

Sustainable Water Management in Ciudad Juarez

by

Gustavo Leopoldo Garduno Angeles.

A Dissertation Presented in Partial Fulfillment  
of the Requirements for the Degree  
Doctor of Philosophy

Approved March 2011 by the  
Graduate Supervisory Committee:

Charles Perrings, Chair  
Rimjhim Aggarwal  
Jim Holway

ARIZONA STATE UNIVERSITY

May 2011

## ABSTRACT

Water resources in many parts of the world are subject to increasing stress because of (a) the growth in demand caused by population increase and economic development, (b) threats to supply caused by climate and land cover change, and (c) a heightened awareness of the importance of maintaining water supplies to other parts of the ecosystem. An additional factor is the quality of water management. The United States-Mexican border provides an example of poor water management combined with increasing demand for water resources that are both scarce and uncertain.

This dissertation focuses on the problem of water management in the border city of Ciudad Juarez, Chihuahua. The city has attracted foreign investment during the last few decades, largely due to relatively low environmental and labor costs, and to a range of tax incentives and concessions. This has led to economic and population growth, but also to higher demand for public services such as water which leads to congestion and scarcity. In particular, as water resources have become scarce, the cost of water supply has increased.

The dissertation analyzes the conditions that allow for the efficient use of water resources at sustainable levels of economic activity—i.e., employment and investment. In particular, it analyzes the water management strategies that lead to an efficient and sustainable use of water when the source of water is either an aquifer, or there is conjunctive use of ground and imported water.

The first part of the dissertation constructs a model of the interactive effects of water supply, wage rates, inward migration of labor and inward investment of capital. It shows how growing water scarcity affects population growth through the impact it has

on real wage rates, and how this erodes the comparative advantage of Ciudad Juarez—low wages—to the point where foreign investment stops. This reveals the very close connection between water management and the level of economic activity in Ciudad Juarez.

The second part of the dissertation examines the effect of sustainable and efficient water management strategies on population and economic activity levels under two different settings. In the first Ciudad Juarez relies exclusively on ground water to meet demand—this reflects the current situation of Ciudad Juarez. In the second Ciudad Juarez is able both to import water and to draw on aquifers to meet demand. This situation is motivated by the fact that Ciudad Juarez is considering importing water from elsewhere to maintain its economic growth and mitigate the overdraft of the Bolson del Hueco aquifer. Both models were calibrated on data for Ciudad Juarez, and then used to run experiments with respect to different environmental and economic conditions, and different water management options.

It is shown that for a given set of technological, institutional and environmental conditions, the way water is managed in a desert environment determines the long run equilibrium levels of employment, investment and output. It is also shown that the efficiency of water management is consistent with the sustainability of water use and economic activity. Importing water could allow the economy to operate at higher levels of activity than where it relies solely on local aquifers. However, at some scale, water availability will limit the level of economic activity, and the disposable income of the residents of Ciudad Juarez.

## ACKNOWLEDGMENTS

I wish to thank my family, they always support my decisions.

I would like to thank my advisor Charles Perrings that believed in me and Ann Kinzig.

I would like to thank my friends Lisa Taylor, Ted Gilliland, and Christopher Bang because without their support I never could have finished this dissertation.

## TABLE OF CONTENTS

	Page
LIST OF TABLES .....	vi
LIST OF FIGURES .....	viii
CHAPTER	
1 INTRODUCTION .....	1
2 THE UNITED STATES MEXICAN BORDER .....	11
Introduction.....	11
Population growth and the maquilas .....	14
Water scarcity .....	18
Binational Institutions .....	25
Conclusions.....	30
3 CIUDADA JUAREZ .....	32
Introduction.....	32
Population and maquiladoras.....	34
Water sector.....	37
Conclusions.....	47
4 SUSTAINABLE WATER MANAGEMENT .....	62
Introduction.....	62
Model.....	67
Water as a constraint on economic growth.....	75
Optimal recycling policy in absence of external water sources .....	80
Looking into the future: Importing water .....	95

CHAPTER	Page
Conclusions.....	107
5 MODEL ANALYSIS .....	114
Introduction.....	114
Water autarky .....	117
Water autarky: Sensitivity analysis.....	122
Water autarky: Costs and welfare .....	127
Water imports .....	136
Conclusions.....	146
6 CONCLUSION .....	181
LITERATURE CITED.....	189
APPENDIX	
I APPENDIX A: STABILITY OF STEADY STATE.....	210
II APPENDIX B: STEADY STATE LEVELS .....	213

LIST OF TABLES

Table	Page
1. Population growth Ciudad Juarez (1950-2005) .....	48
2. Nominal wage per day: (1993-2006).....	48
3. Employment and gross production in Ciudad Juarez 1998 .....	49
4. Water use in Ciudad Juarez by type (1999). .....	50
5. Projected municipal and industrial water demand for Ciudad Juarez by category (2001) .....	51
6. Rates of ground water and ground water transfer in 2002 for El Paso and Ciudad Juarez aquifer sub-components .....	52
7. Water demand for Ciudad Juarez and El Paso by category .....	53
8. Steady state population levels and injection capabilities .....	148
9. Steady state parameters when wages are determined by Brazil .....	149
10. Steady state parameters when wages are determined by S.Q.....	149
11. Sample cases I .....	150
12. Welfare levels when $\phi$ equals 78.84% and wages are determined by the competition with Brazil .....	150
13. Welfare levels when $\phi$ equals 71.65% and wages are determined by the competition with Brazil .....	151
14. Welfare levels when $\phi$ equals 78.74% and wages are determined by current levels .....	151
15. Welfare levels when $\phi$ equals 71.65% and wages are determined by current levels .....	152

Table	Page
16. Samples cases II .....	152



## LIST OF FIGURES

Figure	Page
1. El Paso and Ciudad Juarez .....	55
2. Paso del Norte region's aquifers .....	56
3. Unemployment rate Mexico City and Ciudad Juarez .....	57
4. Unemployment rate Mexico and Ciudad Juarez .....	57
5. Maquiladora plants in Ciudad Juarez .....	58
6. Maquiladora workers in Ciudad Juarez (1974-2006) .....	58
7. Bolson Hueco Aquifer .....	59
8. Ground water extraction by Ciudad Juarez and El Paso .....	60
9. Hueco Bolson aquifer (transversal cross section view) .....	61
10. Behavior of the dynamic equation for the capital stock .....	109
11. Behavior of the dynamic equation for the population .....	109
12. Ground water model .....	110
13. Ground water injection model.....	111
14. Water injection optimal trajectories (no population).....	111
15. Water injection optimal trajectories (natural recharge change).....	112
16. Water injection optimal trajectories (population growth) .....	113
17. Water injection Case 1 .....	153
18. Ground water stock Case 1 .....	153
19. Water injection Case 2 .....	154
20. Ground water stock Case 2 .....	154
21. Water injection Case 3 .....	155

Figure	Page
22. Ground water stock Case 3 .....	155
23. Differences between injection trajectories (Case 1 vs. 3).....	156
24. Water injection Case 4 .....	156
25. Ground water stock Case 4 .....	157
26. Water injection Case 5 .....	157
27. Ground water stock Case 5 .....	158
28. Water injection levels for ( $\phi=1.5, \gamma=1.266, \rho=78.74\%$ , $\phi/\gamma=1.185$ ), ( $\phi=0.1, \gamma=1.267, \rho=78.74\%$ , $\phi/\gamma=0.0789$ ).....	158
29. Welfare levels ( $\phi=1.5, \gamma=1.266, \rho=78.74\%$ , $\phi/\gamma=1.185$ ), ( $\phi=0.1, \gamma=1.267, \rho=78.74\%$ , $\phi/\gamma=0.0789$ ). .....	159
30. Injection levels ( $\phi=0.5, \gamma=1.267, \rho=78.74\%$ , $\phi/\gamma=0.4$ ), ( $\phi=4, \gamma=1.213, \rho=78.74\%$ , $\phi/\gamma=3.3$ ). .....	159
31. Welfare levels ( $\phi=0.5, \gamma=1.267, \rho=78.74\%$ , $\phi/\gamma=0.4$ ), ( $\phi=4, \gamma=1.213, \rho=78.74\%$ , $\phi/\gamma=3.3$ ) .....	160
32. Ground water stock levels ( $\phi=0.5, \gamma=1.267, \rho=78.74\%$ , $\phi/\gamma=0.4$ ), ( $\phi=4, \gamma=1.213, \rho=78.74\%$ , $\phi/\gamma=3.3$ ) .....	160
33. Population trajectories for ( $\phi=4, \gamma=1.213, \rho=78.74\%$ ). .....	161
34. Welfare levels (1996-2029) ( $\phi=4, \gamma=1.213, \rho=78.74\%$ ). .....	161
35. Welfare levels (2030-2060) ( $\phi=4, \gamma=1.213, \rho=78.74\%$ ). .....	162
36. Population trajectories for ( $\phi=0.1, \gamma=1.26714, \rho=78.74\%$ ). .....	162
37. Ground water stock trajectory for ( $\phi=0.1, \gamma=1.26714, \rho=78.74\%$ ). .....	163

