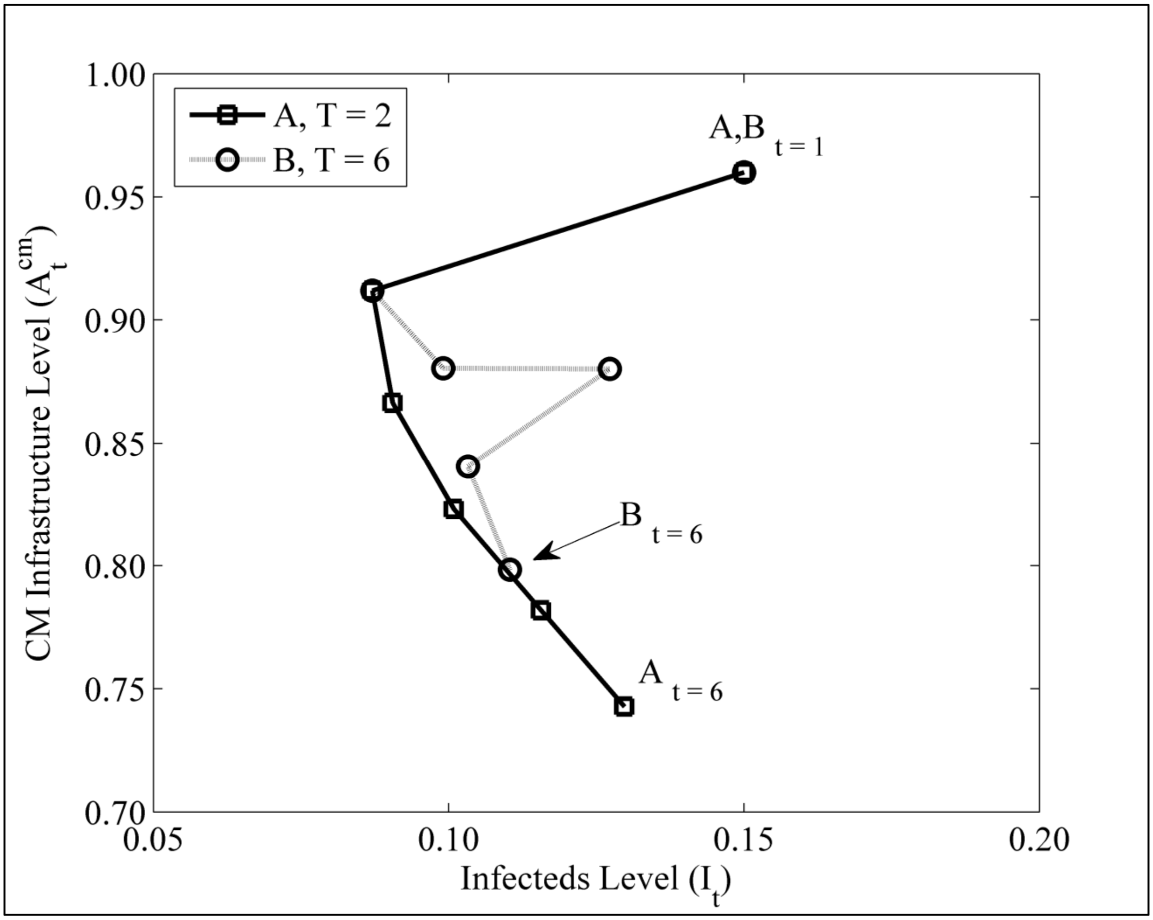

Figure 2-13. Optimal state-paths for the two stock variables, CM water services and infected population levels, as the planning horizon varies (A: $T = 2$; B: $T = 6$) is varied in the context of a public health manager's planning horizon for Hidalgo County, Texas.

The difference in cumulative damages across the two scenarios is an example of the impact and the relevance that institutional design can have on social goals, such as public health. Public administrators elected or appointed to shorter-term offices are incentivized to manage for the short-run. The outcome displayed in Figure 2-14 demonstrates that the modeled public health program is managed better when the

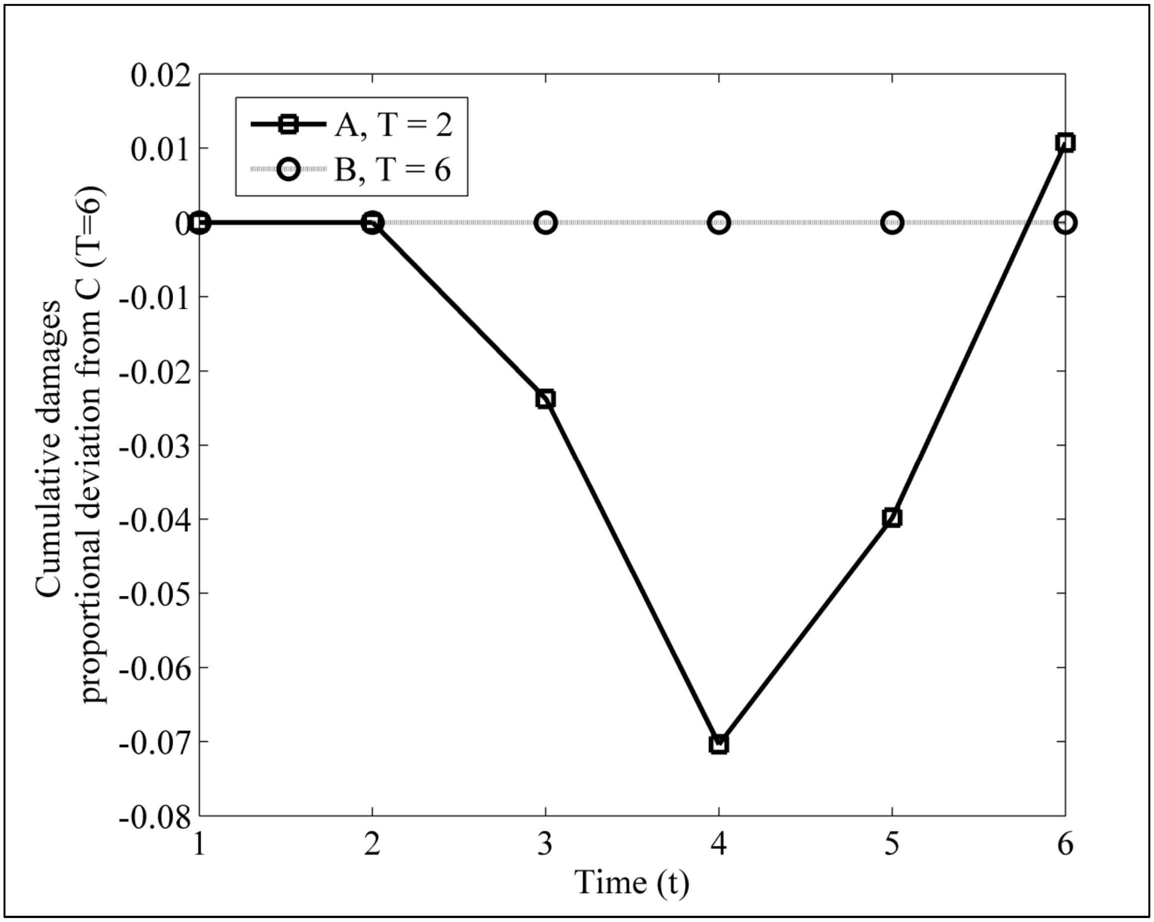

Figure 2-14. Proportional change in cumulative damages of two scenarios, as the planning horizon varies (A: $T = 2$; B: $T = 6$) in the context of a public health manager's problem for Hidalgo County, Texas.

planning time horizon is longer, given the parameters used in this model and focusing on the end point (i.e., cumulated damages at $T = 6$).

Varying the Depreciation Rate and the Panning Horizon

The objective of this section is to examine the influence of depreciation rate and planning horizon when they are varied together. In other words, does the planning horizon become more important or less important for the objective of minimizing community damage as the capital depreciation rate increases/decreases? The results are summarized in Table 2-3. With a planning horizon of two years, increasing the capital depreciation rate from 0.05 to 0.10 increases the total damages to the community by 0.20 (or 20%); as compared to increasing the capital depreciation rate from 0.05 to 0.10 with a six year program, the total damages to the community increase by 0.16 (or 16%).

A clear conclusion is that lower capital depreciation and longer planning horizons improve public health management outcomes. The far right column of Table 2-3 indicates that an increasing capital depreciation rate results in less desirable outcomes. The influence of capital depreciation seems considerably stronger than the influence of time horizon, but this may be a consequence of the parameter values selected for analysis. Over a smaller range of capital depreciation rates, it is perceived

Table 2-3. The present value of cumulative damages (TD) for four scenarios of the public health manager's problem in the context of Hidalgo County, Texas, where the time horizon is varied (T) and the capital depreciation rate is varied (γ).

		Capital Depreciation (γ) (rate)		Proportional change in TD as γ increases from 0.05 to 0.10
		0.05	0.10	
Time Horizon (T) (years)	2	**0.60**	**0.72**	0.20
	6	**0.59**	**0.68**	0.16
Proportional change in TD as T increases from 2 to 6		-0.01	-0.05	

Note: The cumulative damages are the bolded values.

the influence on total damages would likely be smaller, but still maintain the same qualitative directions. However, for a community involved in planning, the time planning horizon and budget level are essentially the primary factors to be considered.

2.6 Summary and Conclusions

This paper contributes a model of public health and water service management to the health and economics literature. Though not empirically tested, application of the model can explain the reasoning behind certain public health choices, as a result of a variety of systemic circumstances, including budget size, accounting stance, planning horizon, and rates of capital depreciation. Several of the model's theoretical aspects are presented and discussed. The optimal disease management activities are selected on the basis of the marginal net benefits that accrue to the Hamiltonian function. Public health managers with a relatively narrow scope, such as those working exclusively with colonia residents perceive a greater proportion of infected individuals and therefore are expected to perceive greater marginal net benefits to medical treatment relative to preventative measures, such as POU. Greater levels of investment in CM stock are associated with lower marginal net benefits to CM expansion. Greater levels of infection of the public are associated with reduced marginal net benefits associated with POU.

A case study is developed to shed light on institutional characteristics of public health and water systems of the Valley. The model is applied to Hidalgo County, Texas, where a small portion of the population does not have access to standard levels of water and wastewater services. The numerical results reinforce the importance of budget size, capital depreciation, and institutional design, in the form of public health planning horizons, to the welfare of the modeled community. The size of the manager's budget dramatically affects the distribution of CM investments through the first years of the public health program. In the latter years, declining CM investments occur. This is a result of the public health manager's perception of the end of time in the model, after which the manager receives no additional benefit from the durability of CM stock.

The manager's planning horizon and the durability of CM stocks are shown to play a role in the well-being of society. Greater capital depreciation rates and shorter time horizons are shown to be associated with lower community welfare. Scenarios with shorter planning horizons invested less in CM stock. Lower capital depreciation rates allow the community to benefit from more durable CM stocks, which prevents new infections and reduces disease damages.

Several limitations and future avenues of research have already been mentioned, but are also included here. This model is highly generalized in this essay, but could still be generalized further, for example, by incorporating the effects of changes to the population size. A non-stationary population-size matters to disease management for several reasons. Population growth can result from birth rates, in which case new members of the population increase the size of the susceptible population, thereby changing the marginal net benefits of preventative measures relative to treatment measures. Alternatively, population growth can result from immigration, in which case new members of the population may be proportionally more, less, or equally infected as the community. Depending if infected people or susceptible people are joining the community, the optimal public health management scheme will change. As one example, results from this study indicate that increasing levels of infection decreases the marginal net benefits of POU water services.

One particularly interesting avenue to explore is the inclusion of disease-induced death rates, or virulence. Disease mortality in the developing world is an significant issue for public health. Including disease mortality in the model described in this essay would likely enhance the marginal net benefit of medical treatment. This may explain, why in areas where there are disease-induced deaths from water-borne diseases, medical treatments are a greater priority than water-supply enhancements. Another avenue to explore is the allowance of a dynamic budget, where the public health manager could borrow and/or store funding. Results from the case study are not intended to be broad generalizations, as they are contingent on the choice of parameter values. The data employed to parameterize the case study are assembled from literature and secondary sources. New data that can be identified or collected would contribute to more accurately tailoring the generalized model to generate numerical results specific to particular regions and illnesses.

Other components of the model that fail to fully capture reality include the linear cost and the complete non-durability of POU water services and medical treatment. Arguments could be made that POU services have some durability and that medical services would eventually encounter increasing marginal costs due to, perhaps, congestion of medical facilities. The continuous nature of CM stock is also an abstraction. CM investments are generally considered “lumpy”. In the case of a single municipal facility and its distribution system, the facility is constructed at a given point in time to serve a discrete portion of the current community's population. Additionally, the effects of capital depreciation to the facility would not occur at a continuous rate. A more realistic description of depreciation is that in year *t*, CM water service coverage is 100%. Then in year *t+15* after a natural disaster, a construction accident, or by some spontaneous force, a pipeline ruptures and leaves water service coverage at perhaps 82%. Modeling any of these items more explicitly is expected to adjust the relative positions of the marginal net benefit curves, and thereby have an effect on optimal disease management activities. The intention of the model is to capture the most important relative characteristics of each of these activities. For example, the characteristic that CM infrastructure is more like a stock than POU devices, even though certain POU devices could be considered stocks. As another example, while CM stocks do not in reality decay at a rate in exact proportion to the size of the stock, CM decay is inevitable and, on average, occurs at some constant depreciation rate. These types of modeling challenges are intrinsic to all efforts directed at the generalization and simplification of complex problems, such as deciding the best approach to manage a community's water supply system and public health.

CHAPTER III

THE WATER MARKET FOR THE TEXAS LOWER RIO GRANDE VALLEY*

3.1 Introduction

The middle and lower portions of the Rio Grande basin of Texas have overall remained outside of the "Water War" variety of banner news headlines. This accomplishment deserves attention, given this area's exposure to near record-setting drought (TWDB 1998), shortfalls in water deliveries from Mexico (Robinson 2002), and exceptional rates of population growth (U.S. Census Bureau 1993, 2007). The Rio Grande (River) originates from headwaters in Colorado, flows through New Mexico, and passes into Texas at El Paso. From El Paso to the Gulf of Mexico, the Rio Grande serves as the international boundary between Mexico and the United States.

Regional water-supply management on the U.S. side of the lower and middle portions of the Texas-Mexico stretch of the River is accomplished through cooperative efforts of several organizations, including: the Rio Grande Regional Water Planning Group (Region M); the Texas Commission on Environmental Quality (TCEQ), specifically TCEQ's Office of the Rio Grande Watermaster (Watermaster); and the International Boundary and Water Commission (IBWC) (Table 3-1). In addition to

Table 3-1. Regional water groups of the Falcon-Amistad region of the Rio Grande basin in Texas, 2009.

Falcon-Amistad water market area	
Counties:	Cameron, Hidalgo, Willacy, Starr, Jim Hogg, Zapata, Webb, Maverick, Dimmit

Rio Grande Watermaster Program	
Function:	Administer, account, and enforce water rights for the Texas Rio Grande Basin
Harlingen Office	
Function:	Conduct Watermaster functions for lower Basin
Counties:	Cameron, Hidalgo, Starr, Willacy, and Zapata
Eagle Pass Office	
Function:	Conduct Watermaster functions for middle Basin
Counties:	Brewster, Dimmit, Hudspeth, Jeff Davis, Jim Hogg, Kinney, Maverick, Presidio, Terrell, and Val Verde

Rio Grande Regional Water Planning Group	
Function:	Coordinate long-range water supply planning by bringing together stakeholders representing a variety of interests
Counties:	Cameron, Hidalgo, Jim Hogg, Maverick, Starr, Webb, Willacy, and Zapata

Rio Grande Regional Water Authority	
Function:	Assist in water deliveries from Rio Grande, desalination, water supply, wastewater treatment, agricultural water conservation, solid waste, state and federal funds; certify water rights held in the Authority's counties
Counties:	Cameron, Hidalgo, Starr, Webb Willacy, and Zapata (excluding the City of Laredo)

Lower Rio Grande Valley Development Council	
Function:	Serves as an administrative agent for the Rio Grande Regional Water Planning Group
Counties:	Cameron, Hidalgo, and Willacy
Website:	http://www.lrgvdc.org/water.html

Source(s): Rio Grande Watermaster Program (2009); Rio Grande Regional Water Planning Group (2009); Lower Rio Grande Valley Development Council (2009); Rio Grande Regional Water Authority (2009).

these groups, the region has a market for the temporary use and for the permanent entitlement of surface water rights from the River.

TCEQ (2009b) refers to water rights in the middle and lower Texas Rio Grande basin as being served by the Falcon-Amistad system. The system is so named for the two reservoirs servicing the area. Similarly, this essay refers to the water right market (i.e. trades and leases of water rights) in this area as the Falcon-Amistad water market, and emphasis is made to classify the market as a subsection, or a tool, of the regional water management system. The Falcon-Amistad system encompasses the Texas counties (Cameron, Dimmit, Hidalgo, Jim Hogg, Maverick, Starr, Webb, Willacy, and Zapata) roughly situated along the Rio Grande from just downstream of the Amistad Reservoir to the mouth of the River at the Gulf of Mexico (Figure 3-1).

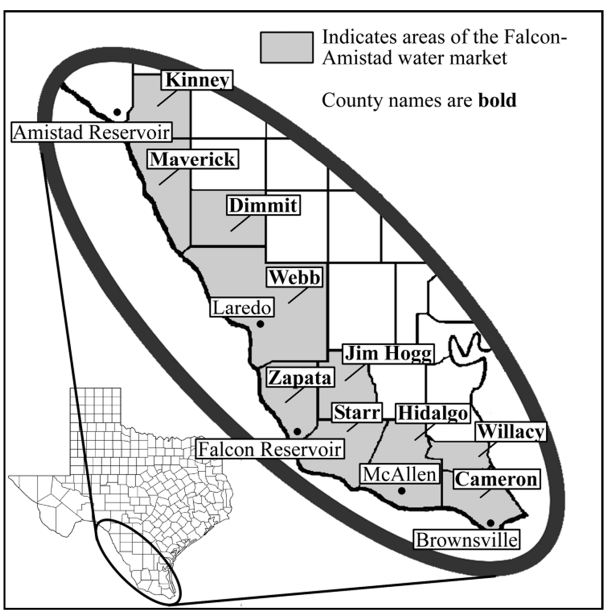

Figure 3-1. The location of the Falcon-Amistad water market area.
Source(s): adapted from Burke et al. (1994).

Immigration-fueled U.S. population growth is maintaining a strong pace in the Falcon-Amistad region, and has accelerated since the 1970s. According to U.S. Census data from 1970 to 2000, average annual population growth rates of three metropolitan statistical areas in the Falcon-Amistad region rival other U.S. cities in high-growth, water-stressed areas (U.S. Census Bureau 1993, 2007).

As regions experience water scarcity, water resource specialists, such as those in the Rio Grande basin of New Mexico, study institutional methods to improve water conservation (Ward et al. 2007), as well as investigate market mechanisms to manage drought (Hadjigeorgalis 2008). More generally, measuring the effectiveness of water marketing and identifying conditions that permit successful water marketing have been frequent topics of study in recent years with reviews by Hadjigeorgalis (2009), Chong and Sunding (2006), and Kaiser and McFarland (1997). The Falcon-Amistad water market provides an example of such a market-based tool serving a diverse, regional water management system that is experiencing constrained supply and increasing demand.

In addition to population growth, the Texas Lower Rio Grande Valley (Valley) (i.e., the collective name for the four southernmost counties of the Falcon-Amistad region: Cameron, Hidalgo, Starr, and Willacy) has witnessed a series of droughts, starting in the late 1980s (Figure 3-2) (National Climatic Data Center 2007). None of these more recent individual droughts have been as severe as the drought of record during the 1950s, but combining the length of term for all of these droughts reveals the area enduring dry conditions for 60% of the time between 1990 and the end of 2007 (Figure 3-2).

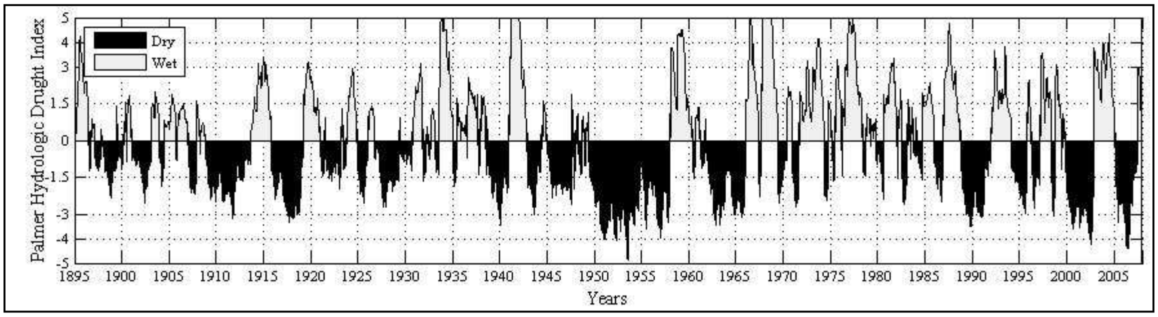

Figure 3-2. The Palmer Hydrologic Drought Index for a portion of the Texas Lower Rio Grande Valley (i.e., Hidalgo and Cameron Counties).
Source(s): National Climatic Data Center (2007).