Figure	Page
38. Welfare levels (1996-2025) for $(\phi=0.1, \gamma=1.26714, \rho=78.74\%)$ .....	163
39. Welfare levels (2026-2060) for $(\phi=0.1, \gamma=1.26714, \rho=78.74\%)$ .....	164
40. Population trajectories for status quo wages I.....	164
41. Population trajectories for status quo wages II.....	165
42. Water demand, importing, and extraction (Brazil) for vector $(\phi=1.5, \lambda=1.3)$ .....	165
43. Water demand, importing, and extraction (status quo) for vector $(\phi=1.5, \lambda=1.3)$ .....	166
44. Water demand, importing, and extraction Case 2 and Case 1 (wages determined by Brazil) .....	166
45. Water demand, importing, and extraction Case 2 and Case 1 (wages determined by status quo) .....	167
46. Water demand, importing, and extraction (Brazil) for vector $(\phi=3, \lambda=1.3)$ .....	167
47. Water demand, importing, and extraction (status quo) for vector $(\phi=3, \lambda=1.3)$ .....	168
48. Welfare trajectories for Case 2 and Case 1 (wages determined by Brazil).....	168
49. Welfare trajectories for Case 2 and Case 1 (wages determined by status quo) .....	169

Figure	Page
50. Population trajectories Case 2 and Case 1 (Brazil) .....	169
51. Population trajectories Case 2 and Case 1 (status quo).....	170
52. Water demand, importing, and extraction Case 2 and Case 3 (wages determined by Brazil) .....	170
53. Water demand, importing, and extraction Case 2 and Case 3 (wages determined by status quo) .....	171
54. Water demand, importing, and extraction Case 3 and Case 1 (wages determined by Brazil) .....	171
55. Water demand, importing, and extraction Case 3 and Case 1 (wages determined by status quo) .....	172
56. Water demand, importing, and extraction (Brazil) for vector ( $\phi=1.5, \lambda=1.1$ ) .....	172
57. Water demand, importing, and extraction (status quo) for vector ( $\phi=1.5, \lambda=1.1$ ) .....	173
58. Water demand, importing, and extraction (Brazil) for vector ( $\phi=3, \lambda=1.1$ ) .....	173
59. Water demand, importing, and extraction (status quo) for vector ( $\phi=3, \lambda=1.1$ ) .....	174
60. Water demand, importing, and extraction (status quo) for Case 4 vs. the other cases.....	174

Figure	Page
61. Population trajectories for Case 3 and Case 4 (Brazil) .....	178
62. Population trajectories for Case 3 and Case 4 (status quo) .....	179
63. Welfare trajectories Case 3 and Case 4 (Brazil) .....	179
64. Welfare trajectories Case 3 and Case 4 (status quo).....	180

## CHAPTER 1

### INTRODUCTION

“Despite the incalculable importance of transboundary resources in the border area between Mexico and the United States, as well as the vast complexity of the matter, one may safely assert that the issue has not yet become central in the political agenda of the bilateral between the two countries. Rather, as point out above, joint or individual action has been taken, in a non-integrated fashion, tackling specific problems for utilization and conservation of isolated resources as they have arisen. There is no doubt that there is a definite lack of a planned bilateral policy to rise to the challenge that all such resources present to the two countries. [...] In attempting to satisfy it, policy makers should carefully take into account the fact that the great social, economic, cultural, political and legal diversity between Mexico and the United States will inevitable have, as it has had often in the past, an enormous impact on the way the two countries will together approach the question of how to better utilize and conserve their transboundary resources.” (Székely (1986), p.672).

Water is indispensable for life and central to poverty relief, sustainable growth, and socio-economic development (UNESCO, 2006; World Bank, 2009). According to the United Nations (UNESCO, 2006), clean water, wastewater removal, and sanitation are three of the most basic foundations for human progress.

However, water scarcity is an increasing problem, and not just in developing countries. Water resources are subject to increasing stress because of the interacting effects of population growth, economic development, climate variability, climate change, and ecosystem protection. On top of that, water pollution adds to the water scarcity problem (UNESCO (2006), OECD (2009)).

In developing countries there are more than 1.1 billion people who still lack access to safe water and 2.6 billion do not have access to basic sanitation (World Bank (2004, 2009) UNESCO (2006)). Whereas, in the OECD countries the challenge is to satisfy different water quality standards and environmental regulations which will require

rehabilitate existing infrastructure and invest in new one; in particular, in the wastewater collection and treatment sector (OECD, 2009). It is argued that poor water management is responsible for these problems rather than physical availability (Biswas (1999), UNESCO (2006), World Bank (2009)).

Efficient water management should provide water to the uses that society values the most in a sustainable manner. Properly designed water management, for example, can potentially protect the ecological systems that depend on water resources, increase (or sustain) the actual water supply in terms of quality and quantity, internalize external effects, and take into account social and cultural issues (OECD (2009, 2006a, 2003), UNESCO (2006)).

Efficient water pricing is an essential part of efficient water for three reasons (OECD (2003, 2006a, 2009)):

- (1) It covers the cost for renewing and developing infrastructure as well as operation and maintenance (e.g., electricity for pumping, labor, water treatment and repair costs).
- (2) It internalizes the associated external effects (either positives or negatives) of water allocation, such as those associated with public health, ecosystems, and eco-services.
- (3) It incorporates the opportunity cost of water in terms of its impact on present and future users.

However, the OECD recognizes that even its member countries have not implemented efficient prices due to affordability issues, political opposition, lack of

information about consumer preferences or external effects, poorly defined property rights, deficient enforceability of property rights, and monopoly practices (Dinar (2000), UNESCO (2006), OECD (2009)).

Therefore, water management typically relies on other mechanisms, besides water tariffs, to allocate water resources. These include stakeholder participation, decentralization, transparent participatory processes, and government intervention (World Bank (2004), UNESCO (2006), OECD (2006a, 2009)).

The role of government is essential for water management because it can help reduce market failures by establishing institutional and regulatory frameworks for infrastructure services; ensuring that low income users have a minimum level of access; setting up enforceable property rights; and regulating the market power of public or private services providers (OECD (2003, 2006a, 2009)).

When two or more countries share a single basin it is even more difficult to implement an efficient water management because there are conflicting competences over the use of water resources (UNESCO (2006)). There are more than 200 river basins currently shared by two or more countries (Just and Netanyahu (1998), UNESCO (2006)) accounting for approximately 60 percent of the global freshwater flow (Dombrowsky, (2007))<sup>1</sup>. This situation makes the resolution of transborder issues a central feature of efficient water management.

The Mexico-United States border exemplifies the difficulties of implementing an efficient water management. These difficulties are particularly marked in the cities along

---

<sup>1</sup> 175 river basins are shared by only two countries (Dinar (2006)).



this border, known as the *sister cities*. In this arid region, water resources are becoming scarcer as a result of, among other things, the growth of population, urbanization and the obsolete institutional framework—i.e., state, national, and international laws. In fact the literature has illustrated extensively how the actual institutional framework has become obsolete—being unable to efficiently meet—future water demand (see Nitze (2003), Mumme and Aguilar (2003), Stromberg (2005)).

One important case is that of the sister cities of El Paso, Texas, and Ciudad Juarez, Chihuahua. In particular, Ciudad Juarez has experienced high population growth rates in the last few decades caused, among other things, by industrialization. Foreign investment has been the driving force behind industrialization; fuelled by the desire to take advantage of the low wages and government incentives in the region. There is no doubt that this industrialization process has contributed positively to Ciudad Juarez in terms of job creation and wages in the region (Stromberg (2005)). However, there are costs associated with both industrialization and population growth. Industrial and municipal waste, air borne pollution, congestion of public services, and misuse of natural resources have all increased (Sanchez (1995, 2002), Ganster *et al.* (2003a), Stromberg (2005), Pena *et al.* (2005), Erickson (2005)). The quality and quantity of fresh groundwater has also been reduced (Sheng *et al.* (2001), Turner *et al.* (2003)). This is especially serious because both cities rely on shared groundwater to cover an important part of their water demand and the use of other water sources is very expensive, especially for Ciudad Juarez (PNWTF (2001), Turner *et al.* (2003)). So, Ciudad Juarez is facing a dilemma. On the one hand, it requires cheap water to maintain its social and

economic development. On the other, water is becoming scarcer (i.e. more costly) not only because there are more users but also because there is less good quality water.

The objective of this dissertation is to identify water management strategies that bring about the sustainable use of water resources whilst providing highest benefits for Ciudad Juarez, using the tools provided by the economic theory. Given the environmental, economic, and social implications of water issues in Ciudad Juarez and the U.S.-Mexican border, we believe that this dissertation can contribute to promoting a sustainable development in the region.

The literature has shown that (1) if the water resources are managed “as usual” the water resources in the border will be insufficient to satisfy future water demand; and (2) that the United States and Mexico need national and binational institutions as well as organizations to provide water infrastructure, and flexible mechanisms to allocate water fairly and efficiently<sup>2</sup>. However, the literature is a less clear on how economic agents (e.g. workers, entrepreneurships, or farmers) will respond as water becomes scarcer and how this feeds back into the economic and demographic dynamics of the region (see Forster (2003), Erickson (2003), Peach (2003)).

Economic theory provides us with the tools to understand how economic agents interact with the natural resources. Moreover, it provides means for selecting among alternatives to reach some desirable outcome under particular constraints.

---

<sup>2</sup> Investment is needed to rehabilitate existing infrastructure, provide different quality levels, and stringent environmental standards (OECD (2009)).

The models developed here are based on the following premises: First, Ciudad Juarez aims to maximize the discounted social welfare of its inhabitants. Second, El Paso uses a fixed amount of water and there is no communication between Ciudad Juarez and El Paso. Third, Ciudad Juarez has the legal, economic and political resources to manage its water resources. Fourth, there is no uncertainty about the stock and flows of water or about the preferences of economic agents. Fifth, all fresh ground water has the same quality.

There are several caveats to make. First, welfare maximization allows economic goals that go in opposite directions, such as inequality over efficiency. Second, any institutional arrangement in Ciudad Juarez with respect to the water resources will need to consider how El Paso manages its water resources. Third, there are legal and political competences (national and international), that constraint how Ciudad Juarez manages its water resources. Fourth, the resources that Ciudad Juarez can allocate to water management are limited (e.g. investment in water infrastructure). Fifth, it is not clear what the preferences are for the economic agents in the region. Sixth, as the stock of ground water is reduced the water quality decreases resulting in an increase in the cost of ground water. Finally, there is an important source of uncertainty with respect to the water resources in the region (in particular, the role of climate change).

The model presented here assumes that the Ciudad Juarez economy comprises workers and foreign assembly plants (i.e., maquiladoras). Foreign capitalists invest in these assembly plants because the wage paid in Ciudad Juarez is lower than in their domestic countries (i.e., all countries have the same technology and the nominal rate of return on capital). However, the wages paid by foreign plants in Ciudad Juarez are

higher than the average wage in Mexico in real terms. As a result, workers from elsewhere in Mexico migrate to Ciudad Juarez to try to take advantage of these higher wages. Finally, water demand in the economy is a function of the number of workers (assembly plants do not consume water) and demand is completely inelastic.

Since the cost of supplying water is an increasing function of the population, there exists a wage level where the flow of foreign investment and migrants will stop arriving to Ciudad Juarez. That is, the population growth will erode the comparative advantage of Ciudad Juarez and, therefore, economic growth will come to a halt at some point. At that point Ciudad Juarez could, in principle, have zero or positive employment, investment, and groundwater levels.

It is shown that there are efficient water management strategies that lead to sustainable use of water resources and positive levels of economic activity—i.e., employment and capital. Two cases are examined: one that assumes water autarky where the only source of water is the Hueco Bolson aquifer. The other supposes that Ciudad Juarez can use ground water or import water from elsewhere. These models are different from others that deal with ground water allocation because we introduce reclaimed water recharge in the analysis.

The first model deals with a private utility that wants to maximize its benefits by selling ground water. The utility can reduce the cost of providing ground water by recharging reclaimed water into the aquifer. Hence, the problem for the utility is finding a set of prices and an optimal recharge trajectory that maximizes profits. The other model is concerned with the conjunctive use of imported water and local ground water. In this case, the problem for the utility is to maximize its profits by extracting and

importing water. As in the first case, the utility can reduce the extraction costs by recharging reclaimed water. We conclude that the social welfare is maximized and the economy reaches a positive steady state by setting the water tariffs equal to the marginal cost of supplying water. In this fashion, the water tariffs take into account the water scarcity and the cost of supplying water (e.g. infrastructure and operational costs). The Ciudad Juarez municipality must guarantee that the utility charges efficient prices.

These models were calibrated and then used to run experiments with respect to different vector parameters to examine the behavior of population, ground water, artificial recharge, water imports and welfare. It turns out in these experiments that welfare relies on the relative cost and importing or recharging cost.

The dissertation is divided in six chapters. Following the introduction, a second chapter presents a short introduction to the main issues between the United States and Mexico regarding their shared water resources. In particular, this chapter first illustrates how water resources have become scarcer in the region because of population growth, pollution, and industrialization in the Mexican border cities. We use the cases of El Paso del Norte and Ambos Nogales to illustrate the situation of the water resources along the border. In addition, it examines the different agreements and binational institutions that United States and Mexico have created to regulate the water resources between both countries and to increase the water resources in the region by improving and creating new infrastructure. This chapter concludes by indicating how current binational institutions may be unable to efficiently meet future water demand.

The third chapter presents the situation in Ciudad Juarez regarding population, industrialization, and water resources. This chapter first describes the history of border industrialization in terms of assembly plants and jobs created in Ciudad Juarez. It also describes the historical population record of Ciudad Juarez over the last 50 years. It then presents a brief description of the water resources of Ciudad Juarez, and especially of the Hueco Bolson aquifer.

The fourth chapter examines the role of water scarcity and water management on the economic sustainability of Ciudad Juarez. The first section of this chapter analyzes the conditions under which the economy of Ciudad Juarez reaches a stable steady state with positive levels of capital and population. The subsequent sections this chapter illustrates those conditions which allow the economy to maximize welfare whilst assuring that employment, capital, and groundwater converge to positive steady state levels. We examine two cases: one at which Ciudad Juarez relies only on ground water; and other where Ciudad Juarez can use ground water or import water from elsewhere. We conclude that Ciudad Juarez can achieve maximize the welfare and a positive steady state level by implementing efficient tariffs that reflect the costs of supplying water.

The fifth chapter analyzes how the models presented in this dissertation work when Ciudad Juarez faces a range of different costs, water demand levels, planning horizons, and recharge capabilities. Contrary to Chapter 4, population growth rates are assumed to be constant. This results in non-convexities that invalidate some of the conclusions of Chapter 4. The first part of this chapter analyzes the first model (the autarkic model). It is shown that the relative extraction cost of groundwater recharge determines the amount of water optimally recycled and recharged by the utility. However, there are

other parameters that affect the amount of water recharged, such as the recharge capability and planning horizon. We finalize the analysis of the first model by examining the link between the planning horizon, costs, and social welfare. It is shown that under some conditions if the extraction cost at the initial period is low, the social welfare will rise at a decreasing rate as the planning horizon increases. The next part of this chapter analyzes the second model. In particular, it analyzes how relative costs affect the amount of water imported, welfare, and population levels. It is found that as the cost of importing water increases the welfare and population growth decreases.

The last chapter presents the conclusions of this dissertation and describes future research directions on ground water management on Ciudad Juarez.

## CHAPTER 2

### THE UNITED STATES-MEXICAN BORDER

#### INTRODUCTION

The U.S.-Mexican border is interconnected in many ways: socially, economically, geographically, and environmentally (Clement (2002), Ganster (2003), Van Schoik *et al.* (2003), Hecht *et al.* (2003)). Hence, actions on one side of the border will likely affect, positively or negatively, the other side of the border. Some of these effects are reflected in the price of labor or resources, and so are mediated by the market. Others are not. These effects are said to be “external” to the market. As the U.S.-Mexican border has experienced higher economic trade, industrialization, and population growth, the magnitude of the externalities has become more important. At the same time, border resources have become increasingly scarce (Spalding (2003)). The border environment, following Siebert (1995), “has fallen from the paradise of free goods to the realm of scarcity”.

Both countries have made efforts to cooperate in solving the problems posed by external effects and resource depletion through coordinated efforts. In particular, both countries have worked to solve problems on the following areas: water supply, wastewater removal, and air quality. Their efforts are reflected in laws, agreements, binational agencies, commissions, and shared infrastructure. However, significant problems remain (see Spalding (2003), Mumme and Aguilar (2003), Nitze (2003), Brown (2005), Fernandez (2006), Ganster and Lorey (2008)).