The Valley is home to a productive agriculture sector. Since initial water rights adjudication in 1971, agricultural users have held the majority of water rights in the Valley, as well as in the Falcon-Amistad system at large (NRS 2006; Stubbs et al 2003). The quantity of water associated with agricultural and municipal water rights has not remained constant. From the initial allocation in 1971 to early 2007, in conjunction with municipal population growth and municipal boundary expansion, 158 million cubic meters (Mm3) (or 127,760 acre feet (af)) of water have been added to municipal water supplies (Jarvis 2007). This addition to the region's municipal water supply is the result of a legal and administrative process that converts a water right from agricultural use to municipal use. The reduction of irrigated farmland associated with the 158 Mm3 (127,760 af) of water converted to municipal water rights during 1971 to 2007 is approximately 381 square kilometers (km2) (94,300 acres or 147 square miles) (Jarvis 2007).

Beyond being a case study with challenging climatic and demographic characteristics, the regional management of the Falcon-Amistad region exhibits water management policies that resemble proposed policies that are under consideration as potential modifications to, and arguably improvements upon, the riparian doctrine that dominates the eastern and Midwestern U.S. Wollmuth and Eheart (2000) and An and Eheart (2006) compare two possible water allocation policies in the context of an agricultural-irrigation-only corridor of a riparian zone. One policy regime is called a “Non-prioritized fixed-volume permits” and the other is termed “Fractional flow set-aside.” Temporarily borrowing their terminology, the Falcon-Amistad system can be thought of as a hybrid regime of “Fixed-volume permits for some; fractional flows for others.” The real-world experiences of the Falcon-Amistad system can provide guidance and insight to water managers and stakeholders in riparian areas of the U.S. who are considering modifications and alternatives to their current policies.

Another feature that is somewhat unique to the Falcon-Amistad system and relevant to other regional management groups considering new policy is the ability for irrigation water rights holders to make use of available storage capacity in the system’s reservoirs. Irrigation water rights holders can “bank” their water month to month, and year to year, in what essentially constitutes a water account that is administered by the Watermaster. Giving irrigation water right holders the option to store their water for future use makes these agents aware of a specific type of opportunity cost associated with using their water; i.e., water that is diverted today must be at least as valuable in use as the discounted value of that diversion in the future. Diverters aware of this opportunity cost will engage in more efficient behavior than those under alternative regimes that adhere to a “use it or lose it” policy. Cornforth and Lacewell (1981) studied farm production in the El Paso, Texas, area and demonstrated that the ability for farmers to store water in the Elephant-Butte Reservoir of New Mexico not only improves net farm returns, but also decreases the year-to-year variation in the returns to farming. Understanding the institutions of the Falcon-Amistad system can lead to tools for regional water management. Institutional knowledge like that identified in this paper is an important input for constructing complex models to analyze polices under a variety of conditions—like, for example, the Rio Grande basin in New Mexico and west Texas (Ward et al. 2006; and Booker et al. 2005).

This article discusses the structure and functionality of the Falcon-Amistad water market, including the institutions and geographic particulars that enable the market to operate. The discussion is facilitated by presentation of data from a variety of sources, with the majority of the data coming from the Texas Lower Rio Grande Valley. The historical trends of water market activity are presented and discussed, followed by a discussion of the Falcon-Amistad region’s water-related institutions. Finally, suggestions are presented to anticipate, and possibly mitigate, potential complications to market operations from groundwater depletion and to the environmental well-being of the River, specifically regarding instream flows.

3.2 Water Market Definition

Certain criteria must be met for a water market to exist within a regional water management system. The criteria are, from Saliba and Bush (1987), (a) that a portion of a supply system's right to use water be owned by individuals (either people or firms), (b) those rights must be transferrable among these market participants, and (c) claims to these rights must be respected and secured property rights. This definition implicitly assumes the transportation of a unit of water to a new point of use within the region is technically feasible, which is the case for the Falcon-Amistad system. Once transfers of secure rights between two different water right holders are allowed to occur, demarcating the location and range of the water market is essentially the same task as locating technical and legal feasibility boundaries that apply to these transactions.

Legal boundaries can be built across distances and across institutions. For example, transactions may only be permitted in a given river basin, such as the Rio Grande, and may only be allowed among specific types of users, such as agriculturalists or municipal suppliers. Restrictions on trades concerning different types of water use exist in the Falcon-Amistad water market. Specifically, short-term trades (or leases) between agricultural use and municipal use are prohibited in the Falcon-Amistad system (Characklis et al. 1999; Stubbs et al. 2003).

Herein, 'water market' is used as an umbrella term, referring to all of the types of water transactions that may occur within the Falcon-Amistad system. A variety of transactions are possible (e.g., permanent sale of water rights, temporary lease of water-right entitlement, and long-term contracts for water-right entitlement). Each type of transaction could constitute its own market, depending on the accounting stance of the market researcher. Within the Falcon-Amistad system, all of these transactions are relatively simple to execute when compared to any hypothetical transaction with entities outside the region. In the State of Texas, interbasin transfers of water are subject to a relatively-extended review process outlined in the Texas Water Code, Chapter 11 (Texas Water Code 2001).

One objective of this article is to determine if the Falcon-Amistad water market behaves in accordance with economic theory. Indications that the market is behaving as theory suggests are evidenced by market transactions that transfer water (i.e., permanent water rights) from those with lower values and to those with higher values for water. Further, given the limited supply of water rights and the area's increasing water demand, driven by population growth, the real price of a water right in a functioning market would be expected to increase. If these two conditions are upheld and market externalities are limited, then economists have reason to believe that transactions are contributing in some capacity to social welfare improvement. To be more explicit, the objective is not to demonstrate any degree of formal market efficiency. The objective is, rather, to evaluate if, overall, market transactions appear to be allocating resources to those groups and individuals who place the greatest value on the resource. In such a case and with minimal externalities, the market may be said to be improving efficiency (Griffin 2006b). In an analysis of selected transactions from the Falcon-Amistad water market, Chang and Griffin (1992) found that the benefits accruing to water-right buyers were greater than the opportunity cost of water-right sellers. This study adopts a different approach than Chang and Griffin (1992) and analyzes an updated catalogue of water right transactions that have occurred since 1992.

An additional objective of this article is to determine what, if any, institutions are promoting the effectiveness of a market, either by minimizing externalities, ensuring the property values of water rights are maintained, or by lowering market transaction costs. Identifying the role played by institutions in the operation and functionality of the market provides a basis for locating areas of potential improvement and policy recommendations to further enhance social welfare in the market area. And further, Falcon-Amistad institutions, once identified as effective, may be replicated in other regions of the world, by other regional water resource managers, whose regions are enduring water scarcity and who are looking to improve, expand, or diversify their portfolio of water resource management policies and tools.

3.3 Falcon-Amistad Water Market Description

Several articles outline the history and functionality of the Falcon-Amistad water market (Chang and Griffin 1992; Characklis et al. 1999; Jarvis 1991, 2007; Kaiser 1987; Levine 2007; Schoolmaster 1991; Stubbs et al. 2003; Wurbs 2004). Like much of the western United States, the majority of the state of Texas follows the prior appropriations doctrine, which employs the principle of “first in time, first in right” (Griffin 2006b). The Falcon-Amistad region is the only place in Texas that follows a different system of water rights. The Falcon-Amistad water rights system was essentially put in place following the conclusion of the Valley Water Suit, i.e. *State of Texas v. Hidalgo County Water Control and Improvement District No. 18* (1969), which defined the water-rights system for the lower portion of the Rio Grande basin of Texas as permitted entitlements to correlated shares of the River. In 1982, water rights in the middle portion of the Rio Grande basin of Texas were defined using essentially the same mechanism (i.e., as had been used in the lower basin since the conclusion of the Valley Water Suit) (NRS 2006). Today the lower and middle portions of the Texas Rio Grande basin combine to form what is essentially called the Falcon-Amistad region in this paper.

In contrast to the prior appropriations doctrine, which gives priority to users with the longest history of withdrawals, the correlated shares doctrine generally gives no such priority and usually treats rights holders as having equal priority. Water rights in the Falcon-Amistad region employ a unique type of correlated shares doctrine that has three tiers of priority, with priority of the right determined by the type of use (i.e., DMI or Irrigation) and by the diversion history (i.e., class A or class B) associated with the water right.

Market Participants

The agents in the Falcon-Amistad water market generally fall into three categories: (a) individuals, (b) irrigation districts, and (c) municipal suppliers. Irrigation districts own the majority of irrigation water rights and “hold” and divert against a significant proportion of municipal rights for the respective municipalities. Thus, they divert the majority of raw water from the River. Municipal water suppliers of the region are privately owned or public utilities. In either case, the municipal supplier typically has its water delivered by an irrigation district, but in some cases, it may divert its own water or lease water from an irrigation district.

Types of Rights

The Falcon-Amistad system makes a clear distinction between water rights used for irrigation and those associated with domestic, municipal, or industrial uses. These latter three uses are afforded greater priority than irrigation water in the Falcon-Amistad system. A DMI water right entitles the right holder to 1.23 thousand cubic meters (TCM) (1 af) diversion per year from the River. An irrigation water right entitles a right holder to a share of the inflows to the Falcon and Amistad reservoirs. Within the sub-category of irrigation rights, an additional tier of priority affords greater reservoir inflow amounts to two different classes of irrigation rights (class A and class B). Unlike municipal water rights, which entitle the right holder to a "use it or lose it" type of annual diversion, irrigation rights are associated with bankable water accounts at the Office of the Watermaster. Therefore, irrigation rights holders' account of divertible water can be low, full, or even overfilled; but the volume of water inside the diverter's account may not exceed 1.4 times the allocation given during the original adjudication of the water rights. Many of these peculiarities of the Falcon-Amistad system, including the duties of the Office of the Watermaster and the operations of releases and storages in the reservoir system, are investigated in greater detail by Characklis et al. (1999), Levine (2007), Stubbs et al. (2003), and Wurbs (2004).

Transferability of Water Rights

*Intra*sectoral water rights are fully transferrable in the Falcon-Amistad water market, which is to say irrigation water rights are fully tradable among irrigation users and DMI water rights are fully tradable among DMI users. To clarify, 'fully tradable' means a right can be permanently purchased or sold and the water entitlement can be leased, contracted, or optioned to other similar users, i.e., users in the same sector. Trades from one sector into another, or *inter*sectoral trades, are more complicated and more closely regulated than intrasectoral trades. Such restrictions on water trades are believed by many economists to be sources of inefficiency. The transfer particulars are explored in several locations (Schoolmaster 1991; Stubbs et al. 2003; NRS 2006; Levine 2007) and are summarized below.

Since DMI rights are afforded a higher priority than irrigation rights (i.e., one year's supply of DMI diversions is reinstated in the municipal reserve monthly), transferring water rights from agricultural use to DMI use involves converting an irrigation right, which is a bankable entitlement to a share of reservoir inflows, into a DMI right, which is a reserved, fixed quantity of a permitted annual diversion and otherwise is not bankable. The A and B subdivisions of irrigation water rights also carry different weights when converted to DMI water rights. Conversion rates correspond to the higher monthly allocation rate accorded to class A rights over class B rights. When class A irrigation water rights are converted into DMI water rights, the amount of water associated with the irrigation rights is reduced to 50% of the original (i.e., irrigation) water value. Similarly, but using a stronger reduction factor, when a class B irrigation water right is converted into a DMI water right, the amount of water associated with the irrigation right is reduced to 40% of original water amount (Schoolmaster 1991; Jensen 1987; Stubbs et al. 2003).

The Falcon-Amistad water-rights system supports a thriving market for leased water, which is also called “wet water,” “contract(s)” water (Chang and Griffin 1992; NRS 2006), or “spot market sales” (Yoskowitz 1999). Unlike permanent sales of water rights, leased water cannot be transferred outside of a sector. Leasing transactions of DMI water to irrigation water or irrigation water to DMI water are forbidden by law (Characklis et al. 1999). Permanent sales are the focus later in this article, because this market transaction captures the Falcon-Amistad system’s *inter*sectoral trading, which may be relevant to other regional water systems that observe competition for water from two different sectors and the expansion of urban/municipal interests into historically agricultural areas.

3.4 Falcon-Amistad Water Market Analysis

Historical Trends of Water Allocations

Population growth and the associated expansion of municipal boundaries, and agricultural acreage reductions are driving the reallocation from agricultural to municipal use in the Falcon-Amistad water market. The data used for much of the following discussion are from the Watermaster’s Harlingen Office which covers the four Valley counties and Zapata County. Since water right ownership of Zapata County is less than 12 TCM (10 af), the following figures are presented as Valley-wide data. Figure 3-3 and Figure 3-4 are displays, respectively, of total allocations of DMI water rights and the total allocation of irrigation water rights in the Valley.

The upward trend of municipal water rights in Figure 3-3 corresponds to an average annual growth rate of 2.62% in the amount of municipal water rights in the

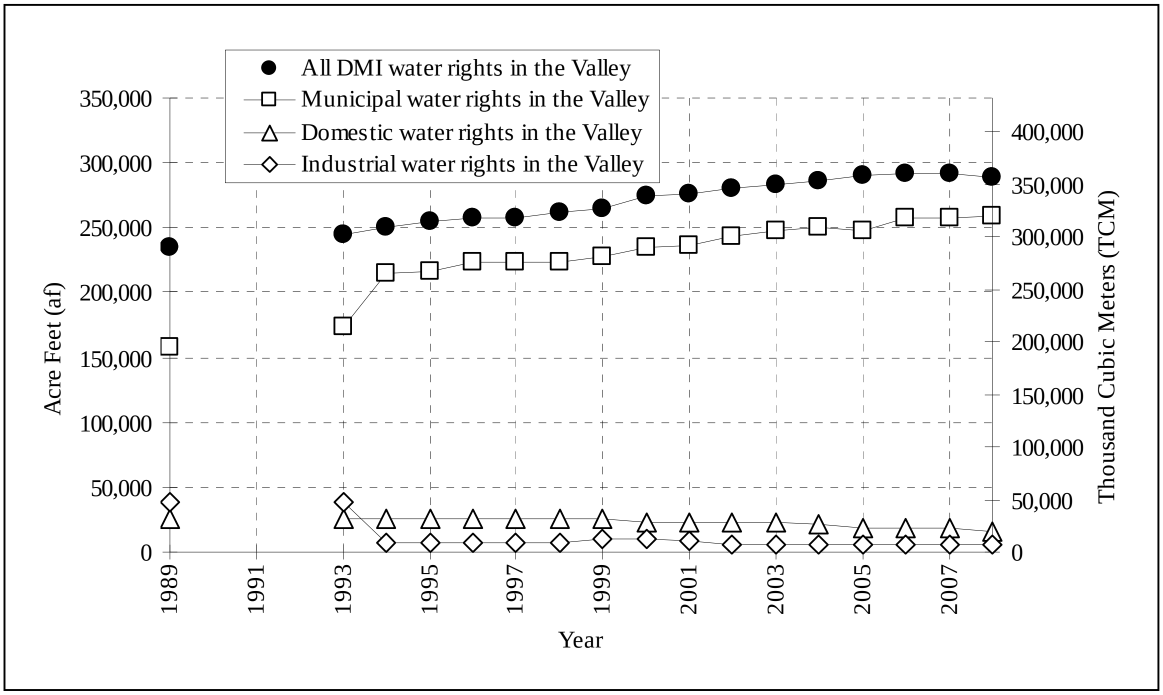

Figure 3-3. Historical trends of total authorized water rights* (use types municipal, domestic, and industrial; and summed up as all DMI) allocated in the Texas Lower Rio Grande Valley.
Source(s): Unpublished data from the Rio Grande Watermaster's office.
Note: ***Data missing for 1990, 1991, and 1992.

Valley from 1989 to 2008. Population projections from the Region M Water Plan (NRS 2006) indicate an estimated population growth rate of 2.94% for the entire region from 1990 to 2010. The similarity between the growth rates suggests regional municipalities are anticipating increasing water demand and acquiring water rights to fill this demand. Note in Figure 3-3, the total quantity of DMI water rights *decreased* from 2007 to 2008. This is due to a sequence of transactions between the City of Laredo, which is not located in the Valley, and Valley IDs in which the City of Laredo purchased 3,330 TCM (2,700 af) of domestic use water rights. The growth in municipal rights is slightly less than the estimated growth in population. This disparity may be explained by past actions of the municipal suppliers in which they purchased water rights in advance of growth and more recently have been expending those rights instead of buying new ones.

The decreasing trend shown in Figure 3-4 corresponds to an annual loss rate of 0.50% for total irrigation water rights in the Valley from 1989 to 2008. Due to municipal development expansion into the Valley irrigation districts, agricultural lands within the Valley irrigation districts were reduced at an annual rate of 0.73% between 1996 and 2006 (calculated from Leigh et al. 2009). The levels of agricultural lands and

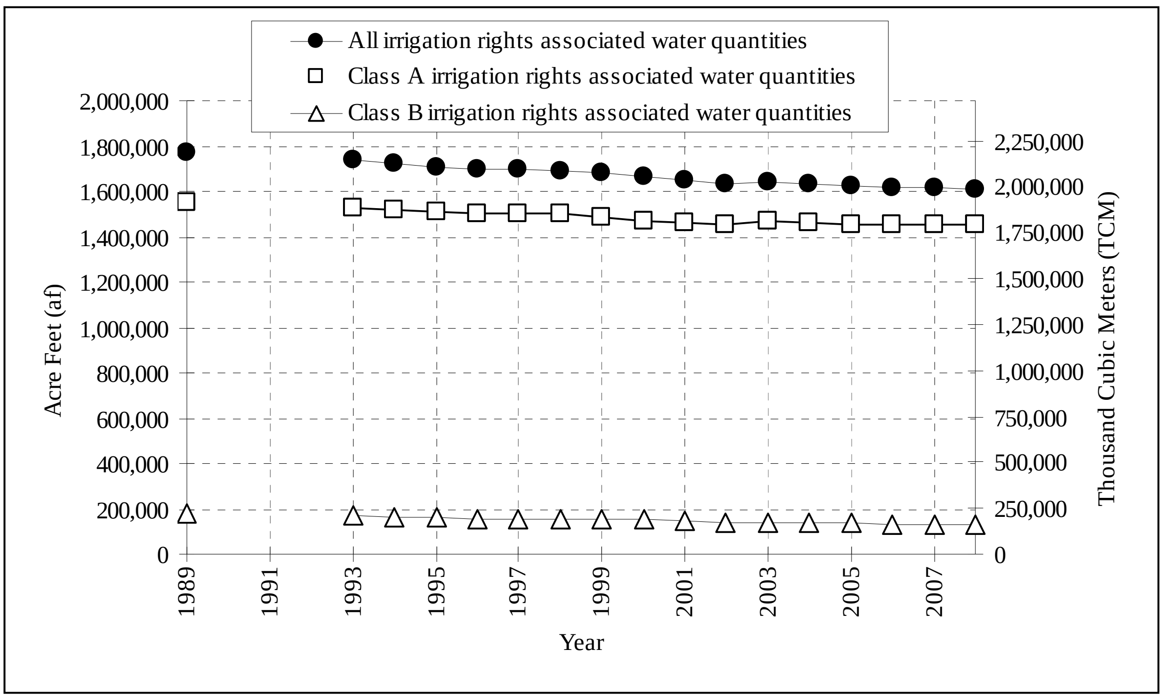

Figure 3-4. Historical trends of total authorized water rights* (use types class A irrigation, class B irrigation and summed up as all irrigation) allocated in the Texas Lower Rio Grande Valley.
Source(s): Unpublished data from the Rio Grande Watermaster's office.
Note: ***Data missing for 1990, 1991, and 1992.

demographic landscape shifts towards the urban and suburban, water resources are allowed to shift from the agriculture sector to municipalities and/or industries. Reasons that the Valley's irrigation districts' lands are being reduced at a faster rate (albeit slight) than the rate irrigation rights are being reduced may be due to resistance on the part of the irrigation districts to relinquish their water rights (e.g., retaining water rights to insure against shortfalls during extended drought).