The water sector in this region is a good example. Most water resources in the region are interconnected (this includes both surface and ground water resources). In addition, water demand has been steadily increasing due to population and industrial growth. While there are binational water treaties, national laws, and state laws, these do not promote efficient water allocation—allowing both pollution and wastage across the border (Sanchez (2002), Nitze (2003), Mumme and Aguilar (2003)).

This chapter provides a brief introduction to the main issues between the United State and Mexico regarding to their shared water resources. This chapter is divided in two parts. The first illustrates how the water resources have become more scarce because of population growth, pollution, and industrialization that have taken place in the Mexican border cities. The second examines the different agreements and binational institutions that United States and Mexico have created to regulate the water resources between both countries and to increase the water resources in the region by improving and creating new infrastructure.

The chapter is divided in four sections. Section 1 introduces two of the main drivers of change on the U.S.-Mexican border: population growth and industrialization. The subsequent sections focus on the water sector on the U.S.-Mexican border. Section 2 describes the state of water demand and supply in the region, showing how the region has become increasingly water scarce as a result of population growth, industrialization, institutional design, and social and climatic conditions. We describe briefly the cases of El Paso del Norte and Ambos Nogales to illustrate the water management problems in this region. Section 3 then takes stock of the binational institutions and organizations

designed to regulate, promote, and protect the water resources of the U.S.-Mexican border. The last section presents the conclusions of the chapter.

## SECTION I

### POPULATION GROWTH AND THE MAQUILAS

The steady population growth in the Mexican border cities has been driven mainly by the immigration from Mexico and Latin America to the United States, and by industrialization in the Mexican border cities (Martin (2002), Hecht *et al.* (2003), Peach and Williams (2003), Stromberg (2005), Carrillo and Schatan (2005), Mendoza (2006), Ganster and Lorey (2008)).

Population in the border region grew from 7 million in 1980 (43% in Mexico) to 10.5 million in 1995 (56% in Mexico), and is projected to grow to 24 million by 2020 (56% in Mexico) (Ganster *et al.* (2002), Díaz-Bautista *et al.* (2003)). The annual population growth rate of the Mexican border region was 3.5% from 1990 to 1995, and 3.6% from 1995 to 2000, both rates being higher than the Mexican national average for the same periods (2.3% and 1.8%) (Clement (2003)). The U.S. border region also had one of the highest population growth rates in the U.S. in that period (Mumme and Aguilar (2003)), increasing by 17.3% during the 1990-1998 period compared to only 8.4% for the United States (Clements (2003)).

Population growth and industrialization have resulted in a soaring demand for public services (e.g., housing, roads, hospitals, energy, waste control, sanitation, and water), especially in Mexico (Clements (2003), Peach and Williams (2003), Pena *et al.* (2005)). Given municipal budget constraints, towns and cities have not been able to meet these demands efficiently creating pollution problems, congestion, and misuse of the natural resources in the region (Pena *et al.* (2005), Erickson (2005), Ganster *et al.*

(2003a)). In particular, lack of infrastructure for sewage and solid waste in Mexico has become a source of pollution threatening human health on both sides of the border (Sanchez (1995, 2002), Stromberg (2005), Carrillo and Schatan (2005)).

Sanchez (2002) provides a graphic description of the problem: "Sewage spills occur because the increase of wastewater generated by the expanding population exceeds the capacity of the existing pipes [...] The combination of uncollected raw sewage in slums and low-income neighborhoods spills in other parts of the city, and gaps in the distribution network for potable water go far toward explaining the high incidence of water-borne diseases in Mexican border communities. Untreated sewage also poses a constant threat of contaminating surface and groundwater resources.[...] Municipal solid waste is one of the most visible environmental problems. [...] On average, only 46 percent of this waste is collected. The remainder is left on the streets, dumped on open land or in waterways, or burned in open fires in the urban area, presenting a major public health risk to border inhabitants. Even collected waste is an environmental threat because it is deposited in landfills that lack coverings, linings, and leachate control, and thus threaten the quality of surface and groundwater."(p.59).

The maquila industry has played an important role in the population growth and pollution problem (Díaz-Bautista *et al.* (2003), Hecht *et al.* (2003), Clement (2003), Mendoza (2006)). Starting in the 1960s maquilas were established in Mexico to take advantage of low salaries, geographical proximity to the United States markets, and

international treaties facilitating export of goods to the USA and Canada (Clement (2003), Carillo and Schatan (2005), Stromberg (2005))<sup>3</sup>.

Most of the maquila plants are located in the Mexican northern border and have become one of the most important sources of employment, exports, and investment not only in the border region but in Mexico as a whole (Ganster *et al.* (2003), Díaz-Bautista *et al.* (2003), Mendoza (2006), Dussel (2009)). It is worth noting that in spite of high population growth, the area has experienced better economic performance in terms of employment and wages than the Mexican average (Clement (2004)). For example, according to the Mexican Ministry of Economy manufacturing companies supported by foreign investment pay 48% higher wages than local companies (Dussel (2009)).

However, conditions have changed since the 1990s. It seems that the era of maquilas as the engine of economic growth is coming to an end as other countries compete with Mexico for the foreign investment (De la Garza Toledo (2007), Dussel (2009)). Low wages are no longer sufficient to attract foreign investment (Dussel (2007)).

There is no doubt that the maquila industry has promoted new opportunities at the border. However, it has also imposed important challenges to the border

---

<sup>3</sup> The maquiladora program allows importing duty free equipment, machinery and materials to assemble products and ship them to other countries or Mexico. Most of the plants are owned by foreign nationals, primarily from the United States. Foreign firms benefit from establishing plants in Mexico due to low labor costs, duty free inputs, and transportation costs (as compared to East Asian and Latin America). For Mexico, the advantage lies in the jobs created and the flow of resources in terms of overhead costs and wages (De la Garza Toledo (2007), Dussel (2007)).

communities. It has affected them directly by increasing the industrial waste (Stromberg (2005)). For example, hazardous waste dumpsites and wastewater samples show concentrations of volatile organo-chlorate compounds (VOCs), heavy metals, and other pollutants used by the maquila and domestic industries, that represent a threat to regional water and air quality (Sánchez (1995, 2002), Stromberg (2005)). Moreover, as stated above, the maquilas have affected the cities indirectly by increasing the population growth which has resulted in a soaring demand for public services (Carrillo and Schatan (2005), Pena *et al.* (2005), Erickson (2005)).

The trade-off that the Mexican border cities face is well described by Ganster *et al.* (2003b), “In the effort to create jobs, many communities have not taken into account social or environmental impacts, nor the medium—and long—term implications of their economic development policies...Economic, population, and urban growth have consumed significant amounts of natural resources. Moreover, they have caused the serious pollution of water, soil, and air resources, and threaten or endanger plant and animal species and important ecosystems and habitats. All these trends clearly indicate increasing environmental problems associated with growth and the potential for declining quality of life for border residents.”(p.14).

## SECTION II

### WATER SCARCITY

Mexico and the United States show similar sectoral water demand. Water usage in the U.S. western states between 1960 and 1990 was 86% for agriculture and 10% for domestic and industrial sectors. In the north of Mexico, agriculture consumes 87% while municipal and industrial sectors utilize 13% (Mumme and Aguilar (2003)).

The U.S.-Mexican border has experienced significant growth in water demand, increasing the water scarcity in a region characterized by limited water resources. The main driver of water demand has been the industrial and population growth of the last few decades. In the U.S. border cities aggregate consumption is growing and currently is 41% higher than in the Mexican border cities (Mumme and Aguilar (2003), Peach and Williams (2003)). For example, municipal and industrial water demand is projected to increase by 30% by 2020 at El Paso, Texas (Mumme and Aguilar (2003), Clement, 2003)).

In spite of this, Mexico is the main driver of the water demand in the region (Mumme and Aguilar (2003), Nitze (2003)). There are several factors involved: water demand is growing faster in per capita terms in Mexico than in the U.S. border cities (Mumme and Aguilar (2003), Nitze (2003), Brown (2005)); at the same time population in the region is growing rapidly—indeed, given current population growth projections water consumption would double by 2020 even if per capita water consumption in the Mexican border cities were to remain at 1995 levels (Mumme and Aguilar (2003), Peach and Williams (2003)).

There are several issues that limit the amount and quality of water resources that are associated with geographical characteristics of the region and with social preferences. For example, climatic variability (e.g., prolonged droughts) increases the uncertainty and constraints on water supply (Ganster *et al.* (2002), Mumme and Aguilar (2003), Nitze (2003)). Other important issues include the environmental regulations (e.g., water allocation for ecological functions) that limit water use by agriculture, industry, and urban areas and that control the water quality returned to rivers and water bodies (Mumme and Aguilar (2003), Nitze (2003)). Moreover, as urban areas increase they require services that demand higher quantities of water of different qualities, such as public parks, artificial lakes and rivers, and private gardens (Mumme and Aguilar (2003), Nitze (2003)).

However, the most important issue constraining water supplies in the region are the binational, national, and state institutions, or rather the lack of them (Székely (1986), Ganster *et al.* (2002), Mumme and Aguilar (2003), Nitze (2003)). These institutions have prevented the efficient allocation of existing resources and have limited increases in water supply—e.g., by limiting trade of different water qualities. On top of that, they have compromised stocks by allowing excessive surface and ground water use, and the pollution the fresh and ground water resources (Székely (1986), Ganster *et al.* (2002), Mumme and Aguilar (2003), Nitze (2003)). Ganster *et al.* (2002) described the problem as follows:

“Surface and groundwater supplies are threatened along the U.S.-Mexican border due to the dumping of raw sewage, agricultural runoff, and industrial and hazardous waste pollution. Such contamination reduces the supply



available for human use and often has serious implications for human health, as well as the viability of animals, plants, and ecosystems. All streams and rivers in the border region have suffered deterioration of water quality due to the lack of adequate municipal wastewater collection and treatment systems. The current infrastructure deficit is enormous, and the added demand created by growing populations will be significant. Thus, it is likely that significantly greater levels of financial resources will be required to adequately address water quality issues by 2020.” (p.16).

The cases of El Paso del Norte and Ambos Nogales are illustrative of the water situation everywhere along the U.S.-Mexican border<sup>4</sup>. El Paso del Norte is located between Texas and Chihuahua, and relies on both the Bolson del Hueco aquifer and the El Rio Grande River to supply water to households, industry, agriculture, and ecosystems. The Bolson del Hueco aquifer has supplied most of the water demanded in the region (Cervera (2007), Turner *et al.* (2003)). Ciudad Juarez meets almost all its water demand from this aquifer (municipal and industrial), and El Paso covers 47% of its water demand from the aquifer (Cervera (2007)). Yet the combined rate of water extraction from this aquifer exceeds its sustainable rate of extraction (Chavez (2000), PNWTF (2001), Cervera (2007))<sup>5</sup>.

---

<sup>4</sup> This is only a brief description of these cases.

<sup>5</sup> It is estimated that the Bolsón del Hueco aquifer has an approximated annual recharge of 35 Mm<sup>3</sup> only in the Mexican side, but Ciudad Juárez extracted on average 12 Mm<sup>3</sup> monthly in 2002 (Cervera (2007)).

Given that Ciudad Juarez is growing faster than El Paso, this has resulted in an increased rate of extraction from this aquifer to meet water demand over the years (Chavez (2000), PNWTF (2001)). During the period 1990 and 1994 Mexico increased its municipal and industrial water extraction by 13% while the U.S. decreased its by 24%. Since Mexico extracted 61% of all the water pumped from this aquifer at the start of the period, this shift dramatically altered the relative reliance of the two cities on this source (PNWTF (2001)).

Because it is a common pool resource without effective regulation of access, the Bolson del Hueco has been poorly managed. It has been overdrawn and has increasingly been affected by salinity. Should current rates of extraction continue, the Bolsón del Hueco aquifer will be depleted by 2030 (Chávez (2000), PNWTF (2001), Cervera (2007)). An efficient water management strategy could prevent this from happening, but it would require an agreement between both cities involving water reuse, ground water recharge, pricing, and water transfers. At present, however, both parties have an incentive to free ride on the other's effort. Other challenges for efficient management include knowledge of the real water recharge rate as well as the quality and quantity of water, especially on the Mexican side.

The other example is the Santa Cruz River, which starts from Arizona in San Rafael Valley weaves through Sonora before returning to Arizona through Nogales, Sonora. Within Nogales Arizona the Nogales International Wastewater Treatment Plant (NIWTP) receives water from Ambos Nogales. Downstream of the plant, flow is increased from additional water inputs, such as the one from Los Alisos basin.

It is worth noting that in this geographical region the Santa Cruz River is the most important source of fresh water. Nogales, Sonora, and Nogales, Arizona, (Ambos Nogales) both use the water from the Santa Cruz basin to cover half of their potable water demands (Sprouse (2005)). In addition, the treated water serves multiple uses in Arizona, benefiting riparian habitats as well as providing water to the communities of Rio Rico, Tumacacori, and Tubac (Sprouse (2005)). Moreover, the treated water recharges some aquifers and is an important resource in drought seasons (Levesque and Ingram (2002), Sprouse (2005)). Of the effluent released from the NIWTP into the Santa Cruz River, two-thirds originates from Mexico while the remainder is primarily from Nogales and Rio Rico, Arizona (Levesque and Ingram 2002).

According to the International Boundary and Water Commission (IBWC) Minute 276 (IBWC 1988), Mexico has the legal right to use its portion of the effluent, even if it is treated in Arizona. That is, in the future Nogales, Sonora, could decide to use the effluent for industrial, agricultural, or aquifer-recharge purposes within its own boundaries (Morehouse *et al.* (2000)). So far Mexico does not receive any compensation for this resource (Sprouse (2005)). A reduction in Mexican supplies to the plant would have a serious impact on the water resources in the County of Santa Cruz. However, Mexico is not in a position to recycle its effluent due to budget restrictions (Levesque and Ingram, 2002).

Water pollution primarily originates in Nogales, Sonora, and is one of the principal environmental and public health problems in the region (Sanchez (1995)). The main sources are the shanty-towns and industry (e.g., Maquiladoras), in combination

with poor sewage conditions (Sanchez (1995)). This pollution affects both ground and surface water.

Maquiladoras are a significant source of dangerous toxic waste that pollutes water resources (Sanchez (1995)). Many hazardous wastes are illegally discharged in land or in water resources, producing high levels of heavy metals and other toxic chemicals in rivers and groundwater on both sides of the border (Sanchez (1995), Levesque and Ingram (2002)).

Newcomers to Nogales, Sonora, frequently settle in shanty-towns where the sewer and water distribution system is of poor quality, and where wastewater removal, and waste collection services are minimal or non-existent (Sanchez (1995))<sup>6</sup>. Because the sewer system is old and poorly maintained, pipes are prone to leakages that pollute aquifers and impact water quality (Levesque and Ingram, 2002). In fact, most inhabitants of Nogales, Sonora, have no access to sewage collection or septic tank systems (Sanchez (1995)). Waste is, therefore, disposed directly into the environment (Sanchez (1995)), polluting both aquifers and surface water.

In summary, the County of Santa Cruz is positively affected by the wastewater that comes from Mexico after treatment (a positive externality) because it is used for satisfying safe yield objectives and for providing water to riparian ecosystems. Although the wastewater that goes into the U.S. provides benefits for Arizona residents, it is also an important asset for the sustainability of Nogales, Sonora. At present, however,

---

<sup>6</sup> In 1988 only 64 percent of the population was connected to the drinking water distribution system (Levesque and Ingram, 2002).

Nogales, Sonora, carries part of the cost for cleaning this wastewater but does not receive any direct benefit from it.

## SECTION III

### BINATIONAL INSTITUTIONS

Mexico and the United States have made a great effort to establish institutions and programs to solve water problems between both countries. However, an important obstacle for these binational institutions and programs has been the different nature of the Mexican and United States legislation (Székely (1986), Spalding (2002), Mumme and Aguilar (2003), Nitze (2003), Hall (2004)). One difference is that water legislation in United States is spread across federal, state, and municipal laws and regulations (Székely (1986), Mumme and Aguilar (2003), Nitze (2003)). In contrast, in Mexico water management is predominantly centralized in the federal government, which regulates how water is used, extracted or disposed (Székely (1986), Nitze (2003), Fernandez (2006)). A second difference is that the U.S. western states have a particular way to maintain water rights called the “use it or lose it” doctrine. This rule requires that appropriators use their entire water rights or risk forfeiting them (Székely (1986), Nitze (2003)). A third is that U.S. courts have established limits to water property rights in order to protect the environment, Indian reservation rights, and downstream users (Székely (1986), Nitze (2003)). One example is the U.S. Endangered Species Act that restricts water withdrawals from basins to protect endangered species and ecosystems (Nitze (2003)).