A disparity exists between municipal allocations and municipal diversions of the Valley, because municipalities do not divert the entire volume of their legal right. This disparity may be accounted for by municipal suppliers' purchases of water rights in anticipation of future growth, such a disparity is typical of urban reliability planning. Note the level of DMI water reserved for the next year's use is based on DMI diversions, not total right ownership.

Historical Trend of the DMI Water Right Market Price

Demand growth, a relatively-fixed supply of water, and a functioning water-right market generate price signals in the Falcon-Amistad system. The price signals are indicative of an overall trend in rising opportunity costs of water rights in the region from the early 1980s to the present, with the most significant price increases occurring 1998 to 2002. An examination of inflation-adjusted data reveals the real price of water rights remained relatively constant during the early 1980s to the late 1990s (Figure 3-5), with market transactions primarily characterized by small irrigation rights holders (i.e., not IDs) as sellers and municipal suppliers as buyers (Stubbs et al., 2003; Chang and Griffin, 1992). By 2000, the municipal suppliers seem to have sought out and cleared the market of many smaller rights holders. In other words, as demand for water rights is increasing, as a consequence of population growth, the supply of water rights is held fixed, ownership levels by irrigators and irrigation districts are not increasing. The outcome suggested by economic theory is that as a market exhausts low cost supplies, in this case water rights' owners with a low willingness-to-accept for their water rights, market demanders will face increasing prices, thereby moving upward and along the water rights' supply curve.

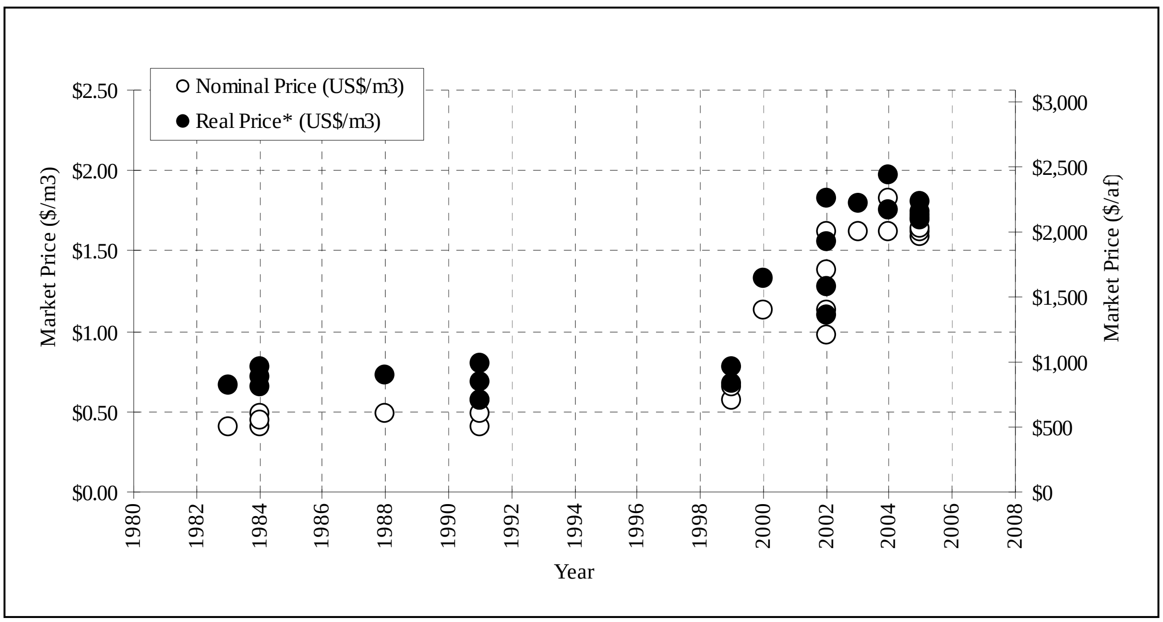

Figure 3-5. Historical data of DMI water rights prices in the Falcon-Amistad water market.
Source(s): Caroom and Maxwell (2005); Chang and Griffin (1992); Characklis et al. (1999); Griffin and Characklis (2002); Levine (2007); NRS (2001, 2003, 2006); Schoolmaster (1991).
Note: *Inflation rate = 2% (Rister et al. 2009); base year is 2008.

Since 2000, the active agents in the market primarily consist of municipal suppliers and IDs (Stubbs et al. 2003), with municipal suppliers purchasing water from IDs. Even though they are highly involved in market activity, IDs seem to be reluctant to sell water rights for two reasons. First, the IDs monthly water account credits (maintained by the Watermaster) are dependent on their *pro rata* share of the system-wide total amount of irrigation water rights. Thus, IDs use the retention of water rights as “insurance” during drought to maximize their pro-rata share of monthly account credits. Secondly, water delivery via irrigation canals and pipelines is an enterprise with increasing returns to scale (Chang and Griffin 1992), meaning that large-volume water delivery businesses are associated with high initial fixed costs, and decreasing average costs as more clients are brought into the delivery network.

The typical ID in the Falcon-Amistad system is evolving to meet the demands of the expanding municipal sector, but the IDs continue to have legal obligations and financial incentives to serve the agricultural users of their districts. Growing demand from the municipal sector, the IDs relative lack of incentive to sell water rights, the 2000-2002 drought conditions, and risk aversion to future drought have contributed to the real price of a water right increasing by more than $1/m3 (or $1,000/af) since 1999 (Figure 3-5).

Anecdotal reports of speculative purchases suggest water rights as a long-term investment opportunity may also be contributing to increases in prices (Hinojosa 2009). A Linear Dummy model and a Liebig model were regressed on the price data (Figure 3-6). The graphs of these two models illustrate similar stories about the market’s price trends. Namely, that from 1983 to the late 1990s, no apparent change in prices occurred; and after a point in the late 1990s, approximately 1998, prices tended to increase (Appendix E).

The independent variables in the Linear Dummy and Liebig model may include the effect of any of many time-correlated phenomena, or time-independent events, which impacted the Falcon-Amistad region from 1983 to 2005. These events may include the passage of Senate Bill 1 (SB1) (TWDB 2009) in 1997. The subsequent execution of the regional water plans mandated by SB1 may have increased water market participants'

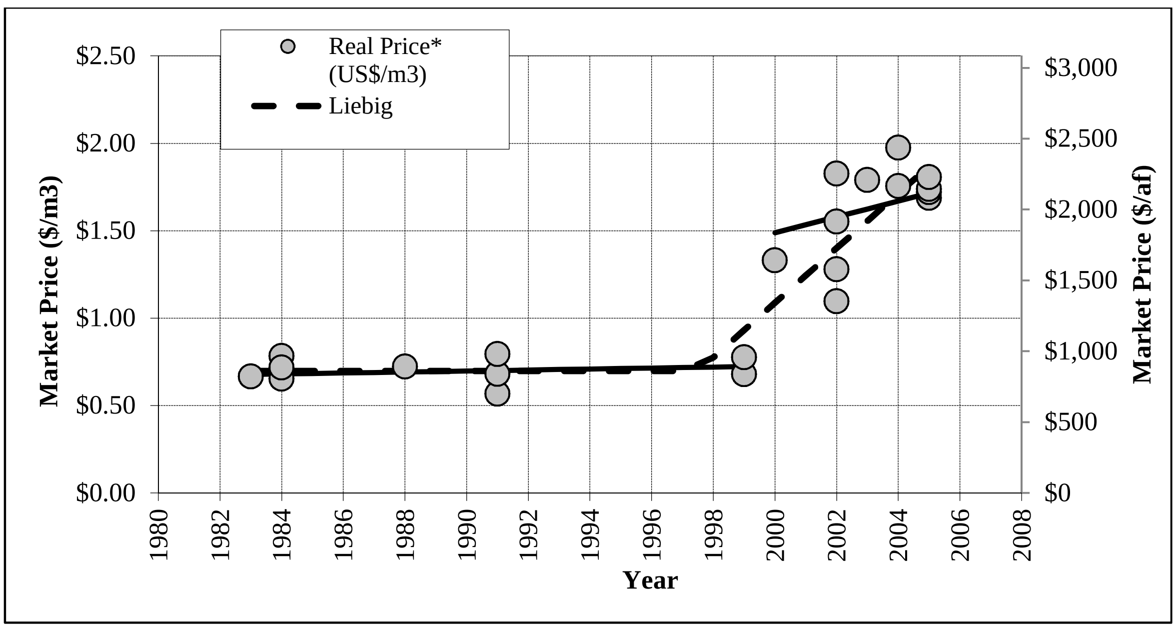

Figure 3-6. Historical data (1983-2005) of DMI water rights prices in the Falcon-Amistad water market and the plots of two regression models, 2009.
Source(s): Analyses and adaptation from nominal prices reported in Caroom and Maxwell (2005); Chang and Griffin (1992); Characklis et al. (1999); Griffin and Characklis (2002); Levine (2007); NRS (2001, 2003, 2006); Schoolmaster (1991).
Note: *Inflation rate = 2% (Rister et al. 2009); base year is 2008.

awareness of the quantity and the prospects for future water supplies in the region. Intermittent drought in the mid-to-late 1990s and the notable drought in the early 2000s, during which the Rio Grande ceased to flow into the Gulf of Mexico (Samson 2008), may also have contributed to the increase in water prices. As indicated by Stubbs et al. (2003), once the small irrigation rights holders sold their water rights to cities and had been cleared of the market, possibly around the year 2000, municipalities were left to purchase any additional water rights from IDs, which have strong incentives to retain their water rights.

Characterization of Past Transactions

From July 1996 to January 2009, title changes, or changes of permanent ownership, associated with Falcon-Amistad water rights have been documented in the Harlingen Watermaster's Office. Once again for simplicity, this five-county administrative area is referred to as the Valley. An analysis was conducted of 418 of those title changes, which involved a variety of individuals/private organizations, irrigation districts, municipal suppliers, government agencies, and environmental groups. Some title changes were omitted from this analysis, including those which appeared to involve two or more members of the same family. Identifying the nature of the title change was no exact science. The general rule of thumb that this study followed was that if two or more title change participants had identical surnames, then the title change was determined to be a gift between kin and not a representative market transaction. Of the 418 remaining title changes, some could be non-market exchanges of property between friends, or family members that do not share the same surname; discerning this from the Watermaster's records was not possible. Nevertheless, the authors are confident that the overall trends in title changes reported in Table 3-2 are qualitatively similar to the trends of the subset containing genuine market transactions. Table 3-2 displays a summary of these title changes, referred to as transactions, and organized by the type of right owner involved in the transaction.

The summary data presented in Table 3-2 indicate that individual rights holders have been the most active sellers of water both in terms of the number of transactions in which they are involved and by accounting for the greatest proportion of water volume sold. The most active water purchasers in terms of number of transactions were also the individual rights holders. However, municipal suppliers are the greatest volume purchaser of water rights. IDs are the second-most frequent user type to participate in transactions as a seller, participating in approximately 11% of sales (Table 3-2). If IDs are sellers, the quantity of water transacted tends to be much higher than if individual rights holders are sellers. From 1996 to 2008, the average quantity per trade with an irrigation district as seller is approximately 563 TCM (457 af), while the quantity per trade with an individual as seller is approximately 164 TCM (133 af) (Table 3-2). As would be expected given the Valley's growth in population during the 1990s and 2000s and the Valley's expanding municipal sector, municipal suppliers are net purchasers of water rights and irrigation districts are net sellers of water rights.

To further evaluate the nature of these transactions, consider the water use values associated with the two water-using sectors, agricultural and municipal. The returns to an acre foot of water used in the Valley agriculture are estimated at $139 (Seawright

Table 3-2. Summary of recorded water market transactions from May 1996 to December 2008 in the Falcon-Amistad water market for the Texas Lower Rio Grande Valley, 2009.

		Individuals	Irrigation Districts	Municipal Suppliers	Environ mental Groups	Government Agencies	Others and Unknown	Total
Total transactions as seller	#	359	46	7	3	1	2	418[d]
	percent	85.89%	11.00%	1.67%	0.72%	0.24%	0.48%	100%
Total quantity[a] of water sold	TCM[b]	58,767	25,916	294	389	7	556	85,930
	af[c]	47,643	21,010	239	315	6	451	69,664
	percent	68.39%	30.16%	0.34%	0.45%	0.01%	0.65%	100%
Average quantity sold per transaction	TCM	164	563	42	130	7	278	206
	af	133	457	34	105	6	226	167
Total transactions as buyer	#	194	19	176	9	17	2	417[d]
	percent	46.52%	4.56%	42.21%	2.16%	4.08%	0.48%	100%
Total quantity of water bought	TCM	28,569	3,937	46,624	1,530	4,390	344	85,393
	af	23,161	3,192	37,798	1,240	3,559	279	69,229
	percent	33.46%	4.61%	54.60%	1.79%	5.14%	0.40%	100%
Average quantity bought per transaction	TCM	147	207	265	170	258	172	205
	af	119	168	215	138	209	140	166
Total net quantity purchased	TCM	-30,198	-21,979	46,329	1,141	4,382	-212	-537[d]
	af	-24,482	-17,819	37,560	925	3,553	-172	-435

Source(s): Unpublished data from the Rio Grande Watermaster's office.

[a] To ease data presentation, all water quantities were converted to their DMI equivalents. For example, a transaction involving 100 thousand m3 (TCM) of Irrigation B water converts to a 40 TCM DMI equivalent in the table.

[b,c] Thousand cubic meters referred to as TCM. Acre feet referred to as af.

[d] Total buyer transactions differs from total seller transactions because one transaction log entry did not list the buyer. Also, for this reason, the total net quantity purchased for all users is -537 TCM, the quantity of the log entry with no buyer.

et al. 2009). In the municipal sector, water treatment costs can provide a lower bound on the value of water to municipal users. Municipal water treatment costs in the Valley have been estimated in the range of $615 to $968 per acre foot (Boyer et al. 2010). Considering that agricultural interests, represented by IDs, are net sellers of water rights and that municipal water suppliers are net purchasers of water rights (Table 3-2) and that agricultural water use values have been estimated to be substantially lower than that estimated for municipal treatment costs, the transfer of water from the agricultural sector to the municipal sector constitutes a transfer of water rights from lower-valued use to higher-valued use.

Has the Falcon-Amistad Water Market Been Successful?

The two criteria established early in this article to determine if the water market is functioning according to economic theory are, by and large, satisfied by the data presented in the previous sections. Namely, in the Falcon-Amistad system, water allocations have shifted from lower-valued agricultural uses to higher-valued municipal and urban uses, with IDs and individuals being net sellers of water rights and municipal water suppliers being net purchasers of water rights. Simultaneously, as competition for water from the growing municipal sector has resulted in increasing demand for water from the River, the real market price of a water right has increased by more than $1/m3 (or $1,000/af) since 1999.

The rules governing transactions and administration of the Falcon-Amistad water market have not changed materially since water rights were adjudicated following the Valley Water Suit of 1969. The system's success spurred adoption of the same doctrine in the middle portion of the Rio Grande basin of Texas, thus forming what is today the Falcon-Amistad water market area. The endurance of this regional water management system under challenging conditions, namely rapid population growth, drought, under-delivery of water by Mexico, and demand competition between two sectors, is noteworthy. Three reasons for the market's apparent success are discussed below.

Howe, Schurmeier, and Shaw (1986) state the "main administrative problem in water markets is the existence of 'third-party' effects that take the form of changed return flows, changed groundwater levels, and water quality changes." Third-party effects are roughly defined as externalities (positive or negative) imposed on a party not directly involved in the market transaction. Many water markets have limitations and procedures in place to protect against these kinds of, usually negative, third-party effects. Examples of market limitations include *no-injury rules*, designed to prevent harmful third-party effects; and *area of origin restrictions*, designed to keep water in its original basin (Anderson and Snyder 1997).

A common procedure for curbing harmful return flow externalities are a series of public announcements of proposed water trades followed up by one or more open-to-public committee hearings, so that any potentially impacted third-parties can voice their opinions (Chang and Griffin, 1992), as is the case of interbasin transfers in Texas. While these processes ensure more trades are neutral (or Pareto) efficient transactions, they do so by ratcheting upward the market's transaction costs, thereby inhibiting trade and possibly slowing the advance towards aggregate efficiency.

A consequence of the market's fairly unique geographic circumstances, transaction costs that are associated with mitigating return flows in many—if not most other—water markets do not affect the Falcon-Amistad water market. Schoolmaster (1991), as well as Chang and Griffin (1992), point out the relative non-existence of third-party effects and return flow externalities in the Falcon-Amistad water market. The geographic location of the Valley as the final leg of the River and the area having its gravity flow away from the Rio Grande (through an extensive network of drainage ditches) combine to all but eliminate third-party effects and return flows from being factors in this market area. In effect, diversions from the River downstream of Falcon Reservoir constitute full and consumptive use of the diverted water, so any would-be return flows exit the water market arena via the drainage ditch system.

"Private property does not enforce itself" (Friedman 2000) and the costs of enforcement and monitoring may prove to be prohibitive to market-based tools for water resource management. In the Falcon-Amistad system, however, the Watermaster heads up an effective monitoring and enforcement effort with its costs paid for by revenues from service fees charged to water diverters in the Falcon-Amistad system. Both Chang and Griffin (1992) and Yoskowitz (1999) note the Watermaster's successful enforcement of water rights. Yoskowitz goes on to note that the Watermaster's enforcement efforts contribute to the overall effectiveness of the market. The Texas Administrative Code empowers the Watermaster to take "necessary actions to effectively cease any unauthorized diversion or impoundment of state water" (Texas Administrative Code 1999). The Watermaster can report the violator to the executive director of TCEQ, who can issue fines of up to $1,000 per day of continued wrongdoing. The issue can also be taken up in court by the state attorney general.

The allowance for irrigation rights holders to bank (or store) their water month-to-month in the Falcon and Amistad reservoirs is worthy of further mention. Brennan (2008) describes the absence of clearly defined property rights over stored water in the context of a missing market, and presents an analysis of an Australian water system whereby incorporating storage values improves the benefits from engaging in water transactions. While irrigation rights holders in the Falcon-Amistad system retain the rights to their stored water (up to 1.4 times the volume of their initial water account), DMI rights holders are not afforded such rights. Therefore, the opportunity costs faced by DMI rights holders to divert water in the current year do not include the value of that water's use in a future year. This aspect of the water market's design does not encourage efficient use of DMI water across time periods as is done by the bankability policy that applies to irrigation rights holders.

What Does the Future Hold for the Falcon-Amistad Water Market?

The rising costs of acquiring Falcon-Amistad surface water rights have been one motivating force which has increased interest in alternative water supply technologies. The Region M water plan identified brackish groundwater desalination as the second-largest projected contributor to regional water supplies, with acquisition of additional water from the Rio Grande via market exchanges as the single largest contributor (NRS 2006). The most recent geologic survey of the Valley concluded that the Gulf Coast Aquifer may experience declining water levels and aquifer storage given a drought of record and a continuation of pumping trends occurring during 1980 to 1999 (Chowdhury and Mace 2007). Chowdhury and Mace (2007) reported extraction rates from prior to 1999 that are likely to be underestimates of current (i.e., 2009) extraction rates, given that multiple brackish groundwater desalination projects have come online after 1999. Since 1999, the development of brackish groundwater desalination facilities across the Valley is expected to have accelerated groundwater withdrawals in the area. Because the Gulf Coast aquifer is hydrologically connected to the River, reduced water levels in the aquifer may induce greater seepage from the River into the aquifer. At some time in the future, the operational reserve of the Falcon-Amistad reservoir may require adjustment, to account for greater conveyance losses due to greater seepage when water is transported from the reservoirs down the River to the diverters.

A component of the Texas Water Bank, which is operated by the TWDB (Wurbs 2004), is the Texas Water Trust. The Texas Water Trust operates as a depository for water rights that have been voluntarily donated to the care of the state to be "dedicated to environmental needs, including instream flows, water quality, fish and wildlife habitat, or bay and estuary inflows" (Texas Water Code 1999). No water rights in the records from the Harlingen Watermaster's office have been designated for environmental use (Texas Commission on Environmental Quality 2009a). Instream flow allocations may have been insufficient in past years, such as 2001, when the River notoriously failed to flow into the Gulf of Mexico and a sandbar developed across the mouth (National Research Council 2005; Samson 2008). As a consequence of the sandbar, the Watermaster's Harlingen Office and U.S. Homeland Security authorities agreed to sustain a minimum flow from the River to the Gulf to prevent the development of any sandbars in the future (Yarrito 2009). Nevertheless, the current arrangement of instream flows management may seem inadequate. Market-based provision of instream flows are likely subject to a free-rider problem and non-market provision of instream flows are motivated primarily by Homeland Security concerns rather than environmental concerns.

Two ownership categories exist for Valley farmers: those who own water rights; and those who are serviced by an ID-owned water right. Farmers of the first group are water market participants and the market's end users. Farmers of the latter group are only end users in the water market. Since they are not right owners and cannot sell the water right, they are not considered to be market participants. The inability of a water market's end user to directly participate in the market, is referred to as a disconnect issue (Griffin 2006a) or a compensation problem (Smith 1989). This may impede market trading and/or the adoption of water conserving practices. IDs and municipal suppliers are not disconnected from the market, and are therefore incentivized (to some degree) to consider the opportunity costs of the water rights they hold and the diverted water they could conserve by making capital improvements. The disconnect of some of the water market's end users (i.e., farmers who are served by an ID) from the market and, by extension, from certain water-conserving incentives constitute valid grounds from which to be critical of the current water market's institutional arrangements.

3.5 Summary and Conclusions

Since the early 1970s, the water market of the lower and middle portions of the Rio Grande basin has functioned like a typical market for a normal good. Demand for water has increased, especially from municipal water suppliers, and the supply of water from the River is more-or-less constrained by the yields of nature and the climate. As a consequence of increasing demand and relatively fixed supply, the price of a water right in the Falcon-Amistad system has risen to reflect higher opportunity costs of diverting water from the River. This market has functioned well as a regional water-management tool, particularly given the region's experiences and the fact that the Falcon-Amistad system has remained operational and largely unchanged. Contributing towards the water market's success is the region's geographic location at the terminus of the Rio Grande and the consequential elimination of return flow complications to market transactions. Equally important, the Watermaster effectively monitors and enforces the diversions along the River, i.e., since water rights are closely administered, their values are well maintained.

The Gulf Coast Aquifer may become an issue for this market in the future. Assuming groundwater pumping accelerates, water tables may fall and reaches of the River may experience increased seepage. Monitoring for any hydrologic changes may be important to determine if future adjustment to the water market's operations could be useful. Protecting instream flows for environmental demand seems fairly straightforward for stretches of the Rio Grande in the Falcon-Amistad region. Water rights can be purchased at the market price and then entered into the Water Trust; even so, some environmental concerns over the River seem to be ongoing. In spite of these potential issues and the compensation problem, the Falcon-Amistad system provides, what is overall, a positive example of the effectiveness of a market-based tool used in regional water management, within the context of existing institutional arrangements.

CHAPTER IV

HYDROECONOMIC ANALYSIS OF THE TEXAS LOWER RIO GRANDE VALLEY WATER SUPPLIES UNDER URBANIZATION AND CLIMATE CHANGE

4.1 Introduction

Hydroeconomic models are computer-based water-management and water-research tools that incorporate aspects of hydrology and economic behavior to advise and provide implications for the water management decision-making process and water management practices (Ward 2009; Harou et al. 2009). Hydroeconomic models can take a variety of forms and include a variety of components, depending on the particular question(s) being addressed. Issues addressed by application of hydroeconomic models in Texas and the southwestern United States may include: water planning (Gillig et al. 2001), groundwater management (McCarl et al. 1999), recreational uses (Ward and Lynch 1996, 1997), water market institutions (Characklis et al. 1999, 2006; McCarl et al. 1999; Cai and McCarl 2009), water pricing (Ward and Pulido-Velaquez 2008, 2009), environmental and species-habitat uses (McCarl et al. 1999), and climate change and drought (Booker et al. 2005; Ward et al. 2006; Cai and McCarl 2009). Recently, the important components and basic structures of these models have been summarized by Ward (2009) and Harou et al. (2009).

The study area for this paper includes three agriculturally-prominent and municipally-diverse southern Texas counties: Cameron, Hidalgo, and Willacy. These counties are located along the Texas U.S.-Mexico border at the mouth of the Rio Grande (the River) (Figure 1-1). Decision makers across the region are considering several alternative water-supply and water-management alternatives to address water issues, including brackish groundwater desalination and seawater desalination (NRS 2008, 2010b). In the next 50 years, more than a doubling of the current population is anticipated in this region (NRS 2010a). This population growth will expand municipal borders into what is currently productive farmland and will require substantial quantities of water from the river system that has traditionally been used to support the irrigated agriculture sector. Compounding increased water competition on the demand side, global climate change may permanently and substantially alter the natural yield of the region's primary water source, the River, as well as the physiological performance of agricultural crops.

The River serves as an international border, and is subject to several long-standing water-sharing agreements between neighboring nations and states (Martin 2010). As recent as a decade ago, some of those terms were tested when Mexico defaulted on obligations to deliver water to the River for use on the U.S. side (Robinson 2002). These circumstances portray a region that likely will experience rising water scarcity in the coming decades and, as such, provide an impetus for research such as this essay to better understand the region's water supply alternatives, water management institutions, and projected impacts. Regional stakeholders have demonstrated forward resolve to address present and future water-scarcity issues (Rister et al. 2011). The goal of this paper is to provide guidance to those efforts, offer a picture of what the future may hold for the Valley's water resources, and suggest policies to mitigate foreseeable challenges to regional water management.

The description of a hydroeconomic model developed for the Valley, incorporating aspects of urban-agricultural change in both water and land resources, is included in this essay. This model captures many of the unique institutions of the Valley, including the modeling of two different methods of water right reallocation, one explicitly linked to land-use change and the other explicitly divorced from land-use change. The model is parameterized to represent the years 2010 and 2060, providing an assessment of the probable effects that 50 years of population growth, land-use change, water-use change, and climate change may have on the region's municipal water supply system benefits and agricultural productivity. The essay proceeds with a presentation of the model, including descriptions of the economic, hydrologic, institutional, and dynamic components. The model description is followed by a presentation and discussion of the results from several scenarios. A summary of results and implications comprises the final section.

4.2 Model Description

The hydroeconomic model is an optimization program, constructed and solved in the General Algebraic Modeling System (GAMS)™ (GAMS Development Corporation 2011). The objective of model application is to maximize social gains across the agricultural and urban sectors. Controls imbedded in the model include the choices of crops, acreages, farming practice (irrigated or dryland), and municipal water supply technologies. Optimization is subject to several hydrologic and institutional constraints designed to represent the conditions found in the Valley. A variety of literature sources and discussions with local experts were consulted in the attempt to build a model that reasonably represents the Valley's hydrologic, institutional, and economic environment (Hinojosa 2009; Leidner et al. 2011b; Thompson 1999; TWDB 2007, 2009; Yarrito 2009).

Objective Function

The objective function maximizes the net benefits of agricultural production and municipal consumers' consumption of water. The source of agricultural water is from River water that is transported from diversion points along the River, but is otherwise untreated. Municipal water use can come from treated River water, brackish groundwater treated by reverse osmosis desalination, or seawater (available only in coastal Cameron County) also treated by reverse osmosis desalination. The benefits that accrue to the agricultural sector are calculated from the revenue of crops, less the costs of production. Municipal water-consumption benefits are calculated as the area under a projected linear demand curve, less the costs of water treatment. The maximized objective function is as follows:

$$\sum_c \left\{\sum_p \left(\sum_i \left(acre_{c,i,p}(price_i yield_{i,p} - prodCost_{i,p})\right)\right.\right.$$

$$\left. -expandCost_{expansion,p}\right)$$

$$+\sum_s \left[\int_w D_s\left(\sum_{treatment} w_{c,s,treatment}\right)dw\right.$$

$$-\sum_{treatment}\left(treatCost_{treatment} w_{c,s,treatment}\right)$$

$$-distCost_{distribute}\sum_{treatment}\left(w_{c,s,treatment}\right)$$

$$-price_{water} w_{c,s,treatment=conventional}]$$

$$-\sum_{transfer}(transCost_{transfer} wRight_{c,transfer}))\}. \quad (4.1)$$

The objective function sums across all counties in c, where $c \in (Cameron, Hidalgo, Willacy)$. Agricultural net returns (benefits) are total revenue minus costs per acre, multiplied by the number of acres employed in growing crop i, where $i \in (cotton,\ sorghum, corn, cantaloupe, onion, cabbage, citrus, sugar\ cane)$; and using farming practice p, where $p \in (irrigated, dryland)$. In the model, only cotton and sorghum produce positive net returns under dryland or no irrigation. The final cost term in the agricultural benefits component of the objective function is the cost of expanding agricultural practices, or where $p = irrigated$, $expandCost_{expansion,p}$ represents the per acre cost of expanding irrigated acreages into dryland acreages; and where $p = dryland$, $expandCost_{expansion,p}$ represents the per acre cost of expanding dryland acreage into ranchland. The expansion of dryland and irrigated acreages are allowed only in the model year 2060 scenarios.

The benefits of water consumption $w_{c,s,treatment}$ are summed across seasons $s \in (spring, summer, fall, winter)$. Seasonal consumer surplus comes from integrating over a demand curve $D_s(\cdot)$ (Appendix F), which takes as an input the total quantity of municipal water from all possible types of water treatment systems, $\sum_{treatment} w_{s,treatment}$, where $treatment \in (conventional\ surface\ water, groundwater\ desalination, seawater\ desalination)$. The cost components for the municipal sector include a per unit treatment cost $treatCost_{treatment}$ and a per unit water transaction cost, $transCost_{transfer}$, by type of transfer where $transfer \in (lease, sale, exclusion)$. A water lease, as considered in this study, is a temporary (single-year) transfer of a water right entitlement. A sale is the permanent transaction of a water right in the water market. An exclusion is a water right transaction that is explicitly linked to the transaction of land which has been under the purview of an irrigation district. When such land is transacted, the land and its associated water rights are excluded from the district. The use of conventionally-treated surface waters from the Rio Grande also incurs an opportunity cost, $price_{water}$, equal to the market price of a Falcon-Amistad water right.

Land Use

Land use for each county can either be urban or agricultural, with agricultural land subdivided into land employed in either irrigated or dryland agricultural practices. In the 2010 model year, the acreages of each land-use type are constrained to be less than or equal to recorded levels (i.e., $\overline{urbanLand}_c$, $\overline{irrLand}_c$, and $\overline{dryLand}_c$). Throughout the model description when there is potential for ambiguity, parameter values that are taken from literature (and not determined endogenously in the model) are indicated as having a fixed value with a bar over the top of the variable name.

$$urbanAcre_c = \overline{urbanLand}_c + newUrbanAcres_c, \forall\, c. \tag{4.2}$$

$$newUrbanAcres_c = \sum_p convertedAgAcres_{c,p}, \forall\, c. \tag{4.3}$$

$$\sum_i acre_{c,i,p} \leq \overline{irrLand}_c - convertedAgAcres_{c,p} + newIrrAcres_c, \forall\, c \text{ and where } = irrigation. \tag{4.4}$$

$$\sum_i \; acre_{c,i,p} \leq \overline{dryLand}_c - convertedAgAcres_{c,p} + newDryAcres_c, \forall\, c \text{ and where } p = dryland. \qquad (4.5)$$

In the model year 2060 scenarios, land use is allowed to change, with new urban land represented by $newUrbanAcres_c$. New urban acreages are the result of converting either irrigated agricultural land ($convertedAgAcres_{c,p=irrigated}$) or dryland acreages ($convertedAgAcres_{c,p=dryland}$). The agricultural sector may in turn expand either irrigated acreage ($newIrrAcres_c$) or dryland agricultural acreage ($newDryAcres_c$), within the constraints of water availability and land.

Crop Acreage Choice

The crop choice in the model is subject to several constraints that ensure model application behaves according to documented, historical behavior in the Valley, called flexibility constraints. Optimized acreages of each crop in each county, $acre_{c,i,p}$, are held equal to or below the acreages reported in the Census of Agriculture (USDA-NASS 2010), $\overline{acre}_{c,i,p}$, inflated by an exogenously imposed technology adoption rate, μ_y, that increases in the model year, y. In this way, model year 2060 scenarios are allowed greater levels of all crop types (but total acreage is still constrained by equations 4.4 and 4.5). Therefore, a reasonable expectation for the model's behavior is for higher-valued crops to be employed over a greater portion of farmland in model year 2060 than occurring in 2010.

$$acre_{c,i,p} \leq \overline{acre}_{c,i,p} * (1 + \mu_y), \forall\, c, \text{ where } p = irrigated, \text{ and where } i \in (cotton,\ sorghum, corn, cantaloupe, onion, cabbage, citrus, sugar\ cane). \quad (4.6)$$

For the model's two dryland crops, cotton and sorghum, the crop choice constraints are more complicated. To accommodate modeling the full effects of a drought, model acreages associated with the Valley's historically vast tracts of irrigated farmland must be convertible to dryland practices. For this reason, the model's dryland cotton and dryland sorghum acreages are only constrained to be in the same ratio as previous years, which is also inflated by a technology adoption rate, μ_y. This requisite ratio preserves the common practice of periodically rotating farmland out of cotton production, which is thought to maintain soil productivity (Bullock 1992).

$$\frac{acre_{c,i=cotton,p}}{acre_{c,i=sorghum,p}} \leq \frac{\overline{acre}_{c,i=cotton,p}}{\overline{acre}_{c,i=sorghum,p}} * (1 + \mu_y), \forall\, c, \text{ where } p = dryland, \text{ and where } i \in (cotton, sorghum). \quad (4.7)$$

<u>*Irrigation Water Use and Conveyance Loss*</u>

On-farm water consumption is defined as the product of per acre water use by crop, $waterReq_{c,i}$, and the number of irrigated acres associated with each crop, $acre_{c,i,p}$. The on-farm water use is summed across all crops in each county and then added to the specific county's conveyance losses. A loss rate, $conveyanceLoss$, is multiplied by the county's irrigated acres. The on-farm water use and the conveyance losses (for both agricultural and municipal water distribution) must be less than or equal to the water available in each county's agricultural water account (equation 4.8). This stipulation implicitly accounts for the irrigation system infrastructure being used to supply urban water users and agriculture incurring conveyance losses related to urban water.

$$\sum_i \left(acre_{c,i,p} waterReq_{c,i}\right) + \sum_i \left(acre_{c,i,p}\right) conveyanceLoss_{ag} + urbanAcre_c conveyanceLoss_{urb} \leq agWater_c, \forall\, c$$

and where $p = irrigated.$ (4.8)

Allocation of Irrigation Water from Rio Grande

The model allocates River water into the accounts of each of the county's irrigation agents according to the following formula.

$$\theta_c\left(inflow - \sum_c \sum_s w_{c,s,treatment} - envFlow\right) = agWater_c, \forall\, c, \text{ and}$$

where $treatment = conventional\ \ surface\, water.$ (4.9)

The term in the parentheses is the total useable agricultural inflows for the region, which is the annual total reservoir inflows for all human uses, $inflow$, less the portion that is used by the municipal sectors, $\sum_c \sum_s w_{c,s,treatment}$, and less the annual amount (if any) apportioned for environmental flows, $envFlow$. The region's total useable agricultural inflows are divided into county-level allocations based on the portion of total agriculture water rights held within each county, which is represented by θ_c.

Allocation of Municipal Water from Rio Grande

Two equations constrain the amount of water that is useable by the model's municipal sector. Each equation is activated based on the availability of reservoir inflows for municipal uses. The first equation is associated with reservoir inflow levels that are in excess of the municipal sector's legal allocation of River water (equation 4.10). In this "non-drought" case, a county's annual conventionally-treated water supplies ($\sum_s w_{c,s,treatment}$) are less than or equal to the number of that county's owned water rights ($w_{c,owned}$) plus any additional rights acquired through transfers ($\sum_{transfer}(w_{c,transfer})$). The next constraint (equation 4.11) is associated with severe drought-level inflows, whereby reservoir inflows fall below the legal entitlement of the municipal sectors. In such a drought scenario, no agricultural sector receives any water, and the municipal sectors of each county are allocated water based on the portion of municipal rights owned in each county.

$$\sum_s w_{c,s,treatment} \leq w_{c,owned} + \sum_{transfer}(w_{c,transfer}), \forall\, c, \text{ and}$$
$$\text{where } treatment = conventional\ surface\ water. \qquad (4.10)$$

$$\sum_s w_{c,s,treatment} \leq \phi_c(inflow) - urbanAcre_c lossRate_{urb}, \forall\, c,$$
$$\text{and where } treatment = conventional\ surface\ water. \qquad (4.11)$$

In selected drought scenarios in the model application, if reservoir inflows are insufficient to supply each municipal agent's legal entitlement to water, then equation 4.11 is activated with equation 4.10 ignored. In this case, the municipal agents must divide the flows between them according to each agent's portion of water rights owned, ϕ_c, while also being charged for any conveyance losses in the municipal distribution network, $lossRate_{urb}$. In non-drought scenarios, conveyance losses for both urban and agricultural reduce agricultural water accounts.

Conveyance Loss Rates

Conveyance losses included in the model for the agricultural sector are represented as a weighted average of lined and unlined irrigation canal seepage rates per mile of canal ($lossRate_{lined}$ and $lossRate_{lined}$, weighted by ρ_{lined}). This loss rate per mile of irrigation canal, $lossRate_{agAvg}$, is multiplied by the density of canal miles per acre of irrigated farmland ($milesPerAgAcre$). The equations that govern conveyance losses for agriculture are as follows:

$$lossRate_{agAvg} = \rho_{lined} lossRate_{lined} + (1 - \rho_{lined}) lossRate_{unlined}, \quad (4.12)$$

$$conveyanceLoss_{ag} = lossRate_{agAvg} milesPerAgAcre * \sum_i acre_{c,i,p}, \forall c \text{ and where} = irrigation. \quad (4.13)$$

The other conveyance loss term used in the model represents per acre conveyance losses of waters that are distributed through the urban sector, $lossRate_{urb}$. This value is directly calculated from previous studies of the Valley's water distribution system seepage losses ($\overline{conveyanceLoss}_{total}$), the model application estimation of agricultural-related seepage losses ($conveyanceLoss_{ag}$), and urban acreage ($\overline{urbanLand}_c$) (equation 4.14).

$$lossRate_{urb} = \frac{(\overline{conveyanceLoss}_{total} - conveyanceLoss_{ag})}{\overline{urbanLand}_c}. \quad (4.14)$$

Groundwater

Since the majority of Valley groundwater is in the primarily brackish Gulf Coast Aquifer (Chowdhury and Mace 2007), the availability of groundwater for irrigation purposes is assumed to be negligible. Apart from the Gulf Coast Aquifer, the only other tabulated source of groundwater for the three-county region of interest to this study is found in Hidalgo County (NRS 2010a), which identifies 10,000 acre feet in "other aquifers", which includes primarily the Rio Grande Alluvium. By way of comparison, for the three-county region, where the "other aquifers" contain 10,000 acre feet, the Gulf Coast Aquifer and surface water yields from the River amount to almost 0.25 million and 1.9 million acre feet, respectively (NRS 2010a). Building on the assumption that the Gulf Coast Aquifer contains mostly brackish water, desalination is the technology required to put Gulf Coast Aquifer to use in the municipal sector. The extraction and production capacities of brackish groundwater for municipal purposes are limited by the estimated physical scarcity of the groundwater resource.

$$\sum_s w_{c,s,treatment} \leq \bar{w}_{c,brackish} \; \forall \, c \text{ and where } treatment = groundwater\ desalination. \tag{4.15}$$

Since brackish groundwater is a relatively-innovative water supply technology when compared to conventional surface water treatment, an additional institutional constraint is placed on the development of brackish groundwater desalination facilities, whereby a county's treatment capacity is linked to the county's *in situ* desalination activities prior to 2010. Following a similar constraint on crop choice (equation 4.6), the municipal water produced from brackish desalination of groundwater, $\sum_s w_{c,s,treatment}$, cannot exceed the production level established between 2000 and 2010, $w_{c,treatment}$, inflated by a technology adoption rate, v_y.

$$\sum_s w_{c,s,treatment} \leq w_{c,treatment} * (1 + v_y), \forall \, c \text{ and where } treatment = groundwater\ desalination. \tag{4.16}$$

Seawater

Allowed in the model is seawater desalination in Cameron County, but not Willacy or Hidalgo Counties. In terms of physical scarcity, no limit is placed on seawater desalination. While potential water supplies from seawater are physically vast, the economic potential of the resource is limited by the costs associated with seawater desalination production technologies. The cost of seawater desalination technology is relatively greater than either of the other two alternatives (i.e., conventional surface water or brackish groundwater desalination). Energy and capital required to treat relatively more saline seawater contribute to the higher costs associated with seawater desalination (Leidner et al. 2011a).