The allocation of freshwater resources between Mexico and United States is regulated under the 1944 Water Treaty. However, this treaty does not address environmental concerns, groundwater extraction and pollution, tribal water demands, water savings, or climate variability (e.g., long term drought). Nor it address water

bilateral allocation mechanisms to meet increasing water demand in the region (Mumme and Aguilar (2003), Nitze (2003)). These issues have become more pressing as border conditions have changed in recent years.

The Water Treaty established the International Boundary and Water Commission (IBWC). This is a bilateral organization established by both governments under the 1944 treaty “to provide solutions to issues that arise during the application of the United States-Mexico treaties” (IBWC (2010)). The IBWC has legal capacity to establish binding bilateral agreements under the 1944 water treaty. However, it only deals with freshwater water issues. When a formal agreement is reached, the IBWC issues a Minute that is implemented by the both governments. These are binding agreements but less formal and rigid than a bilateral treaty (Brown (2005)). Unfortunately, this institution has been limited by its hierarchical structure which tends to favor the national interests of each country (Mumme and Aguilar (2003)).

In addition to the water agreement, in 1983 both countries signed the La Paz Agreement to deal with transboundary environmental pollution (U.S Embassy (2009)). In this document both countries agree to cooperate “in the field of environmental protection in the border area of basis of equality, reciprocity and mutual benefit” (Article 1). For instance, it established a basic framework in a series of annexes for municipal wastewater in the San Diego-Tijuana area, as well as addressing hazardous waste and air pollution issues.

Other institutions that have an important role in the solution and study of water issues between Mexico and United States are: the North American Commission for Environmental Cooperation (CEC), North American Development Bank (NADBank), and

the Border Environment Cooperation Commission (BECC). These are by-products of the NAFTA negotiations. In particular, both the NADBank and BECC have been especially important for binational water management in the border (Carter and Ortolano (2002), Frisvold and Caswell (2002), Mumme and Aguilar (2003), Nitze (2003), Fernandez (2006)).

The objectives of the BECC are to preserve and enhance human health and the environment around the border by assisting public and private entities (e.g., states, cities, public agencies or private investors) in developing project proposals and finding funds from either the NADBank, federal government, state governments, federal agencies (e.g., USEPA) or the private sector (Nitze (2003), BECC (2009)).

The objectives of the NADBank are to finance and assist projects related to environmental issues. The NADBank has financed several projects, mostly drinking and wastewater projects, on both sides of the border (Nitze (2003)). However, it has been criticized for investing relatively little and also for not adequately addressing other environmental issues (e.g., air quality or hazardous waste) (Mumme and Aguilar (2003), Nitze (2003)). NADBank is also criticized for being more reactive than proactive. Nonetheless, sovereign decisions and administrative differences also have limited the action of the NADBank (Mumme and Aguilar (2003), Nitze (2003)). Moreover, according to Fernandez (2004) there is evidence of asymmetry in credit access for environmental projects between Mexico and the United States. Yet, as Carter and Leonard (2002) point out, the BECC and NADBank remain amongst the most significant components of the two governments' cooperative attempt to address the environmental problems of the shared border region. The projects that these institutions support include water



pollution (e.g., potable water treatment, water supply systems, water pollution prevention, projects to improve or restore quality of water resources) and wastewater (e.g., wastewater collection systems, wastewater treatment plants, water reuse systems, systems for treatment and beneficial use of sludge) (BECC (2009)).

The Border 2012 (and Border XXI Program) is a program lead by both the EPA and the Mexican Minister of Environment as bilateral stakeholders to analyze border environmental and health issues, such as water, air, hazardous and solid waste, pollution prevention, contingency planning and emergency response, and cooperative enforcement (EPA (2009), Border (2012)). This program has been an essential mechanism to coordinate the responses of both countries to environmental and health problems. However, the effectiveness of the program has been limited by the different interests of stakeholders and by differing legislation (national and binational) (Mumme and Aguilar (2003), Nitze (2003)).

As stated earlier, the binational treaties have not fully addressed environmental concerns, groundwater extraction and pollution, environmental regulations, and the effect of climate variability (Ingram (1999), Mumme (1999), Mumme and Aguilar (2003), Nitze (2003)). Nor have they considered bilateral water allocation mechanisms to meet the increasing water demand in the region (Mumme and Aguilar (2003), Nitze (2003)). However, groundwater use and long term drought can lead to conflict between the two countries. The latter issue brought Mexico and United States into conflict when Mexico failed to meet its treaty obligation to deliver the agreed water supplies from Rio Conchos to the United States from 1987 to 2002. The groundwater issue is a key element in the water supply across the border: there are seventeen groundwater

basins across Mexico and the United States and most of them are overused (Ingram (2000), Mumme and Aguilar (2003), Nitze (2003), Hall (2004)). Some border cities, such as El Paso or Ciudad Juárez, critically depend on this resource to meet their water requirements. As Hall (2004) put it: "(...) the convergence of factors such as population growth along the border the lack of adequate sub-national and national legal institutions to control groundwater pumping, and the absence of international agreements regulating shared aquifer use and protection creates a situation where there is nothing to prevent either nation from "stealing its neighbor's water" or polluting a critical shared water resource" (p.877).

## CONCLUSIONS

Water demand along the U.S.-Mexican border, especially in Mexico, has been steadily increasing mainly due to population and industrial growth. On top of that, water demand has become more diverse in terms of quality to satisfy the different needs of parks and recreation, drinking water, environmental protection, and agriculture (Mumme and Aguilar (2003), Nitze (2003)). Against this, water supply in this arid region is vulnerable to climatic variability (e.g., prolonged droughts) and has been limited both by declining groundwater levels and by surface and ground water pollution.

Existing binational water treaties, national laws, and state laws do not provide mechanisms to promote efficient water allocation and have done little to prevent pollution and misuse across the border. In 2002 all Mexican border communities faced water supply problems (Sanchez (2002), Mumme and Aguilar (2003)). If this trend continues water resources in the border will be insufficient to satisfy the water demand. Thereby, United States and Mexico need national and binational institutions and organizations to provide water infrastructure and flexible mechanisms that assign water fairly and efficiently<sup>7</sup>. This will require further bilateral cooperation.

There are three main obstacles to achieving an efficient solution: the multiplicity of authorities, economic differences between Mexico and the United States, and how the bilateral-stakeholders will share the costs and benefits of any agreement (Székely (1986), Sánchez (2002), Spalding (2002), Mumme and Aguilar (2003), Nitze (2003), Brown (2005)). In the words of Mumme and Aguilar (2003), "Policy is still fundamentally

---

<sup>7</sup> Investment is needed to rehabilitate existing infrastructure, provide different quality levels, and stringent environmental standards (OECD, 2009).

national, driven by sovereign concerns, and coordinated binationally at the federal level. Water priorities are set in an ad hoc manner and water disputes resolved in similar fashion. [...] (p.63) Planning horizons also vary, though most, including Border XXI, fall well short of the longer-term strategic aims necessary for truly sustainable development. Most investment decisions, whether taken in the context of Border XXI, BECC, NADBank, IBWC, or some combination thereof, are still reactive and politically driven rather than proactive or precautionary and based on a long-term calculus of sustainability” (p.80).

## CHAPTER 3

### CIUDAD JUAREZ

#### INTRODUCTION

Ciudad Juarez is located in an arid area along the U.S.-Mexican border in the Mexican state of Chihuahua. Ciudad Juarez interacts closely with El Paso, Texas, in economic, social and environmental terms. These cities lie in the geographical region called “El Paso del Norte”. Figure 1, illustrates this geographical area.

Ciudad Juarez and El Paso rely both on ground water and on the Rio Grande River to supply water to households, industry, agriculture, and ecosystems. The Bolson del Hueco aquifer (Figure 2), an alluvial-aquifer system, is a transboundary aquifer that has historically met most of the water demand in the region (Heywood and Yager (2003)). In particular, Ciudad Juarez covered all municipal and industrial water demand from this aquifer until six months ago, and El Paso uses ground water from this aquifer to meet approximately 30% of its water demand at the present time (EPWU (2010)).

In the last five decades the Municipio of Ciudad Juarez has been transformed demographically because of in-migration and industrialization (Ganster *et al.* (2003a), Erickson (2005))<sup>8</sup>. This has led to population growth and, therefore, a *radical* transformation of the city (Stromberg (2005), Pena et al., 2005). As a result, the demand for public services (e.g., parks, schools, hospitals, and roads), housing, energy, and water has soared. Besides, the industrial and municipal waste has also risen very rapidly

---

<sup>8</sup> We will denote Municipio Ciudad Juarez as Ciudad Juarez.

(Erickson (2005), Carillo and Schatan (2005)). However, Ciudad Juarez has not been able to cover these demands efficiently creating pollution problems, congestion, and misuse of the natural resources in the region (Ganster *et al.* (2003a), Carillo and Schatan (2005), Pena et al. (2005), Erickson (2005)).