Urban Water Use

The value to consumers of urban water use is estimated by calculating consumer surplus under a demand curve in the objective function. Additionally, the model imposes minimum per capita water consumption levels.

$$\sum_s w_{c,s,treatment} \geq population_c perCapitaUse. \quad (4.17)$$

Population Growth and Land-use Change

Population growth affects the model in two direct ways. First, population growth increases municipal water consumption, which is represented by increasing the $population_c$ in equation 4.17. Secondly, population growth expands urban boundaries into agricultural land, which reduces land available for agricultural production and, by a process known as exclusion, reduces water available for agricultural irrigation by transferring excluded water rights to the municipal sector.

$$newUrbanAcres_c = \frac{\Delta population_c}{urbPopDensity_c}. \quad (4.18)$$

$$newUrbanAcres_c = \sum_p \left(convertedAgAcres_{c,p}\right), \forall\ c, p. \quad (4.19)$$

$$w_{c,transfer} = convertedAgAcres_{c,p}, \text{ where } transfer = exclusion \text{ and } p = irrigated. \quad (4.20)$$

In the model, the amount of acreage that is converted from agricultural use to urban use in each county is the anticipated change in total population $\Delta population_c$ divided by the density of the new population, $urbPopDensity_c$. These newly-converted acres, $newUrbanAcres_c$, diminish the county's acreages in irrigated or dryland agriculture. A relevant assumption made in the model is that new urban acres initially expand into irrigated farmland and then followed by expansion into dryland acreages.

As a consequence of converting irrigated acres to urban acres, represented by $convertedAgAcres_{c,p}$ where $p = irrigated$, a transfer of the Falcon-Amistad water rights associated with those formerly irrigated acreages occurs from the irrigation agent to the municipal agent. In the Valley, irrigated agricultural land that is developed into urban or municipal tracts constitutes those acreages being excluded from the irrigation district's purview; therefore, these types of water transfers are called transfers by exclusion (as opposed to strictly market-based water rights transfers). In either the case of exclusion or a market transfer, irrigation water rights are converted to municipal rights at a rate of two to one, which is a simplification of the actual transfer process described more completely by Leidner et al. (2011b).

Climate Change

For selected model year 2060 scenarios, climate change adjustments are made to crop yields and crop water usages, where the yields and water requirements under climate change (i.e., $yield_{i,p,a}^{cc}$ and $waterReq_{i,a}^{cc}$) are a function of the 2010 yields and water requirements (used in equations 4.1 and 4.8) multiplied by a proportional change (i.e., $\delta_{i,p,a}^{yield}$, $\delta_{i,a}^{water}$) due to changing climate.

$$yield_{i,p,a}^{cc} = yield_{i,p} * (1 + \delta_{i,p,a}^{yield}), \forall\, i, p, a. \quad (4.21)$$

$$waterReq_{i,a}^{cc} = waterReq_{i} * (1 + \delta_{i,a}^{water}) \;\forall\, i, a. \quad (4.22)$$

Yield effects associated with climate change are included for all crops under both irrigated and dryland practices. Changes in water use are only included for the irrigated crops. The availability of water across the entire system, specifically inflows into the Falcon-Amistad system, may also change as a result of climate change. This possibility is modeled by adjusting the inflow levels into the River system as follows:

$$inflow^{cc} = inflow * (1 + \delta^{inflow}). \quad (4.23)$$

where, as with equations 4.21 and 4.22, the climate-change-influenced parameter is the product of the original parameter (used in equation 4.11) and a proportional change, δ^{inflow}.

4.3 Data Description and Empirical Parameterization

Data used to parameterize the model are found in a variety of sources, including extension publications, regional and state water planning documents, published academic literature, and personal communications with engineers and water planners in the Valley. Many of these parameters are described more completely throughout this document, where Table 4-1 is a guide to the locations of those descriptions and more information on the parameterization. A few components in Table 4-1, such as the assumed price of irrigated farmland ($15,000/acre) and the price of a water right ($2,218/af) do not have representation in the model per se. These prices are used to calculate wealth trends for the model following the optimization step. The term 'relic' refers to values found in the literature, which serve as an anchor to the values selected for the model, e.g., the use of $\overline{urbanLand}_c$.

Table 4-1. Summary of selected parameters for the hydroeconomic model of Cameron, Hidalgo, and Willacy counties in Texas.

Description	Notation	Unit	Citation / More Details
Crop prices	$price_i$	$/unit	Appendix G
Crop yields per acre	$yield_{i,p}$	unit/acre	Appendix G
Crop production costs per acre	$cost_{i,p}$	$/acre	Appendix G
Water right price	N/A	$/acre foot	Leidner et al. 2011b
Agriculture land price	N/A	$/acre	User defined
Water treatment costs	$cost_{treatment}$	$/acre foot	Table 4-6
Urban water distribution cost	$cost_{distribute}$	$/acre foot	Appendix I
Water market transaction costs	$cost_{transfer}$	$/acre foot	User defined
Relic urban acreage	$\overline{urbanLand}_c$	acres	Leigh et al. 2008
Relic irrigated acreage	$\overline{irrLand}_c$	acres	Table 4-2
Relic dryland acreage	$\overline{dryLand}_c$	acres	Table 4-2
Relic crop acreages	$\overline{acre}_{c,i,p}$	acres	Table 4-2
Crop adoption rate	μ_y	rate/year	User defined
Crop water usage	$waterReq_{c,i}$	acre feet/acre	Table 3, Appendix H
Reservoir inflows	$inflow$	acre feet/year	Calculated from TCEQ 2009a
Environmental flows	$envFlow$	acre feet/year	User defined
Agricultural inflow shares	θ_c	portion	Calculated from TCEQ 2009a

Table 4-1 continued.

Description	Notation	Unit	Citation / More Details
Owned municipal water rights	$w_{c,owned}$	acre feet/year	NRS 2010b
Seepage loss in lined canal	$lossRate_{lined}$	acre feet/mile/year	Leigh and Fipps 2011
Seepage loss in unlined canal	$lossRate_{unlined}$	acre feet/mile/year	Karimov et al. 2009
Portion of lined canals	ρ_{lined}	portion	Based on Fipps 2000
Total conveyance losses	$conveyanceLoss$	acre feet/year	Based on Fipps 2000
Canal miles per irrigated acre	$milesPerAgAcre$	mile/acre	Appendix J
Municipal inflow shares	ϕ_c	portion	Calculated from NRS 2010b
Relic brackish desalination	$\overline{w}_{c,brackish}$	acre feet/year	NRS 2010b
Brackish desalination adoption rate	ν_y	rate/year	User defined
Population level	$population_c$	persons	NRS 2010a
Per capital water use	$perCapitaUse$	acre feet/year	Based on Thompson 1999
Population growth	$\Delta population_c$	persons	NRS 2010a
Crop yield climate change effect	$\delta_{i,p,a}^{yield}$	portion	Beach et al. 2009
Crop water use climate change effect	$\delta_{i,a}^{water}$	portion	Beach et al. 2009
Reservoir inflow climate change effect	δ^{inflow}	portion	Based on Chen et al. 2001

Source(s): Beach et al. (2009); Boyer et al. (2010); Chen et al. (2001); Fipps (2000); Karimov et al. (2009); Leigh et al. (2009); Leigh and Fipps (2011); NRS (2010a, 2010b, 2010c); Thompson (1999).

4.4 Model Year 2010 Results

Results from model application for 2010 are presented in this section. These results primarily serve as validation that the model behaves reasonably with respect to expectations and previously published records regarding the agricultural and municipal water use for this three-county region (Cameron, Hidalgo, and Willacy counties) of south Texas.

Agricultural Sector

Displayed in Table 4-2 are 2010 baseline agricultural acreages alongside the values from the Census of Agriculture (USDA-NASS 2010). Crop acreage changes are in the direction of higher-valued crops. The only crop acreages decreasing are irrigated and dryland sorghum, which have the lowest per acre returns among both irrigated and dryland crops. The acreages of the more profitable crops are increasing within the confines of the assumed rate of new technology adoption. Dryland acreage expands overall for Cameron and Hidalgo counties due to the nature of the crop choice constraint on cotton and sorghum. The results in the right three columns of Table 4-2 represent proportional changes of model acreages as compared to acreages documented in the Census of Agriculture (USDA-NASS 2010). These proportional changes are qualitatively the same as percentage changes, where 0.05 equals 5%. Notice that acreages from the model are not more than 0.05 more than documented acreages, except for dryland acreages of cotton and sorghum in Hidalgo County. This occurrence is due to dryland acreages being constrained by the ratio of cotton to sorghum (equation 4.7), instead of the actual acreages as with the other crops (equation 4.6).

Water use in the agricultural sector for the 2010 model year is summarized in Table 4-3. On-farm water usage as well as seepage losses are displayed with seepage losses accounting for 0.22 of the total agricultural water use. This result assumes that exactly one-half of the irrigation distribution network uses lined canals and the other half uses unlined canals, which corresponds to the range of lined and unlined canals identified by Fipps (2000).

Table 4-2. Cropping acreage (in 1,000s of acres) for a three-county region (Cameron, Hidalgo, and Willacy) in Texas, a comparison between Census of Agriculture data in 2007 and the 2010 model year.

		Census of Agriculture 2007			Hydroeconomic Model 2010			Modeled proportional changes in acreage		
		County			County			County		
	Crops	Cameron	Hidalgo	Willacy	Cameron	Hidalgo	Willacy	Cameron	Hidalgo	Willacy
Dry	Cotton	16.45	3.36	41.20	17.20	3.75	42.78	0.05	0.12	0.04
	Sorghum	63.25	111.81	96.17	62.97	118.99	95.10	0.00	0.06	-0.01
Irrigated	Cotton	9.71	14.86	3.30	10.20	15.60	3.47	0.05	0.05	0.05
	Sorghum	51.29	57.82	8.91	50.18	53.28	8.74	-0.02	-0.08	-0.02
	Corn	0.00	15.56	0.00	0.00	16.34	0.00	n/a	0.05	n/a
	Cantaloupe[a]	0.24	1.01	0.00	0.25	1.06	0.00	0.05	0.05	n/a
	Onion[a]	0.79	7.56	0.00	0.83	7.93	0.00	0.05	0.05	n/a
	Cabbage[a]	0.92	2.70	0.00	0.97	2.84	0.00	0.05	0.05	n/a
	Citrus[a]	2.56	24.79	0.05	2.68	26.03	0.05	0.05	0.05	0.04
	Sugar Cane[a]	8.07	24.39	0.14	8.48	25.61	0.14	0.05	0.05	0.05
	All Irrigated	73.59	148.69	12.40	73.59	148.69	12.40	0.00	0.00	0.00
	All Dryland	79.70	115.17	137.36	80.17	122.74	137.87	0.01	0.07	0.00
	All Cropland	153.29	263.86	149.76	153.75	271.43	150.27	0.00	0.03	0.00

Source(s): USDA-NASS (2010) and modeling results.

[a.] For the Census of Agriculture, all reported acres are assumed to be irrigated.

Many of the vegetable and fruit crops, such as cantaloupe, onion, and cabbage, have lower per acre on-farm water use than cotton or sorghum. The crop budgets (Extension Agricultural Economics 2011) assume that the high-value fruit and vegetable crops are grown using drip irrigation systems as compared to furrow irrigation. Furrow irrigation is assumed for cotton, sorghum, citrus, and sugar cane. Sugar cane and sorghum are associated with a majority of all irrigation water use (164 and 162 thousand acre feet, respectively).

Table 4-3. Summary of agricultural sector water use (in 1,000s of acre feet) for a modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas in model year 2010.

Annual On-Farm Water Use Summary

Irrigated Crops	Per Acre Water Use (acre-feet)	Model Results: 1,000s Irrigated Acres	Model Results: On-Farm Water Use (1,000s acre-feet)
Cotton	1.72	29.27	50.34
Sorghum	1.44	112.19	161.55
Corn	1.85	16.34	30.23
Cantaloupe	1.20	1.31	1.57
Onion	1.07	8.77	9.38
Cabbage	1.29	3.81	4.91
Citrus	3.19	28.76	91.76
Sugar Cane	4.79	34.23	163.98
Totals		234.68	513.72

Agricultural Sector Water Use Totals

Use Category	Water Use (1,000 acre-feet)	Portions
Total On-Farm Use	513.72	0.78
Seepage Loss	146.14	0.22
Total Agricultural Use	659.86	1.00

Source(s): Extension Agricultural Economics (2011) and modeling results.

Municipal Sector

Model results for the use of water in the municipal sectors are presented in Table 4-4. Water use through the year follows a seasonal pattern where use in the growing seasons of spring and summer that during exceed the fall and winter. This seasonality in municipal water demand has been established in the literature (Griffin and Chang 1991).

Table 4-4. Summary of municipal sector water use by season (in 1,000s of acre feet) for a modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas in model year 2010.

	County			Region	
Season	Cameron	Hidalgo	Willacy	Totals	Portions
Spring	23.36	30.67	0.90	54.93	0.25
Summer	23.40	42.73	1.25	67.38	0.31
Fall	18.95	32.75	0.96	52.66	0.24
Winter	17.82	25.70	0.75	44.28	0.20
Annual	83.53	131.86	3.87	219.25	1.00

The Falcon-Amistad water rights system and the conventional treatment of surface water diverted from the Rio Grande comprise a large portion, 0.91, of regional municipal water supplies, with brackish groundwater desalination comprising or contributing the remaining 0.09 (Table 4-5). In model year 2010, only the Willacy County municipal agent was projected to purchase leased water to meet urban water use requirements. Such leasing is possible due to the “extra” water rights owned by municipal agents in Cameron and Hidalgo. The Cameron County municipal agent owns nearly twice the number of water rights than are typically used each year. This result is similar to findings in Leidner et al. (2011b), where municipal rights holders possessed many more water rights than used annually, presumably to prepare for the anticipated rapid levels of population growth along the US-Mexico border. For the entire three-county region in model year 2010, conventionally treated water, both owned and leased, accounted for approximately 0.72 of the region's total municipal water right ownership being utilized.

Table 4-5. Summary of municipal sector water use by water treatment method (in 1,000s of acre feet) for a modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas in model year 2010.

	County			Region	
Treatment Method	Cameron	Hidalgo	Willacy	Totals	Portions
Conventional produced[a]	72.61	125.14	2.75	200.49	0.91
Brackish produced	10.92	6.72	1.12	18.76	0.09
Brackish capacity[b]	10.92	6.72	1.12	18.76	
Rio Grande/Falcon Amistad Water Rights					
Owned[a]	135.17	144.53	1.00	280.71	1.00
Used	72.61	125.14	1.00	200.49	0.71
Leased			1.75	1.75	0.01

[a] The amount of municipal that can be produced by conventional water treatment is only limited by the availability of water rights.
[b] Brackish capacity and the amount of water rights owned by each county are taken from the Region M water plan (NRS 2010c).

Hidalgo County has the greatest use of municipal water use of 132 thousand acre feet followed by Cameron County at 84 thousand acre feet. Willacy County is located to the north with a limited urban population and only uses 3.9 thousand acre feet of municipal water. Future population growth is expected to be especially strong in Cameron and Hidalgo counties (NRS 2010b).

A summary of municipal water supply costs are presented in Table 4-6. Across the modeled three counties, the total estimated cost for the ownership, treatment, and the delivery of municipal water is more than $150 million for 2010. The largest component of municipal supply system costs is the conventional treatment of water diverted from the Rio Grande at 0.70 of total cost. The ownership costs of water rights associated with the Rio Grande or the Falcon-Amistad water market constitute the second-largest component of the municipal water system costs at 0.20 of total cost. The desalination of groundwater and distribution constitute smaller amounts of total system costs. No cost is incurred from seawater desalination because that water treatment technology does not enter the 2010 solution during optimization. Seawater desalination has a substantially higher per-unit cost of production, approximately double that of the other two municipal water treatment alternatives (Table 4-6).

Consumer Benefits and Returns to Agricultural Production

The benefits to urban consumers from urban water supply systems exceeds by almost double the estimated costs of urban water supply. In Table 4-7, the results for model year 2010 are presented alongside the results for the baseline for model year 2060. Additional 2060 scenarios are investigated in later sections. The consumer benefits double from 2010 to 2060 because the population in the region is presumed to more than double. From 2010 to 2060, the agricultural sector receives revenue from land and water sales. Interestingly, despite selling tracts of land and water rights over 50 years to the urban sector, returns to agricultural production also increase over the 50-

Table 4-6. Summary of municipal sector water system costs for a modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas in model year 2010.

		Model Results		
Water Service Cost Type	Per Unit Cost ($ Per Acre-Foot)	Quantity (1,000 Acre-Feet)	Total Cost ($1,000s)	Portions of Total Cost
Water Treatment Methods				
Conventional Treatment	525	200.49	105,226	0.63
Brackish Groundwater Desalination	665	18.76	12,483	0.07
Seawater Desalination	1,340	0.00	0	0.00
Others Costs				
Falcon-Amistad Water Rights Ownership (average annual)	143	207.33	29,649	0.18
Distribution	91	219.25	19,864	0.02
Totals		**219.25**	**167,222**	**1.00**

Table 4-7. Summary of benefit and cost measurements (in $100,000s) in the municipal and agricultural sectors for a modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas in model year 2010 and 2060.

	2010	2060
Annual Benefits and Costs		
Urban Consumer Benefits	2,738	6,172
Urban Water Treatment Costs	1,662	3,604
Net Urban Consumer Surplus	1,075	2,567
Returns to agricultural production	4,007	5,302
Cumulative Revenues		
Water right sales revenue	0	320
Land sales revenue	0	3,371

year period. This increase in agricultural profitability is due to the relaxation of the crop choice constraints (equations 6 and 7), allowing for acres of higher-valued crops to expand across the three-county region.

4.5 Model Year 2060 Results

To provide further insight on implications for 2060, various scenarios are imposed on the model and those results are presented in this section. The scenarios are characterized by different assumptions regarding the expected pattern of land-use changes, institutional changes, and the potential effects of climate change. Presented first are the land-use change and institutional scenarios, followed by several climate change scenarios.

Population Growth and Land-use Change

Each scenario for 2060 is associated with a set of assumptions regarding urban population density, the adoption of brackish groundwater desalination technology, legal institutions relevant to the price of excluded water rights, and climate. The scenarios and their assumptions, and their selection are discussed below. Selected results from the 2060 scenarios are presented in Table 4-8 and Table 4-9.

Baseline 2060. The Baseline 2060 scenario is used for a point of reference and comparison to the other model year 2060 scenarios. The assumptions in this scenario include: The density of population assigned to new urban growth is maintained at the 2010 level, calculated from population levels found in U.S. Census (2011a; 2011b; and 2011b) and urban land area found in Leigh, Barroso, and Fipps (2009). The price of excluded water rights is fixed at the 2010 level of $2,218/af. The technology adoption rate with respect to brackish groundwater desalination is held constant at the observed rate that occurred between 2000 and 2010, i.e., every 10 years, municipal agents are allowed to replicate the brackish desalination capacity that was added between 2000 and

Table 4-8. Summary of water- and land-use changes, municipal water supply sources, municipal water-system benefits and costs, and agricultural production levels for a modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas in model year 2060.

Scenario:	Baseline 2060	El Paso	Laredo
Population density:	Constant at 2010 level	New growth 50% denser	New growth 500% denser
Excluded water right price:	2010 Market Price	2010 Market Price	2010 Market Price
Maximum desalination adoption rate:	Replicate / 10yrs	Replicate / 10yrs	Replicate / 10yrs
Drought Level:	None	None	None
Ag water rights converted to municipal use [a]			
Water market (1,000s acre feet)	0	0	29
Exclusion (1,000s acre feet)	224	206	58
Agricultural Water Sales Revenue ($100,000)	320	294	124
Ag Land converted to municipal use [a]			
From irrigated (acres)	224	206	58
From dryland (acres)	125	26	0
Agricultural Land Sales Revenue ($100,000)	3,371	2,247	562
Municipal water supply sources			
Rio Grande (1,000s acre feet / year)	389	378	351
Brackish (1,000s acre feet / year)	129	129	129
Seawater (1,000s acre feet / year)	0	0	0
Urban Benefits and Ag Returns ($100,000)			
Urban Consumer Benefits	6,172	6,077	5,838
Urban Water Treatment Costs	4,244	4,132	3,941
Net Urban Consumer Surplus	1,928	1,945	1,897
Returns to Agricultural Production	4,982	5,137	6,068

[a] Cumulative difference between 2010 and 2060; i.e., not an annual return.

2010. Added capacity from 2000 to 2010 is found in the Regional Plan (NRS 2010b). Climate change effects are ignored for this scenario, so no changes to crop production or water availability are assumed. Model solution levels for water supply system sources, land-use changes, water-use changes, and agricultural production are reported in Table 4-8.