This has created unintended external effects in both cities (Turner *et al.* (2003), Erickson (2005)). This is especially serious in the case of water. For instance, as a result of population growth, misuse and pollution of water resources, and industrial and municipal waste the amount and quality of fresh ground water have been decreasing (Sheng *et al.* (2001), Turner *et al.* (2003)). Ciudad Juarez has been more affected because it has not been able to diversify its water supply to meet the water demand as El Paso has done by using water from the Rio Grande River, importing water, increasing the use reclaimed water, and desalinating water (PNWTF (2001), Turner *et al.* (2003)).

The objective of this chapter is to present the evolution of population and maquila industry of Ciudad Juarez. In addition, it illustrates the state of the water resources available of Ciudad Juarez. However, it does not examine other adverse effects of population and industrial growth in Ciudad Juarez such as waste control, air borne pollution, and congestion of public services.

The chapter is divided in three sections. The first describes trends in population, maquiladora plants, and employment in the last few decades. The second section illustrates the main water resources and users in the area. In particular, this section examines the characteristics of the Hueco Bolson aquifer. The last section summarizes and discusses the main findings of this chapter.

## SECTION I

### POPULATION AND MAQUILADORAS

One of the distinct features of the Mexican border cities has been the population growth experienced in the last few decades. Ciudad Juarez, from 1950 to 2005, grew from 131,308 to 1,313,338 inhabitants—an increase of 900%. From 1950 to 2000, the population average annual growth rate was 4.6%. However, more recently it seems that the growth rate has been decreasing. For instance, from 2000 to 2005 the average growth rate was 1.5% (INEGI (2010)). In Table 1 we present this information. Internal migration is largely responsible for the high rate of population growth in Ciudad Juarez (Peach, 2005; Ericson (2005)). In 2000, 32% of the population in Ciudad Juarez was born elsewhere in Mexico (INEGI, 2010). However, the rate of natural population growth is also increasing in Ciudad Juarez because population is relative young—the median age was 23 years in 2000, *ceteris paribus* (Peach and Williams (2003), Peach (2005)).

The total population of El Paso County was 200,000 in 1950 and 751,296 in 2009—an average annual rate of increase of 2.75% (U.S. Census Bureau (2010)). The total population in El Paso del Norte region totaled at least two million inhabitants at the end of 2009.

The maquiladora industry has played an important role in Mexican border cities by creating jobs (Ganster *et al.* (2003a), Pena *et al.* (2005), Erickson (2005)). In 2000, approximately half of the maquiladora plants in Mexico were located at the border. In particular, Tijuana and Ciudad Juarez shared about one third of the plants (Pena *et al.*

(2005)). In that year, 46% of people employed in Ciudad Juarez were working in the maquiladora industry (INEGI (2010)).

Given the expansion of the maquiladora industry and trade with U.S. the rate of unemployment has been low in Ciudad Juarez by Mexican standards (Clement *et al.* (2003), Erickson (2005)). Figures 3 and 4 compare the averages among Mexico, Mexico City and Ciudad Juarez. From these figures we observe that the rate of unemployment in Ciudad Juarez is extremely sensitive to the level of employment in the maquiladora industry (e.g. in 2002-2003, when employment in the maquiladora industry declined, the rate of unemployment in Ciudad Juarez increased).

Figure 5 depicts the number of plants from 1970 to 2006. We observe a fast increase in the early years—the maquiladora program started in 1965 when the first plant was established in Ciudad Juarez. Then, since the 80s, the number of plants has fluctuated between 250 and 300. Figure 6 describes the number of jobs created by the maquiladora industry in the same period. As in the previous figure, in the early years the number of jobs created *soared*. After this, the number of jobs in the maquiladora industry continued to increase, at a slower rate, until the turn of the century. The peak was in 2000 when almost a quarter of a million people were employed in the industry. At the end of that year, the maquiladora industry experienced a decline—due to the U.S. recession in that year—causing a decrease in the number of plants and jobs. Between then and the recent recession, employment in the maquiladora industry remained constant.

Migratory flows, population growth and maquiladora plants are closely related (Turner *et al.* (2003), Peach and Williams (2003), Ganster *et al.* (2003a), Peach (2005), Carillo and



Schatan (2005))<sup>9</sup>. We know that maquiladora industry is responsible for most of these jobs not only directly but indirectly (see Table 3). That is, migrants are able to stay in Ciudad Juarez because there are jobs for them.

In migration is depends both on the rate of unemployment and the level of real wages in the industry relative to real wages elsewhere. According to Ganster *et al.* (2003b) point out that the per capita income and employment of the Mexican border region is improving relative to the rest of Mexico. Table 2 reports the average nominal wage in the maquiladora industry and the average Mexican minimal official wage for the period 1993-2006. The maquiladora wage was higher for every year. At the same time, the rate of unemployment in Ciudad Juarez was lower on average than elsewhere in Mexico and the wages in Ciudad Juarez were higher than the average Mexican minimal official wage. Moreover, as stated above, 46% of people employed in Ciudad Juarez were working in the maquiladora industry in 2000.

---

<sup>9</sup> For example, Ganster *et al.* (2003) state: "Domestic migration has likewise been a key contributor to the high growth rates in Mexican border cities. Mexicans move to the northern border due to the increased economic opportunities in the border compared to elsewhere in Mexico. Many also consider the possibility of crossing the border and working in the United States."(p.8).

## SECTION II

### WATER SECTOR

The water sources of El Paso del Norte include the Rio Grande River, the Mesilla Bolson aquifer, the Hueco-Tularosa Bolson aquifer, and the Rio Grande aquifer (see Figure 1), which are all interconnected hydrologically (Hibbs *et al.* (1997), Heywood and Yager (2003)). The Mesilla Bolson aquifer is comprised by the Jornada del Muerto and Mesilla Bolson aquifers. The Hueco-Tularosa aquifer is comprised by the Hueco Bolson aquifer, the Tularosa aquifer, and Southeastern Hueco aquifer (Hibbs *et al.* (1997)). These aquifers are connected by interbasin ground water flows (Hibbs *et al.* (1997); Sheng *et al.* (2001), Heywood and Yager (2003)).

Before the maquiladora program started in the late 1960s, Ciudad Juarez was predominately an agrarian society. Nowadays agriculture still plays an important role in water demand Ciudad Juarez, but it has little weight in the economy. Table 3 reports the gross production, aggregated value and employment of the main economic sectors in Ciudad Juarez in 1998. The relative importance of these sectors has remained stable in the period since then.

The surface water used in Ciudad Juarez is supplied from the Elephant Butte Reservoir in New Mexico which is allocated entirely to irrigation (Irrigation District 009-Valle de Juarez). By a treaty signed in 1906 by the United States and Mexico, the amount of water allocated to Mexico is 74.1 million m<sup>3</sup> (60 000 acre-ft) per year. The Mexican irrigation district, in addition, uses fresh water from the Rio Grande River, ground water from the Hueco Bolson aquifer, and waste water from Ciudad Juarez. In 1999,

agriculture used 197.4 Mm<sup>3</sup> (160324.9 acre-feet) of which approximately 38% was wastewater and 24% was pumped ground water (Turner *et al.* (2003)).

Municipal water demand has historically been met entirely by the Hueco Bolson aquifer. This year, 2010, Ciudad Juarez started to use ground water from the Mesilla Bolson aquifer. In 1999, municipal water supply was distributed among the following sectors and proportions: residential (78.2%), commercial (9.11%), municipal (4.3%), and industrial (8.38%) (Pena *et al.*, 2005)<sup>10</sup>. Demand has increased at a decreasing rate stable since that time. For instance, it was approximately 120 Mm<sup>3</sup> (97,461.9 acre-feet) in 1990, 145 Mm<sup>3</sup> (117,766.5 acre-feet) in 1998, 150 Mm<sup>3</sup> (121,827.4 acre-feet) in 1999, 153 Mm<sup>3</sup> (124,263.9 acre-feet) in 2000, 154,362,733 m<sup>3</sup> (125,370.7 acre-feet) in 2003, and 147.3 Mm<sup>3</sup> (119,634.5 acre-feet) in 2005 (PNWTF (2001), Sheng and Devere (2005), JMAS (2005), Cervera, (2007))<sup>11</sup>. Per capita daily consumption in Ciudad Juarez in 1999 was 322 liters or 85 gallons (Pena *et al.*, 2005). Ciudad Juarez is now working to reduce per capita consumption through prices and conservation programs (JMAS (2010)). In tables 4 and 5 we present the water use in Ciudad Juarez by sector in 1999 and the projected water use, respectively.