El Paso. This scenario is named "El Paso" because the population densities of new municipal growth in Cameron and Hidalgo counties (Cameron and Hidalgo are the focus of these population density scenarios, since they are more populated than Willacy county) are assigned levels that are approximately equal to that of El Paso County, Texas. The city of El Paso is another border and high-growth community located on the Rio Grande, but much farther upstream than the cities in the Valley. El Paso, and later Laredo, provide natural points of comparison (i.e., ranges of potential population density) as to the type of population growth and urban development that may occur in the Valley. Specifically, new municipal growth in all of the three counties is assumed to be 50% denser in this scenario than the level in 2010. Apart from population density, this scenario is the same as the baseline, using $2,218/acre foot for the exclusion water right price; the prior assumed replication speed of new desalination capacity; and no climate change effects. Compared to the baseline, fewer acres are converted from agriculture to urban and less acre feet of water are taken by exclusion. Benefits to urban consumers and production returns to agriculture increase slightly, but the projected changes are not dramatic (Table 4-8).

Laredo. This scenario assumes new population density is similar to that of Webb County, Texas, i.e., location of the City of Laredo. Webb County is far denser than El Paso or any of the Valley counties; the result is new Valley urban density is set at 500% the 2010 levels for this scenario. As with the El Paso scenario, all other institutional and climatic constraints remain the same as they are in the 2060 Baseline. Results for this scenario (Table 4-8) indicate that with denser population growth, less agricultural land is converted to urban land. This reduces the amount of water rights acquired by municipalities through the process of exclusion. With fewer excluded rights obtained, the municipalities are forced toward the water market to obtain additional water rights. Since less agricultural land is converted to urban, agricultural returns to production for the region increases. The agricultural sector also does not receive as many returns from the sale of land and water.

BD-Fast. This scenario assumes baseline levels of population density and exclusion water right price, but allows for faster adoption of brackish desalination (i.e., BD-Fast). Specifically, brackish desalination capacity is allowed to expand at a rate that doubles the 2000-2010 capacity every 10 years. The cost of conventional water treatment added to the ownership cost of River water is slightly higher than the cost of brackish groundwater desalination (which has no associated ownership cost). Additionally, River water that is not converted to municipal use can still be used to produce returns in irrigated agriculture. For those two reasons, the model prefers brackish groundwater as a source of municipal supplies to conventional surface water.

This scenario explores the benefits of substituting groundwater for surface water in the region. Apart from the adoption of brackish desalination technology, all assumptions are the same as in Baseline 2060.

Results for this scenario are found in Table 4-9, where the amount of acre feet of municipal treated water produced from brackish groundwater increases to 163 thousand acre feet per year from the baseline level of 129 thousand acre feet per year. This increase is offset by a decrease in the acre feet produced by conventional water treatment. Water-use changes, land-use changes, and agricultural productivity all remain at the same levels as the Baseline 2060 case.

SB3. Scenario SB3, which is shorthand for Senate Bill Three (Texas Legislature Online 2011), imposes a recent institutional modification to the exchange of land and water between municipalities and irrigation districts. This bill grants Valley municipalities the right to petition the purchase of excluded water rights at a modified price equal to 68% of the price posted by the Rio Grande Regional River Authority (2011). Theoretical analysis by Yow (2008) suggests that, on the margin, such a policy would result in a comparative advantage windfall accruing to the treatment of surface water via conventional water treatment. In this model, such an advantage would manifest itself in the substitution away from brackish groundwater desalination and into more conventional surface water treatment of municipal waters. This scenario tests these theoretical findings within a slightly-more empirical context than pursued by Yow (2008).

Table 4-9. Summary of water- and land-use changes, municipal water supply sources, municipal water-system benefits and costs, and agricultural production levels for a modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas in model year 2060.

Scenario:	BD-Fast[a]	SB3[b]	Avg
Population density:	Constant at 2010 level	Constant at 2010 level	Constant at 2010 level
Excluded water right price:	2010 Market Price	68% of 2010 Market Price	2010 Market Price
Maximum desalination adoption rate:	Double / 10 yrs	Double / 10 yrs	Replicate / 10yrs
Drought Level:	None	None	35%
Ag water rights converted to municipal use [c]			
Water market (1,000s acre feet)	0	0	0
Exclusion (1,000s acre feet)	224	224	224
Agricultural Water Sales Revenue ($100,000)	320	217	320
Ag Land converted to municipal use [c]			
From irrigated (acres)	224	224	224
From dryland (acres)	125	125	125
Agricultural Land Sales Revenue ($100,000)	3,371	3,371	3,371
Municipal water supply sources			
Rio Grande (1,000s acre feet / year)	355	355	360
Brackish (1,000s acre feet / year)	163	163	129
Seawater (1,000s acre feet / year)	0	0	11
Urban Benefits and Ag Returns ($100,000)			
Urban Consumer Benefits	6,172	6,172	6,015
Urban Water Treatment Costs	4,243	4,140	4,183
Net Urban Consumer Surplus	1,929	2,031	1,832
Returns to Agricultural Production	4,982	4,982	3,503

[a] Brackish desalination capacity can expand rapidly.
[b] Senate Bill Three water prices assumed.
[c] Cumulative difference between 2010 and 2060; i.e., not an annual return.

To ensure that any technology substitution that can occur (between conventional surface treatment and brackish groundwater treatment) will occur during the optimization of the model, this scenario adopts the rapid rate of technology adoption of brackish groundwater used in the BD-Fast scenario. In the same vein, population density is maintained at 2010 levels. This level of population density imposes a high (relative to the El Paso and Laredo scenarios) level of land-use change from agriculture to municipal, so that municipalities will obtain the highest amount of excluded water rights to use in their supply system. The results for this scenario (Table 4-9) indicate that little substitution away from brackish desalination occurs in the model. One clear finding from the reduction in the price of an excluded water right is that agricultural revenues from excluded water rights sales decrease from the baseline.

Climate Change. The scenario referred to as Avg presents results from a model run that averages crop water use and crop production effects for four climate change models. Subsequent sections discuss climate change results in greater detail. In addition to crop production effects, the Avg climate scenario presented in Table 4-9 imposes a 35% reduction in available reservoir inflows. The climate effects reduce yields on dryland cotton and sorghum production, such that dryland agriculture is abandoned in the region. The reduction in inflows makes the remaining irrigated acreages composed entirely of high-value citrus, vegetables, and sugar cane, which now have greater yields and increased profitability under this climate scenario (relative to profitability without imposing climate effects). The greater value of these, already high-value, crops make the sale of additional water rights to the urban sector sub-optimal. For this reason, the model chooses to introduce an (admittedly small) amount of seawater desalination into the optimal portfolio of municipal water supplies.

An additional model-run scenario, which is not presented in the Tables 4-8 or 4-9, restricts the flexibility constraints on crop acreage selection (equation 4.6) so that the maximum acres of high-value crops (vegetables, sugar cane, and citrus) are equal to the level in the Baseline 2010 scenario presented in Table 4-2. One argument for maintaining maximum crop acreage levels for high-value crops at the 2007 or 2010 level, even for 2060 scenarios, is based on the risk aversion of farmers and institutional limits. This suggests farmers plant a mixture of crops to hedge against unforeseeable changes in prices or yields of a single crop or input (McCarl 2011). This scenario is run as a robustness check on the model to examine the degree to which the modeled flexibility in crop shifts contributes to agricultural sector productivity.

As may be expected, the scenario with the greater flexibility (i.e., Baseline 2060) contains proportionally-greater levels of higher-valued crops. In particular, the Baseline 2060 scenario has greater (as a portion) acreages of citrus (0.14), irrigated cotton (0.02), cantaloupe (0.01), onion (0.04), cabbage (0.02), sugar cane (0.001), and dryland cotton (0.1). With respect to lower-valued crops, the Baseline 2060 scenario has fewer (as a percentage) acreages of irrigated sorghum (0.02) and dryland sorghum (0.12). These crop shifts resulted in the Baseline 2060 scenario having $164 million in additional annual returns to agriculture (0.33 of Baseline 2060 returns) over the scenario with the flexibility constraints in place. While the effect of the lack of a flexibility constraint allows the agricultural sector to shift the crop mix towards higher-valued crops seems large, accounting for approximately one-third of Baseline 2060 returns, the qualitative direction of results within a given scenario group (i.e., the group of land-use change scenarios or climate change scenarios) is likely to be unchanged, whether the flexibility constrain are included or not. While the direction of these results may not change, imposing the flexibility constraints may affect the magnitude of those shifts. Sensitivity to different assumptions about crop choice adoption is left for future research.

Climate Change

This study employs four different General Circulation Models (GCMs) to give a range of possible future states of climate, thereby accounting for some of the uncertainty that is inherent when climactic conditions are forecast into the future. The GCMs used here are also used by Beach et al. (2011). These GCMs include two developed by the Geophysical Fluid Dynamics Laboratory, denoted GFDL-CM2.0 and GFDL-CM2.1. This study includes another GCM developed by the Canadian Centre for Climate Modeling and analysis, denoted as CGCM3.1. The final GCM used in this study was developed by the Meteorological Research Institute in Japan, denoted as MRI-CGCM2.2. Crop effects for each GCM are found in Appendix K.

Each of these GCMs assumes a particular scenario described in the International Panel on Climate Change (IPCC), Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart 2000). The SRES scenario employed in the GCMs used in this study is denoted as the A1B scenario, which assumes a number of global economic development levels including: global population peaks mid-century and declines thereafter, new and more efficient technologies are readily adopted, and energy use does not emphasize either fossil fuels or non-fossil fuels (Beach et al. 2009). Each GCM forecasts temperature and precipitation data for the south Texas region in the year 2050. This model assumes population growth levels for 2060, so climate forecasts for 2050 are not ideal. However, this group of GCMs represents the most recently generated and most up-to-date climate forecasts available. This study assumes that the 2050 crop effect changes will be similar to any of the crop effects ten years later in 2060.

Table 4-10. Summary of climate effects for the United States from several General Circulation Models (GCMs) used to generate climate change effects in the modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas in model year 2060.

GCM	Season	Change in Max Temp (^{0}C)	Change in Min Temp (^{0}C)	Change in Precipitation (%)
GFDL-CM2.0[a]	Spring	2.78	2.41	-7.4
	Summer	4.34	3.44	-8.5
GFDL-CM2.1[a]	Spring	1.66	1.72	0.6
	Summer	4.03	3.45	-16.5
CGCM3.1[b]	Spring	2.45	2.41	2.1
	Summer	2.27	2.17	0.7
MRI-CGCM2.2[c]	Spring	1.23	1.37	9.5
	Summer	1.28	1.57	8.7
Avg[d]	Spring	2.03	1.98	1.2
	Summer	2.98	2.66	-3.9
No GCM	Spring/Summer	0.00	0.00	0.0

Source(s): Modified from Beach et al. (2009).
a. GCMs developed by Geophysical Fluid Dynamics Laboratory.
b. GCM developed by Canadian Centre for Climate Modeling.
c. GCM developed by Meteorological Research Institute in Japan.
e. Averages the climate effects from the four other GCMs presented.

Several relevant climatic effects for the entire US of each GCM are displayed in Table 4-10. These attributes include that overall the GFDL-CM2.0 and GFDL-CM2.1 scenarios are hotter and drier than CGCM3.1 and MRI-CGCM2.2. All of the climate scenarios predict increased temperatures. The primary difference between GFDL-CM2.0 and GFDL-CM2.1 is their forecasted distribution of rainfall across seasons.

GFDL-CM2.0 forecasts rainfall changes in similar magnitudes for spring and summer months. But, GFDL-CM2.1 forecasts much more severe rainfall changes for the summer than for the spring. The scenario denoted Avg is an average across the other four scenarios.

Figure 4-1 is an illustration of the agricultural returns to land under six different climate scenarios as the inflows to the Falcon-Amistad reservoirs are exogenously varied. Five of the scenarios are based on GCMs described in Table 4-10. “No GCM” assumes no change in crop responses to climate. Only one scenario, GFDL-CM2.1, exhibits more valuable returns to agricultural land than the No GCM scenario. In fact, over much of the range of the varied reservoir inflows along the x-axis of Figure 4-1, the GFDL-CM2.1 returns are almost double the No GCM returns. GFDL-CM2.1 is characterized by relatively hotter and drier summers and milder springs than the other scenarios. However, results for the other three GCM scenarios as well as the Avg scenario exemplify a much less prosperous future for agriculture over most of the range of inflow reductions (Figure 4-1).

In all of the climate scenarios, the significance of reservoir inflows is evident. As soon as reservoir inflow levels decrease by approximately 0.40, the agricultural sector realizes decreasing returns to production, a consequence of shifting acreages from higher-valued irrigated crops to less-profitable dryland crops. No recent hydrologic model for the lower Rio Grande basin could be identified for use in this study to estimate the change to reservoir inflows, or watershed flow levels, based on a particular GCM. However, a previous study of the south-central Texas region suggests that climate

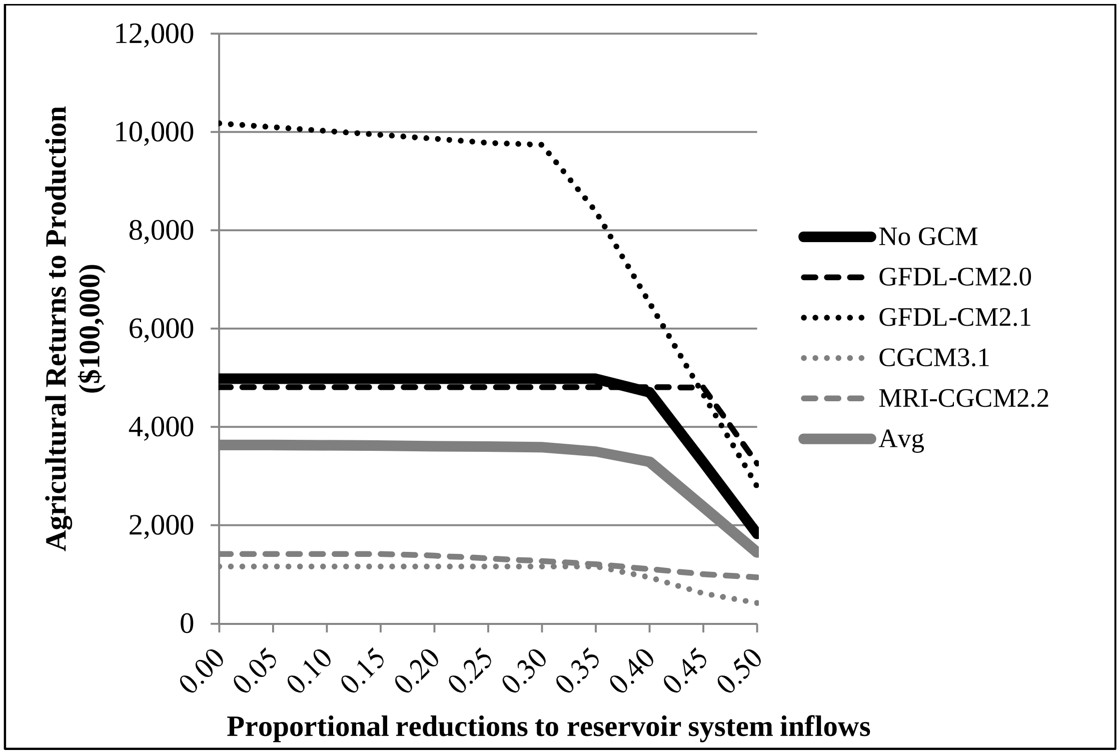

Figure 4-1. Agricultural returns to production in the modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas in model year 2060 under different climate change scenarios.

change may reduce water available to regional water storage systems in south-central Texas around the Edwards Aquifer on the order of 0.20 to 0.50 (Chen et al. 2001). Therefore, from Chen et al. (2001), the current study extrapolates that climate change may induce similar reductions in the water system of the neighboring lower Rio Grande basin. To further ensure model results are robust and evaluated in appropriate context, the model is solved under a sequence of assumptions about reservoir inflow levels for each GCM. The inflow reduction levels used in the model range from 0.0 to 0.5, where 0.0 indicates no deviation from historical average annual reservoir system inflows and a 0.5 indicates a reduction by half (or 50%) of annual reservoir system inflows.

4.6 Assumptions and Limitations

This model is parameterized and solved under a multitude of assumptions for the region as it may be in the year 2060. A few of the assumptions are listed below as caveats to an overgeneralized interpretation of the model's results:

- Crop, water, and land prices are held constant.
- Crop and water production technologies (except for adoption rates) are held constant.
- Ownership costs (opportunity cost of ownership) of brackish groundwater and seawater are assumed to be zero in 2060.
- Crop, water treatment, water delivery, and land-use change costs are held constant.
- Several smaller-acreage crops are excluded from analysis due to unavailable or unreliable data.
- Per capita urban water consumption is held constant.
- Price elasticities of water consumption are held constant.
- Urban water consumption is not subject to temperature, precipitation, or any other climate-related elasticity.
- The portion of lined and unlined canals is held constant.
- Proxies are used for the climate effects of onions, cabbage, and cantaloupe.
- Municipal water consumption is not a function of municipal water prices, including any conservation pricing schemes such as increasing block rates.

- If sugar cane acreages fall below 30,000 acres, the sugar mill for the region may not be economically viable.
- Seawater desalination can only be used in Cameron County.

All reasonable efforts are made to represent the hydroeconomic system of the Valley in the most realistic and plausible framework possible. Nevertheless, these assumptions imply profound limitations on the interpretation of the model results. The most reliable results include the model's more qualitative, or relative and consistent, findings. One example is that the climate change scenarios exhibit, on average, reduced returns to the agricultural sector relative to agriculture production in the absence of climate change. Assigning a great amount of weight or significance to any specific quantitative finding (such as the exact level of agricultural returns under any given climate scenario) is not advised, in light of the assumptions and limitations listed in this section.

4.7 Summary and Conclusions

The construction and the implementation of a hydroeconomic model are described in this paper. The model represents water resource management for a three-county region in south Texas that includes Cameron, Hidalgo, and Willacy counties. The model is calibrated to resemble documented behavior in 2010 and then the model is solved under a variety of scenarios representing the year 2060. Model year 2060 scenarios include a variety of assumptions about land-use changes, institutions, and climate. The model is generated to capture as many of the most relevant aspects of

Valley water management, but in many cases caveats to over-generalization of results are warranted.2

The land-use scenarios are defined by different assumptions about population density. In these scenarios, as population density increases, spatial expansion of urban lands is reduced. This results in less land sales revenue and less revenue from excluded water rights accruing to the agriculture sector. This effect becomes more apparent moving from the El Paso to the denser Laredo scenario. In the Laredo scenario, urban expansion is so dense and consequently new water right acquisitions by exclusion so low for urban agents, that urban agents enter the market to purchase water rights required for municipal use. While returns to agricultural production increase as the scenarios assume greater urban population density, agricultural sector revenues from land sales and water sales decline.

In the two institutional scenarios, where brackish desalination adoption is accelerated, quantities of brackish desalination produced expand until production capacity reaches the resource’s physical limit. In the SB3 scenario, a reduced price on excluded water rights is imposed. This reduces water sales revenues to the agricultural sector and reduces the opportunity costs of water treatment in the municipal sector. Lower treatment costs result in an increase in urban water consumer surplus, but do not shift urban supply sources away from brackish groundwater desalination.

The climate change scenarios impose on the model climate-based crop effects and system-wide reductions in reservoir inflows. If climate change substantially reduces the average inflows to the reservoirs serving the region, seawater desalination may optimally constitute a small component of regional water supplies. These results hold given certain highly-profitable irrigated crops maintain and/or increase in profitability under climate change. Of the five climate change models used in this analysis, only one is associated with significant gains to the agricultural sector. If climate change substantially reduces reservoir inflows, then the agricultural sector is likely to face losses in production and economic benefits.

One of the broad goals of the model presented in this essay is to generate useful information to water resource planners and managers in the Valley. One broad issue that follows from the population density scenarios is the degree to which regional water-use planning groups communicate with their counterparts in regional land-use planning groups. This essay demonstrates that land-use changes, in particular the expansion of urban areas into previously agricultural land, have dramatic effects on production returns to the agricultural sector as well as on water and land sales revenues to the agricultural sector. Therefore, one policy implication following from this finding is that such groups (i.e., land and water planning groups) may benefit from greater communication and, to some degree, conjoint management of their legally-bound resources.

Another policy recommendation includes a suggestion that the groundwater resources of the Valley be more explicitly understood and incorporated into regional water planning. From this essay, the cost-competitiveness of brackish groundwater desalination is likely to induce a greater portion of future municipal water supplies coming from brackish groundwater. From the second essay of this dissertation, the hydrologic relationship between the River and the region’s aquifer has not been recently studied, especially in light of increasing groundwater pumping for brackish groundwater desalination activities. Since the aquifer is likely to be a continuing, if not a growing, source of water for the region, understanding the capacity of that resource will become more important in the coming decades. Many policy options are available to manage such a resource, such as imposing pumping limits for groundwater users (which is essentially modeled in this essay) and installing a system of property rights (such as those used to manage surface water in the region).

A final broad issue underscored by this essay is the importance of anticipating and preparing for climate change. Four out of five climate change scenarios discussed are associated with less prosperity for the agricultural sector, with greater losses in productivity as reservoir inflow levels decline. A final issue is the importance of technology adoption in the portfolio of municipal water supplies. Brackish groundwater desalination can provide a substitute to singular dependence on the River, whose flows may become less reliable and less sizable over the next 50 years. For this reason, the most expensive municipal water supply alternative, seawater desalination, enters the model’s optimal portfolio of municipal supplies under a climate change scenario with a 0.35 reduction in River system inflows.

CHAPTER V

SUMMARY AND CONCLUSIONS

The focus of this dissertation is water issues in the Texas Lower Rio Grande Valley, geographically the region of south Texas near the mouth of the Rio Grande. The common threads across the three essays presented include the impact and relationship between water resource institutions and the well-being of the Valley community. A few of the institutions at work across the region include: a functioning water market, governmental and regulatory agencies, and water suppliers to both municipal consumers and agricultural producers. The challenges to the Valley water management system are abundant. The region is relatively economically-poor compared to the United States and is experiencing rapid population growth in the urban sector. Increasing population levels in the urban sector drive greater municipal water demand, which brings out equity concerns between the growing municipal sector and the longstanding agricultural sector. Additional equity concerns exist within the municipal sector, where newly-formed immigrant communities do not have access to water and wastewater services that are assumed to be standard across much of the United States.

Another issue that is likely to impact and test the region's water management institutions is the need for future water planning considering both the rapidly-increasing population and the potential of global climate change to permanently alter the reliable yields of the region's natural water sources. These topics are addressed through a theoretical study of water and health inter-relationships, a conceptual study of water management institutions, and a computational evaluation of present and future water supplies for regional well-being. The underlying motivation for the selection of these topics is a strong interest in the inter-relationships between water resources, public health, and economic well-being.

The first essay highlights water and public health-related issues of the Valley. A theoretical model of water-related disease management is developed. The essay discusses an empirical case study that is based on Hidalgo County, Texas. The results from this study underscore the importance of capital depreciation, institutional design, and how the two are linked by a water manager's planning horizon. Greater capital depreciation rates and shorter planning horizons are shown to be associated with lower community welfare. When these two undesirable forces combine, even less desirable consequences for the community are produced. More desirable water and public health management objectives can be achieved by either extending the planning horizon of the manager and/or by investing in long-lasting, relatively-durable capital in municipal water supply systems.

Implications from the first essay are that a public health accounting stance is important. Public health managers with a relatively narrow scope, such as those working exclusively with colonia residents, perceive a greater proportion of infected individuals than, for example, state-level public administrators. From the results of the control model, perceiving a greater portion of infected is expected to inflate the perceived marginal net benefits to therapeutic disease management strategies, such as medical treatment, relative to preventative measures, such as water treatment. Another finding from essay 1 is that greater capital depreciation rates and shorter time horizons are shown to be associated with lower community welfare. Scenarios with shorter planning horizons invested less in centralized-municipal stock. Lower capital depreciation rates allow the community to benefit from more durable centralized-municipal stocks, which prevents new infections and reduces disease damages.

The second essay is a largely, qualitative evaluation of the performance of the region's water market. This water market is shown to effectively reallocate water resources from low-valued agricultural use to higher-valued municipal and urban use. As the region's population growth and urban expansion has progressed over the last few decades, the price of a water right in the water market has risen to reflect the rising scarcity of water and change in structure of the region. These are encouraging signs that the market is operating to the benefit of society as a whole. As the region anticipates large population growth and potentially significant changes to physical water availability due to potential climate change, complications may arise that pose a concern for the functionality of the water market and pose a challenge for regional water managers.

More specific findings from the water market study include that the real price of a Falcon-Amistad water right has approximately doubled since the mid-1990s. During approximately the same period across the region, the numbers of agricultural water rights have fallen and the numbers of DMI water rights have increased. The major purchasers of water rights were individuals (33%) and municipal water suppliers (55%). Major water rights sellers included individuals (68%) and irrigation districts (30%).

Overall, municipal water suppliers were the only net purchasers of water rights, with individuals and irrigation districts being net sellers.

The final essay addresses a few of the potential challenges raised in the second essay by constructing and implementing a hydroeconomic model for the region. The model represents water resource management for a three-county region in south Texas that includes Cameron, Hidalgo, and Willacy counties. The model is calibrated to resemble documented behavior in 2010 and then the model is solved under a variety of scenarios representing the year 2060. Model year 2060 scenarios include several assumptions about land-use changes from agriculture to urban with population growth, water-related institutions, and climate change. In particular, the results from the hydroeconomic model highlight the importance of population density, land-use change policy, and technology adoption. Land-use and water-use institutions in the region are explicitly linked, through excludable water rights transactions. As such, coordinated management of water and land resources may be an advisable course of action in the future. The adoption of innovative technologies is expected to play a larger role in the region's municipal water supply system, particularly in the case of climate change, which may result in significant reductions to inflows into the region's reservoir system.

In particular, the 2060 scenario results indicate that greater population density, which reduces the amount of land converted from agricultural-use to urban-use, leaves more agricultural land in production and so increases the agricultural sector's returns to production. However, this increase in production returns comes at the cost of reduced revenues from the sale of land and water rights. In the scenario with the most dense assumption about the density of new population growth, the municipal sector could not attain sufficient water rights by the exclusion process and therefore entered the open market to purchase additional water rights from the agricultural sector. According to the 2060 scenarios, climate change may have a profound effect on the region's water supplies and water-related economic activity. Assuming climate change brings a 0.35 reduction in reservoir system inflows, seawater desalination may constitute a small portion of the region's municipal water supplies. In only one General Circulation Model scenario, do the climate change effects on crop yields and water use result in a prosperous estimate of 2060 agricultural production. In the other General Circulation Model scenarios, returns to agricultural production declined. In all scenarios, agricultural production falls dramatically as greater reductions on reservoir inflows are imposed. As a final word of caution, all of the 2060 results constitute long-term predictions conditional on an array of assumptions and, therefore, any interpretation of the 2060 results should be limited. Overgeneralizations or unqualified interpretations of those results would not be prudent.

Overall, this dissertation examines several characteristics of a region with challenging and looming water-resource planning and management issues. The ability for regional water managers to address these issues may depend on their understanding of the nexus of institutions and environmental conditions that affect water resource planning and management. Institutions may be challenged by changing demographics and changing climate; and emerging demographic and climatic realities may drive the adoption of new institutions.

Several important issues are likely to face the region in coming decades, such as finding water supplies for an urban population that is expected to double in the next 50 years. Many of these new residents are likely to be immigrants from Mexico with limited means to support municipal water infrastructure investment. The degree to which and the means by which these new residents receive municipal water, wastewater, and sanitation services are likely to continue to be issues of importance. Finally, if new municipal water supplies are to be reallocated from the agricultural sector, by either the process of exclusion or the open market, then the effect on the agricultural community requires additional study and understanding. This is true especially in the light of climate change, which may reduce water supplies but may also adjust the profitability of crops in south Texas.

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APPENDIX A

THE DISCRETE VERSION OF THE CONTROL PROBLEM

This discrete version of the optimal control problem presented in equations (A.1-7) was used to generate the numerical results.

$$\max_x \sum_t^T \left((-k_I I_t)(1+d)^{-t}\right) \tag{A.1}$$

subject to:

$$I_t = I_{t-1} + \frac{-bI_0 + \left(\beta^w A_0^w + \beta^p a_0^p + \beta^s\left(1 - A_0^w - a_0^p\right)\right)(1 - I_0) - (\delta^s(I_0 - a_0^m) + \delta^m a_0^m)}{1 - vI_0} \tag{A.2}$$

$$A_t^w = A_{t-1}^w + \frac{(1 - A_0^w)}{C^w} x_0^w - \gamma A_0^w \tag{A.3}$$

$$x_t^m = C^m a_t^m \tag{A.4}$$

$$x_t^p = C^p a_t^p \tag{A.5}$$

$$x_t^m + x_t^p + x_t^w = E_t \tag{A.6}$$

$$a_t^M \le I_t \tag{A.7}$$

$$a_t^P \le 1 - A_t^w \tag{A.8}$$

$$A_t^w, a_t^P, a_t^M \ge 0. \tag{A.9}$$

APPENDIX B

DETAILS ON THE PARAMETERIZATION OF THE NUMERICAL ANALYSIS

The numerical results come from a parameterized version of the discrete model. Numerical values for the parameters are displayed in Table B-1. The sources of these values come from literature sources and from reasonable approximations, in many cases derived from literature sources. The sources of individual parameter values are discussed below in greater detail.

Table B-1. Baseline parameter values for numerical solution of public health manager's water-services and waterborne disease optimization model for the case of Hidalgo County, Texas.

Parameters	Model Notation	Values
Population birth rate	a	0.02
Population death rate	b	0.02
Spontaneous transmission rate	β^{s}	0.462
CM transmission rate	β^{cm}	0.11
POU transmission rate	β^{pou}	0.11
Spontaneous recovery rate	δ^{s}	0.786
Medically-enhanced recovery rate	δ^{m}	1
Initial Infected Level	$I_{t=0}$	0.15
Initial CM Level	$A^{cm}{}_{t=0}$	0.96
CM cost factor	C^{cm}	1
POU cost factor ($10 Million)	C^{pou}	3.874
Medical cost factor ($10 Million)	C^{m}	3.990
Capital depreciation rate	γ	0.1
Manager's budget ($10 Million)	E_{t}	0.5
Social time preference rate	r	0.06
Morbidity damage factor	k_{I}	1
Total Population Level		424,762
Medical cost per person ($)		93.79
POU cost per person ($)		91.2

Source(s): WHO and UNICEF (1998); Jones (1999); Kommineni et al. (no date); Sargent-Michaud et al. (2006); Miguel and Gugerty (2005); Reynolds (2000); U.S. Census Bureau (2011b); Reynolds et al. (2008); Messner et al. (2006); Imhoff et al. (2004); Moe et al. (1991); Snyder and Merson (1982).

Medical Services Costs (cMed)

Assuming the medical treatment occurs at a community clinic and the treatment is the relatively inexpensive Oral Rehydration Salts (between $0.06 - $0.10 per dose at an average of two doses per case) (WHO and UNICEF 1998), the largest component of medical costs to the public health system is the time and productivity opportunity costs of the patient and the medical staff. This combined charge is approximated as wages for a single day for the patient ($7.25/hour * 8 hours = $58.00) and wages for one half hour for the medical staff, consisting of a general practitioner (0.5* $50.04/hr = $25.02/case) and a registered nurse (0.5 * $21.38/hour = $10.69/case) (Jones 1999). The sum of these costs yields a total medical cost of ($58.00 + $25.02 + $10.69) $93.79 per case.

The per case cost times the populations of interest in Hidalgo County (424,762 in 2010), Hidalgo County colonias (114,284 in 2007), and Hidalgo County "Red" Colonias (17,253 in 2007) is equal to: $39,838,428 for Hidalgo County, $10,718,697 for all Hidalgo County colonias, and $1,618,159 for residents in Hidalgo County "Red" colonias. Medical payments of this magnitude for a single county are unrealistic, but these amounts reflect the cost of providing everyone in Hidalgo County with medical treatment for diarrheal disease were they all to be infected. Since at one time only a fraction of total residents are infected, full medical coverage would cost a fraction of the amounts listed above. For the numerical portion of this study, the value for all of Hidalgo county is set equal to C^m, which, during optimization, is then multiplied by a^{Med}, the portion of the total population that actually receives treatment.

Point-Of-Use Costs (c^{POU})

The per household cost of providing POU services is estimated by considering the costs to install and operate an in-home water filtration systems for a year. Kommineni et al. (no date) report monthly costs for POU reverse osmosis systems at $50/month and POU adsorption systems at $38/month. This is equal to an annual cost of

\$600/year for RO and \$456/year for adsorption. These values are likely to exceed the costs for the health issues studied in this paper because the Kommineni et al. values also include an annual arsenic test of \$15/year. These annual costs from Kommineni et al. are relatively close to annual costs for similar treatment processes reported by Sargent-Michaud et al. (2006).

Multiplying the annual POU household costs by the number of households in Hidalgo County, which is taken to be total population divided by an assumed average household size of five individuals (424,762 / 5 = 84,952 households), yields the total cost of distributing POU to the entirety of Hidalgo County, which is found in the range of \$38,738,294 (84,952 households * \$456/yr) on the low end and \$50,971,200 (84,952 households * \$600/yr) on the high end.

Initial Centralized-municipal Service Level ($A^{w}_{t=0}$)

To approximate the initial level of centralized-municipal water services, this study identifies the number of reported colonia residents that were reported to have no access to either potable water or wastewater disposal, which is 17,253 individuals in Hidalgo County (USGS 2010b), approximately 15% of the county's colonia population and about 4% of the county's total population. Note, while this number of individuals is the number counted in 2007 and since then many such households may have acquired drinking water or wastewater services, it nonetheless represents the best available information on the subject. Therefore the initial level of A^{cm} is set equal to 96% (i.e., $A^{w}_{t=0}$=0.96).

Centralized-municipal Costs and Depreciation

Cost structuring the stock of CM infrastructure is more complicated than the either of the other two disease management strategies. This involves taking equation 2.8 and imposing $A_t^{cm} = 0$, and rearranging to yield the following relation: $\frac{x_t^{cm}}{C^{cm}} = \dot{A}_t^{cm}$. This relation (and its assumptions) captures the idea that in a community with no existent CM stock, all expenditures on CM are weighted by c^{cm} to yield the corresponding amount of CM infrastructure that will be available in the next period. A reasonable value to use for c^{cm} is not known. A value of $C^{cm} = 4$ suggests that in a given year, the community can go from 0% of the population having CM services to 25% having CM services by expending all of the disease management budget available to a community on CM. A quarter of the population of a community the size of Hidalgo County is more than 100,000 individuals.

An estimate for the value of the annual capital depreciation rate is similarly difficult to identify. Miguel and Gugerty (2005) report that in western Kenya nearly 50 percent of borehole wells dug in the 1980s, and subsequently maintained using a community-based maintenance model, had fallen into disrepair by 2000. This decay level, 50% lost in a period of 20 years corresponds to an annual decay rate of about 0.035. Such a rate is likely too high for a more economically developed location characteristic of Hidalgo County   For robustness, several depreciation rates will be used 0.01, 0.05, and 0.1, and the resulting system characteristics explored.

Recovery Rates

There are two recovery rates associated with the model, coming from the recovery function: $\delta(a_t^m) = \delta^0(I_t - a_t^m) + \delta^m a_t^m$. The medically-enhanced recovery rate is assumed to be $\delta^m = 1$, which implies that all individuals included in the portion of the receiving medical care move to the susceptible class the next time period. Intuitively, medication results in a full and complete recovery.

Morbidity danger associated with waterborne illnesses is different depending on a population's level of young, old, and otherwise immune-compromised individuals (Reynolds 2000). Estimation of a value for the spontaneous recovery rate δ^0 begins with considering the infected population as being composed of immune-compromised and immune-sufficient individuals. The immune-compromised individuals are defined as being children under the age of five and adults over the age of 65. In Hidalgo County, these individuals make up, respectively, 9.5% and 11.9%, of the population (U.S. Census Bureau 2011b). This suggests that if a randomly selected person in Hidalgo County gets a diarrheal disease 21.4% of the time that person will be immune-compromised and the other 78.6% of the time that person will be a relatively healthier adult. By this reasoning, the spontaneous recovery is set as: $\delta^0 = 0.786$. Intuitively, this rate implies that as individuals get infected and do not receive medical care, those individuals are moved back into the susceptible class (i.e., they recover) at a rate equal to the portion of the healthy adult population. By this assumption, healthy adults recover in one time period and the immune-compromised portion of the infected lingers in the infected class for at least one more time period.

Transmission Rates

The transmission rates for diarrheal illness with access to treated drinking water comes from the review by Reynolds et al. (2008), who, citing Messner et al. (2006) and Imhoff et al. (2004), summarize that gastrointestinal illness prevalence that is attributable to drinking water is equal to 0.11 cases/person/year. Since no distinction in those studies is made with respect to drinking water treatment technologies, this essay assumes both technologies have equal effectiveness as devices to prevent diarrheal episodes: $\beta^{cm} = \beta^{pou} = 0.11$. A limitation of this study is that the model, and specifically, this transmission rate, abstracts away from other sources of diarrheal illness, which can occur through infection routes that may be unrelated to water quality (Moe et al. 1991).

In one of the earlier world-wide surveys of diarrheal disease burden studies, Snyder and Merson (1982) report that the average number of episodes for individuals in Asia and Latin America were, respectively 2.013 and 1.075 per person per year, with increasing episodes with the youngest age groups. During the 1960s and 1970s, when these studies were conducted, water service coverage in those regions was likely minimal. So, arguably, these values provide a reasonable proxy for a baseline transmission rate that might occur in the absence of water treatment. The worldwide episode rates for individuals younger than (older than) five years are 1.91 (0.27) cases/person/year. By weighting these two rates by the demographic percentages for Hidalgo County found in U.S. Census Bureau (2011), the total estimated population transmission rate for population portions with no water treatment of any kind is assumed to be $\beta^0 = 0.462$.

APPENDIX C

DESCRIPTION OF NUMERICAL COMPUTATION

The numeric computation procedure follows a fairly standardized formula for genetic algorithm computation (Forrest 1993; Holland 1992). At the beginning of the program, several thousand candidate solutions are randomly generated. The objective function values of each candidate solution are reviewed and the best solution is recorded. For this study, “best” is equivalent to “greatest”, since the objective is to maximize $\sum_t^T\left((-k_I I_t)(1+d)^{-t}\right)$. Next, for each of the candidate solutions, the value of a single control variable is changed slightly. Once again the program is designed to review the objective function values of the candidate solutions and record the best solution from the new generation. This process is repeated for several thousand generations of solutions. The best solution from each new generation is compared to the best solution from all previous generations. The program terminates at the end of a specified maximum number of generations and then outputs the best solution. The following pseudo-code describes the program more succinctly:

1. Initialize the population of solutions
2. Evaluate the objective function values of each solution
3. Record the best solution in the generation
4. Generate a new set of solutions from the previous, or parent, generation

5. Check that each new solution is located in feasible solution space and if the solution is not feasible, then move the solution to the nearest feasible solution.
6. Record the best solution in the generation
7. Compare current generation best solution to previous generation best
8. If maximum number of generations has been reached, then terminate; if not, return to step 4.

APPENDIX D

BUDGET CONSTRAINT SENSITIVITY TABLES

Table D-1. Baseline results from the public health manager's disease management problem for the case of Hidalgo County, Texas, using the baseline budget level (E_t = 0.5).[a]

Time:	1	2	3	4	5	6
Controls[b.]						
x^{CM}	0.00	0.00	0.50	0.50	0.00	0.00
a^{POU}	0.04	0.13	0.00	0.00	0.13	0.13
a^{M}	0.09	0.00	0.00	0.00	0.00	0.00
State Variables						
Infected	0.15	0.09	0.10	0.17	0.16	0.12
Centralized-municipal	0.96	0.86	0.78	0.81	0.82	0.74
Budget shares						
Centralized-municipal	0.00	0.00	1.00	1.00	0.00	0.00
Point-of-use	0.31	1.00	0.00	0.00	1.00	1.00
Medical	0.69	0.00	0.00	0.00	0.00	0.00
Water Services						
Centralized-municipal	0.96	0.86	0.78	0.81	0.82	0.74
Point-of-use	0.04	0.13	0.00	0.00	0.13	0.13
None	0.00	0.01	0.22	0.19	0.05	0.13
Medical Services						
Portion of Total Population	0.09	0.00	0.00	0.00	0.00	0.00
Portion of Infected	0.58	0.00	0.00	0.00	0.00	0.00
Cumulative Damages[c.]	**0.15**	**0.23**	**0.32**	**0.47**	**0.59**	**0.68**

a. E_t = 0.5 refers to a budget size that is equal to the baseline.
b. x^{CM} are the expenditures on centralized-municipal water services. a^{POU} is the portion of population receiving point-of-use water services. a^{M} is the portion of the infected population receiving medical treatment.
c. Cumulative damages are measured as $\int_0^T \left((-1)k_I I_t\right)e^{-rt}$.

Table D-2. Sensitivity results from the public health manager's disease management problem for the case of Hidalgo County, Texas, using a budget level reduced from the baseline to 50% (E_t = 0.25).[a]

Time:	1	2	3	4	5	6
Controls[b]						
x^{CM}	0.00	0.25	0.25	0.25	0.00	0.00
a^{POU}	0.04	0.00	0.00	0.00	0.06	0.06
a^{M}	0.02	0.00	0.00	0.00	0.00	0.00
State Variables						
Infected	0.15	0.10	0.14	0.16	0.17	0.16
Centralized-municipal	0.96	0.86	0.81	0.78	0.76	0.68
Budget shares						
Centralized-municipal	0.00	1.00	1.00	1.00	0.00	0.00
Point-of-use	0.62	0.00	0.00	0.00	1.00	1.00
Medical	0.38	0.00	0.00	0.00	0.00	0.00
Water Services						
Centralized-municipal	0.96	0.86	0.81	0.78	0.76	0.68
Point-of-use	0.04	0.00	0.00	0.00	0.06	0.06
None	0.00	0.14	0.19	0.22	0.18	0.26
Medical Services						
Portion of Total Population	0.02	0.00	0.00	0.00	0.00	0.00
Portion of Infected	0.16	0.00	0.00	0.00	0.00	0.00
Cumulative Damages[c]	**0.15**	**0.24**	**0.37**	**0.51**	**0.64**	**0.76**

[a] E_t = 0.25 refers to a budget size that is one quarter of the baseline.
[b] x^{CM} are the expenditures on centralized-municipal water services. a^{POU} is the portion of population receiving point-of-use water services. a^{M} is the portion of the infected population receiving medical treatment.
[c] Cumulative damages are measured as $\int_0^T \left((-1)k_I I_t\right)e^{-rt}$.

Table D-3. Sensitivity results from the public health manager's disease management problem for the case of Hidalgo County, Texas, using a budget level increased from the baseline by 100% (E_t = 1.0).[a.]

Time:	1	2	3	4	5	6
Controls[b.]						
x^{CM}	0.25	0.51	0.42	0.34	0.09	0.00
a^{POU}	0.04	0.13	0.15	0.17	0.20	0.26
a^{M}	0.15	0.00	0.00	0.00	0.04	0.00
State Variables						
Infected	0.15	0.07	0.10	0.10	0.10	0.09
Centralized-municipal	0.96	0.87	0.85	0.83	0.80	0.74
Budget shares						
Centralized-municipal	0.25	0.51	0.42	0.34	0.09	0.00
Point-of-use	0.15	0.49	0.58	0.66	0.76	1.00
Medical	0.60	0.00	0.00	0.00	0.15	0.00
Water Services						
Centralized-municipal	0.96	0.87	0.85	0.83	0.80	0.74
Point-of-use	0.04	0.13	0.15	0.17	0.20	0.26
None	0.00	0.00	0.00	0.00	0.00	0.00
Medical Services						
Portion of Total Population	0.15	0.00	0.00	0.00	0.04	0.00
Portion of Infected	1.00	0.00	0.00	0.00	0.37	0.00
Cumulative Damages[c.]	**0.15**	**0.22**	**0.31**	**0.39**	**0.47**	**0.54**

[a.] E_t = 0.25 refers to a budget size that is one quarter of the baseline.
[b.] x^{CM} are the expenditures on centralized-municipal water services. a^{POU} is the portion of population receiving point-of-use water services. a^{M} is the portion of the infected population receiving medical treatment.
[c.] Cumulative damages are measured as $\int_0^T \left((-1)k_I I_t\right)e^{-rt}$.

APPENDIX E

DETAILS ON PRICE TREND REGRESSION

The regression results supporting the models presented in Figure 2-6 are displayed in Table E-1. Table E-1 contains estimated values for coefficients, p-values for estimates, measures of explanatory power (i.e., R^2 and Adjusted R^2), and the F-test values for the models. These models were selected because, visually, prices in the market appear to be relatively constant during the years 1983 to approximately 1998,

Table E-1. Regression analyses on real market prices for water rights in the Falcon-Amistad water market, 2009.

Model Name	Model Formula[a,b,c]	Coefficient values[d]			Model statistics: R^2	Adj-R^2	F-test[e]
Liebig	$p = b_0{*}D_1 + b_1{*}D_2 + b_2{*}t{*}D_2$	b_0	b_1	b_2	0.873	0.859	64.99
		0.698	-1.73	0.157			
		0.000	0.003	0.000			
Linear Dummy	$p = b_3 + b_4{*}t + b5{*}t{*}D_3$	b_3	b_4	b_5	0.892	0.880	78.08
		0.675	0.003	0.042			
		0.000	0.778	0.000			

Source(s): analyses of nominal prices reported in Caroom and Maxwell (2005); Chang and Griffin (1992); Characklis et al. (1999); Griffin and Characklis (2002); Levine (2007); NRS Consulting Engineers (2001, 2003, 2006); Schoolmaster (1991).

[a] y is the time-adjusted real market price, using a 2% inflation rate and 2008 as the base year.

[b] t is years in the sample, with year 1 starting at 1983.

[c] D_1, D_2, D_3 are a dummy variables for, respectively, the years 1983-1991, 1999-2005, and 2000-2005.

[d] P-values are listed below coefficient estimates with p-values in bold corresponding to coefficient estimates that have a level of significance of 5% or less.

[e] F-test values in bold correspond to a level of significance of 5% or less.

and thereafter prices appear to be increasing. The formal description of the Liebig model presented in Figure 2-6 is presented in equation E-1, below:

$$\hat{p} = \max \quad (b_0, b_1 + b_2 t), \tag{E.1}$$

where the predicted price trend (i.e., $\hat{p}$ and/or the dashed line in Figure 2-6) is a function of the maximum value of either the constant price trend in the early years of the sample (i.e., b_0), or the increasing price trend in the latter portion of the sample (i.e., $b_1 + b_2 t$).

APPENDIX F

DEMAND CURVE PROJECTION

The consumer surplus values for municipal water consumption were projected by assuming a linear demand form (Nicholson and Snyder 2008), as follows:

$$w = \mathrm{m}p + b, \tag{F.1}$$

where w is the quantity of water consumed, m (equal to dw/dp) is the slope of the demand curve, p is the price of water, and b is a constant. The inverse demand equation is found by inverting equation F.1 to yield:

$$p = (\mathrm{w} - b)\mathrm{m}^{-1}. \tag{F.2}$$

Equation 4A.2 is the demand equation included in the objective function as $D_s(\cdot)$. Integration over w results in the equation for consumer surplus (i.e., CS) that is used to compute the consumer surplus component of the objective function value:

$$CS = \int_w \left((\mathrm{w} - b)\mathrm{m}^{-1}\right)dw = 0.5w^2\mathrm{m}^{-1} - wb\mathrm{m}^{-1}. \tag{F.3}$$

To compute this value, the following parameters must be identified or assumed: $w, m,$ and b. The quantity of water, w, is calculated in the model. By substituting in a single data point for quantity and price and invoking an estimated price elasticity from literature, the slope of the demand curve, m, can be calculated. The formula for price elasticity is (Nicholson and Snyder 2008):

$$\varepsilon = \frac{dq}{dp}\frac{p}{q}. \tag{F.4}$$

Replacing q with w, and rearranging results in the following estimate for the slope of the demand curve:

$$m = \frac{dw}{dp} = \varepsilon \frac{w}{p}. \tag{F.5}$$

Once the value for m is calculated from assumed values of elasticity, water quantity, and price, the constant term, b, can be calculated by solving the linear demand form for b (using the same assumed single data point for quantity and price):

$$b = w - mp. \tag{F.6}$$

This study averaged over monthly price elasticities reported in Bell and Griffin (2006) to generate seasonal price elasticities. Water quantities by season and county are calculated from unpublished county-level diversion data collected by the Watermaster's office in Harlingen. The price of municipal water is assumed to be $679/acre foot (or $20.67/1,000 gallons). This price is selected as a relatively-low, conservative value based on a recent survey of water rates (Ohio EPA 2010). A demand curve is calculated for each county and each season.

APPENDIX G

RELEVANT DATA FROM VALLEY CROP BUDGETS

Crop budgets developed by AgriLife Extension (Extension Agricultural Economics 2011) were used to advise the selection of crops to include in the agricultural component of the model. In most cases, parameter values for yield, prices, and production costs were taken directly from crop budgets. Those values are listed in Table G-1.

Table G-1. Crop prices, yields per acre, and costs per acre used in the model of a three-county region (Cameron, Hidalgo, Willacy counties) in south Texas.

crop (*i*)	practice (*p*)	Price ($)	Yield (per acre)		Cost ($/acre)
cotton	dryland	0.81	596.17	lbs[a]	416
cotton	irrigated	0.81	997.64	lbs[a]	609
sorghum	dryland	8.50	22.00	cwt	159
sorghum	irrigated	8.50	43.00	cwt	207
corn	irrigated	4.90	100.00	bu	285
sugar cane	irrigated	19.00	50.00	tons	803
onion	irrigated	12.00	550.00	sacks	3,374
cantaloupe	irrigated	10.00	600.00	crtn	4,581
cabbage	irrigated	8.00	930.00	crtn	3,501
citrus	irrigated	100.00	23.00	tons	1,066

Source(s): Extension Agricultural Economics (2011).
[a.] According to the crop budgets, cotton crops produce two marketable items, lint and seed. For this model, seed revenues are converted into “lint-yield equivalent”. These lint-yield equivalents were then added to the crop budget’s documented lint yields to produce the values reported in the table.

APPENDIX H

CROP WATER CONSUMPTION TABLES

Estimates for water application by crop using the irrigation values reported in the Valley's crop budgets. Following consultations with local crop scientists, the crop budget water use values were modified and the following table of crop water use values is applied in the model (Table H-1).

Table H-1. Selected crop water usages (acre feet) in the Texas Lower Rio Grande Valley for one acre of a given crop adjusted from crop budget data, 2011.

	Season				
	Spring	Summer	Fall	Winter	Annual
Cotton (irrigated)	0.76	0.96			1.72
Cotton (dryland)					
Sorghum (irrigated	1.08	0.36			1.44
Sorghum (dryland)					
Cabbage	0.18		0.66	0.45	1.29
Sugarcane	1.17	2.33	0.94	0.35	4.79
Citrus	0.84	1.18	0.75	0.42	3.19
Cantaloupe	0.80			0.40	1.20
Onion	0.15		0.55	0.37	1.07
Corn	0.69	1.16			1.85

Source(s): Crosby (2011); Extension Agricultural Economics (2011); Jifon (2011); Koo (1975); Texas Board of Water Engineers (1960); Wiedenfield et al. (2004).

APPENDIX I

DISTRIBUTION SYSTEM COSTS

The calculations used to estimate the cost of municipal water service distribution is presented in Table I-1. The assumptions are based on a municipal water distribution expansion project for a water supplier located in Hidalgo County (Correa 2011). The piping details are related to the water suppliers' current distribution size. The pumping details are based on a possible expansion of the system. The estimated costs are $26/year/person served, or $91/year/acre foot delivered (Correa 2011).

Table I-1. Assumptions and calculations used to generate a per unit cost ($/year/acre foot) of municipal water distribution (i.e., without treatment) for a modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas.

Piping details	
System capacity (gallons per day)	16,000,000
System capacity (acre feet per year)	17,922
Approximate service size (population served)	64,144
Piping ($)	20,932,636
Amortization period (years)	50
Discount rate (rate)	0.06125
Annualized piping cost ($/year)	1,351,285
Annualized piping cost ($/year/acre foot)	75.40
Pumping details	
System capacity (gallons per day)	8,000,000
System capacity (acre feet per year)	8,961
Approximate service size (population served)	36,697
Pumps ($)	519,000
Pump installation and housing ($)	389,250
Piping, controls, valving, apperturances ($)	1,197,000
Pumping capital subtotal ($)	2,105,250
Amortization period (years)	50
Discount rate (rate)	0.06125
Annualized pumping cost ($/year)	135,902
Annualized pumping cost ($/year/acre foot)	15.17
Continuing cost details	
Operations and maintenance ($/year)	48,180
Annualized continued costs ($/year/acre foot)	0.04
Cost summary	
Annual costs per capita served ($/year/person)	26.08
Annual cost per acre foot delivered ($/year/acre foot)	90.60

Source(s): Correa (2011) and user defined.

APPENDIX J

IRRIGATION AND DRYLAND EXPANSION COSTS

Table J-1. Estimated costs of land-use changes, conversion of dryland agriculture to irrigated agriculture and conversion of ranchland/wilderness to cropland for a modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas.

Irrigation Expansion Cost	
Estimated irrigation infrastructure cost/mile	$4,200,000
Agricultural acres per mile	242
Cost per acre	$17,355
Amortization period (years)	50
Discount factor	0.06125
Annualized cost ($/acre/year)	$1,120.36
Dryland Expansion Cost	
Estimated dryland expansion cost/acre	$1,000
Amortization period (years)	50
Discount factor	0.06125
Annualized cost ($/acre/year)	$64.55

Source(s): Correa (2011) and user defined.

Some of the key assumptions used in the calculation of the per mile cost of irrigation infrastructure are as follows (Correa 2011) (Figure J-1): canal size and flow capacity are based on 10,000 acre delivery area, servicing summer-season sugar cane production, where water deliveries occur during 24 days in the three-month summer season. These assumptions reflect the greatest plausible volume of water to be conveyed through an irrigation canal and imply a rate of 0.05 cubic feet per second per acre. Restricting maximum flow velocity through the canal to be less than two feet per second, the physical design parameters are calculated for an earthen canal that is 120.6 feet wide at the base and 52.2 feet wide at the top, with 22.2 feet of water surface and two 12-feet wide, drivable embankments on either side of the water surface. The canal is 17.1 feet tall, with the bottom of the water channel located three feet above natural ground and the top of the embankments located three feet above the designed water surface. The assumed price of earthen fill (delivery, manipulation, and compaction) is $12.40 per cubic yard (Correa 2011). The canal is also assumed to be equipped with a 4-inch thick concrete liner, with an assumed, in-place cost of $450 per cubic yard (Correa 2011).

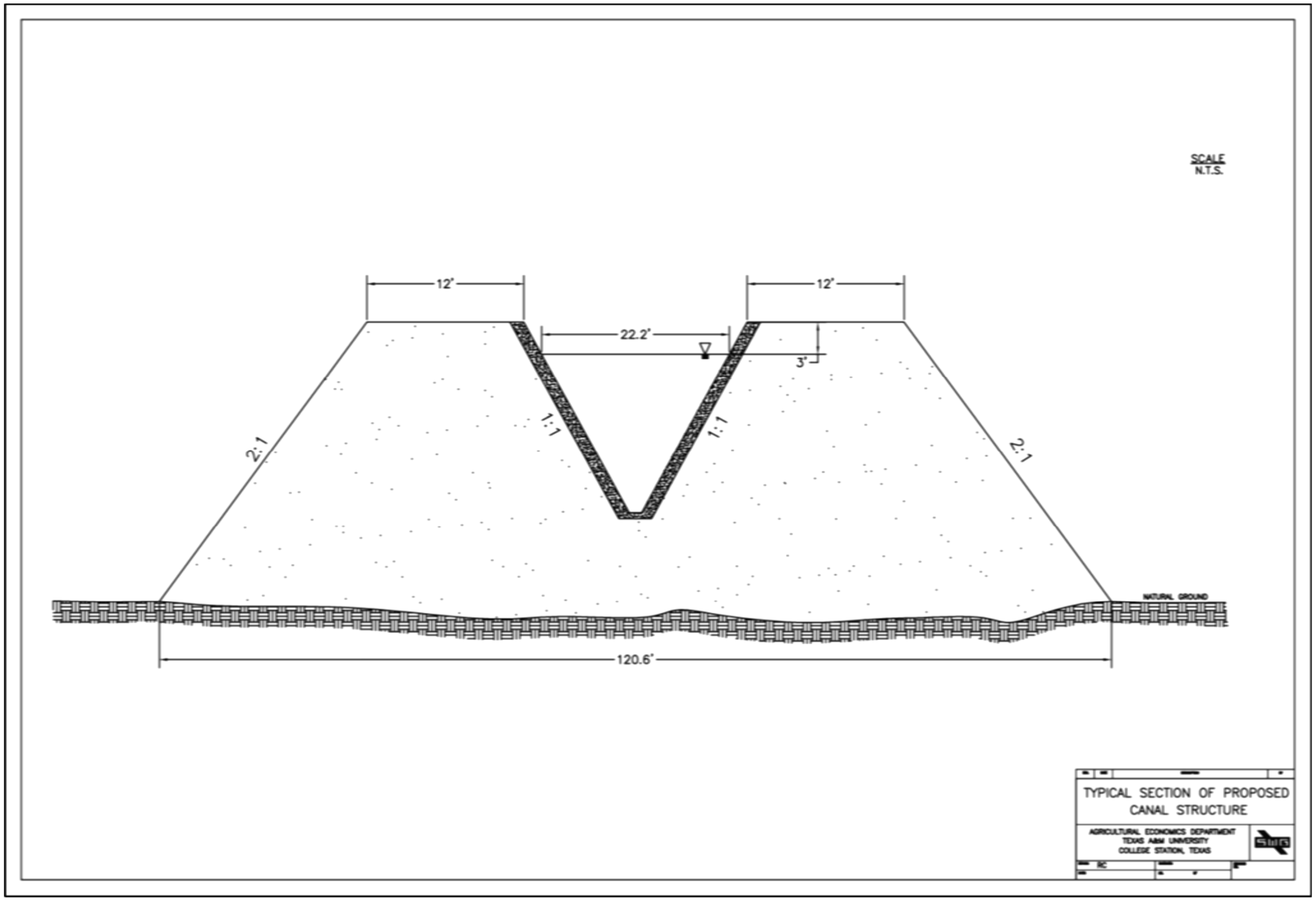

Figure J-1. Cross-sectional view of hypothetical canal used to calculate the cost of expanding irrigation infrastructure to dryland agricultural areas for a modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas.
Source(s): Correa (2011).

APPENDIX K

CROP EFFECTS BY GLOBAL CIRCULATION MODEL

Following Beach et al. (2009), climate forecasts from the GCMs are used as inputs into Environmental Policy Integrated Climate models (EPICs), which output changes in yields and water consumption for several crops in south Texas (cotton, corn, soybeans, soft red winter wheat, hard red winter wheat, durum wheat, hard red spring wheat, sorghum, rice, oats, barley, silage, hay, sugar cane, sugar beets, potatoes, tomatoes, energy sorghum, sweet sorghum, oranges, grapefruits, grazing oats, grazing wheat). For several crops included in the hydroeconomic model of the Valley discussed herein, crop response data are unavailable; those crops include onion, cabbage, and cantaloupe. For this study, the crop response effects of sugar beets are assumed to be a proxy for missing effects for onion. Tomatoes are assumed to be the proxy for cabbage and cantaloupe. The climate effects on crop water use and crop yield are presented in Table K-1.

Table K-1. Proportional changes in crop yields and crop water use for the south Texas region from several General Circulation Models (GCMs) used to generate climate change scenarios in the a modeled three-county region (Cameron, Hidalgo, and Willacy counties) in Texas in model year 2060.

			Global Circulation Model (GCM)				
crop (*i*)	practice (*p*)	crop attribute	CGCM 3.1	MRI-CGCM2.2	GFDL-CM2.0	GFDL-CM2.1	Avg
Cotton	dryland	yield	0.13	-0.30	-0.42	-0.62	-0.30
cotton	irrigated	yield	0.00	-0.12	-0.03	0.44	0.07
cotton	irrigated	water use	-0.07	0.44	-0.09	0.30	0.14
sorghum	dryland	yield	-0.02	-0.10	-0.11	-0.39	-0.15
sorghum	irrigated	water use	-0.05	-0.28	-0.02	0.41	0.01
sorghum	irrigated	yield	-0.07	0.23	-0.15	0.43	0.11
corn	irrigated	yield	-0.09	-0.57	-0.03	0.41	-0.07
corn	irrigated	water use	-0.04	0.17	-0.18	0.66	0.15
sugar cane	irrigated	yield	-0.02	0.58	-0.07	0.73	0.30
sugar cane	irrigated	water use	-0.05	0.52	-0.09	0.60	0.24
onion	irrigated	yield	0.08	1.00	0.17	0.07	0.33
onion	irrigated	water use	-0.03	-0.62	0.19	-0.58	-0.26
cantaloupe	irrigated	yield	-0.09	-0.57	-0.03	0.41	-0.07
cantaloupe	irrigated	water use	-0.04	0.17	-0.18	0.66	0.15
cabbage	irrigated	yield	-0.09	-0.57	-0.03	0.41	-0.07
cabbage	irrigated	water use	-0.04	0.17	-0.18	0.66	0.15
citrus	irrigated	yield	-0.33	-0.61	-0.02	0.36	-0.15
citrus	irrigated	water use	-0.24	0.22	-0.60	0.52	-0.02

Source(s): Modified from Beach et al. (2009).

VITA

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