Across the El Paso del Norte region, water consumption was as follows in 2000: 156 Mm<sup>3</sup> (126,420 acre-feet) El Paso, Texas; 25 Mm<sup>3</sup> (20,680 acre-feet) Las Cruces, New Mexico; and, 153 Mm<sup>3</sup> (124,000 acre-feet) in Ciudad Juarez, Chihuahua. The total water

---

<sup>10</sup> According to Cervera (2007) municipal water supply was distributed among the following sectors and proportions: residential (81.7%), commercial (7.7%), and industrial (3.56%), and municipal (3.56%).

<sup>11</sup> The reduction in the water extracted in 2005 with respect to previous years is due to a per capita decrease in the water consumed (Cervera (2007)).

use for irrigation was in the same year 325 Mm<sup>3</sup> (264,127 acre-feet) in El Paso County Water Improvement District Number One (EPCWID), 647 Mm<sup>3</sup> (525,435 acre-feet) in the Elephant Butte Irrigation District (EBID), and 214 Mm<sup>3</sup> (173,500 acre-feet) in Ciudad Juarez. Other important users include the U.S. military in Fort Bliss, that used 6 Mm<sup>3</sup> (4882.5 acre-feet) in 2000, and residential users not served by the major utilities, that consumed 22 Mm<sup>3</sup> (18,000 acre-feet) in El Paso County in 1997 and 27 Mm<sup>3</sup> (22,000 acre-feet) in Doña Ana County in 1995 (PNWTF (2001)). We present a table summarizing this information (Table 7).

All of these users compete with each other for the water resources in the area and it is projected that this competition will become more intense as demand for water increases. In the case of the ground water, resource competition creates reciprocal externalities and, consequently, strategic behavior that increases the depletion of ground water (see Provencher and Burt (1993)).

#### HUECO BOLSON AQUIFER

The Hueco Bolson aquifer is an unconfined and a semi-confined aquifer with a width of 40 km (25 miles) bounded in the west side by the Franklin, Organ, San Andres, and Sierra de Juarez Mountain ranges, and in the east side by the Quitman, Malone, Finlay, Hueco, and Sacramento Mountain ranges (Hibbs *et al.*, 1997). It has a length of 322 km (200 miles) starting in the southwest corner of the County of Otero, New Mexico, and ending in the southwest corner of the County of Hudspeth, Texas, along the U.S.-Mexico border, passing beneath the City of El Paso, Texas, and the north corner of Ciudad Juarez, Chihuahua (Hibbs *et al.* (1997) Sheng and Devere (2005)). Figure 7 depicts the Hueco Bolson aquifer.

Historically, withdrawals from the Hueco Bolson aquifer have been at a rate higher than the natural and artificial aquifer recharge (Sheng and Devere (2005)). As a result, water table declines have occurred in the municipal well fields in both countries (Heywood and Yager (2003)). The decline tends to be more pronounced in the urban areas of Ciudad Juarez and the city of El Paso.

Sheng *et al.* (2001b) indicate, "Little drawdown has been recorded in the northern part of the aquifer. The drawdown in Hueco Bolson along the Texas-New Mexico border has been relatively small, not exceeding 30 ft (Hibbs and others, 1997). In heavily developed parts of the Hueco Bolson aquifer, drawdowns since predevelopment in 1903 are up to 170 ft. The focal point of drawdown is beneath the City of El Paso and Ciudad Juarez (Hibbs and others, 1997)"(p.69).

Texas, New Mexico and Mexico pump water from this aquifer. For instance, in 1999 Texas, New Mexico, and Mexico pumped approximately 236 Mm<sup>3</sup> (191,508 acre-feet) (Fahy and Sheng (2000)) and 312 Mm<sup>3</sup> (253.121 acre-feet) in 2001 (Sheng and Devere (2005)). However, Ciudad Juarez and El Paso are the most important water users. In 2001, for example, Ciudad Juarez and El Paso extracted 60% and 20% respectively (PNWTF (2001))<sup>12</sup>.

Figure 8 illustrates the water extraction quantities of Ciudad Juarez and the City of El Paso. We observe that El Paso has decreased pumpage over the last two decades passing from approximately 97 Mm<sup>3</sup> (79,000 acre-feet) in 1989 to 49 Mm<sup>3</sup> (40,000 acre-

---

<sup>12</sup> The rate of extraction depends on the climatic conditions. For example, in 2002 the average monthly extraction was 12.82 Mm<sup>3</sup> in Ciudad Juarez. Ciudad Juarez extracted 10.786 Mm<sup>3</sup> in February and 14.51 Mm<sup>3</sup> in September (Cervera (2007)).

feet) in 2002 (Hutchison (2004)). This reduction is due to reuse of reclaimed water, diminishing per capita water usage, increasing the use of surface water, and low population growth (EPWU (2010); Hutchison, 2004; US Census Bureau, 2010)<sup>13</sup>. Furthermore, El Paso is using other measures that extend the life of the Hueco Bolson aquifer: (1) desalination of brackish water and (2) recharging treated wastewater with tertiary treatment by recharge (Hibbs *et al.* (1997), Sheng *et al.* (2001), Turner *et al.* (2002), EPWU (2010)). The latter could also prevent brackish water intrusion (Sheng (2005)).

Ciudad Juarez has increased the ground water pumping over the last three decades to meet the increasing water demand becoming the largest user of the Hueco Bolson aquifer. It is expected that this rate of pumping will continue to increase as population grows since it is more cost-effective to pump from the Hueco Bolson aquifer than other options (e.g. using freshwater from the Rio Grande River or pumping from the Mesilla Bolson aquifer (Turner *et al.* (2003)).

However, Ciudad Juarez is working to reduce its per capita consumption rate through conservation programs and reuse of reclaimed water (Ciudad Juarez has two plants with primary treatment and is planning other plants (Cervera (2007)). Moreover, it is expected to use fresh water from the Rio Grande River and import water to reduce the ground water extraction from Hueco Bolson aquifer (JMAS (2001)). In theory, Ciudad Juarez plans to meet approximately half its water demand from Hueco Bolson ground

---

<sup>13</sup> According to the U.S. Census Bureau the population was 679 622 in 2002 and 751 296 in 2009. This is approximately 1.26% the rate of growth. (<http://quickfacts.census.gov/qfd/states/48/48141.html>)

water by 2020 (JMAS (2001)) which translates into approximately 150 Mm<sup>3</sup> (121,827.4 acre-feet) per year.

The reduction in pumpage by the El Paso has not compensated the increase in ground water withdrawals by Ciudad Juarez (Sheng *et al.* (2001), Sheng and Devere (2005)). Forster and Hamlyn (2005) point out: "EPWU [El Paso Water Utilities] finds that ground water pumping in excess of 50,000 acre-feet (61.7 million m<sup>3</sup>) per year causes serious ground water mining and consequent water level declines. By drawing increasing amounts of water from the Rio Grande, combined with withdrawals from the Mesilla Bolson, the need for ground water pumping from the Hueco Bolson has been reduced and water levels have risen. Heywood and Yager (2003), however, estimate that about 11,000 acre-feet (13.6 million m<sup>3</sup>) was removed from storage in 2002 while pumping 31,151 acre-feet (38.4 million m<sup>3</sup>) from the aquifer. Pumping rates in Ciudad Juarez have not declined as they have in El Paso because the Hueco Bolson is the sole source of water for Ciudad Juarez. Pumping in Ciudad Juarez currently exceeds the 124,000 acre-feet (153 million m<sup>3</sup>) pumped in 2000. Thus, current pumping rates greatly exceed the estimated recharge rate of 40,000 acre-feet (49.3 million m<sup>3</sup>) to Ciudad Juarez sub-component and continue to cause water level declines and fresh ground water depletion in the Hueco Bolson." (p.316). In fact, reduction in pumpage by El Paso could provide an incentive for Mexico to keep pumping and not investing in other mechanisms, such as water reuse or diminishing per capita usage.

Fresh ground water storage in the Bolson Hueco aquifer was estimated to be 13,000 Mm<sup>3</sup> (10.6 million acre-feet) in 1974 (Muller and Price (1979)). Fresh ground water is defined by water with total dissolved solids (TDS) less than 1,000 milligrams per

liter (Turner *et al.* (2003))<sup>14</sup>. Figure 9 depicts a cross section of the form and water quality of the Hueco Bolson aquifer. In this figure we observe that fresh ground water (Zone 1) is above the brackish ground water. According to Hutchison (2004), storage depletion of total fresh ground water between 1974 and 2002 was about 1,477 Mm<sup>3</sup> (1.2 million acre-feet), leaving an estimated 11,570 Mm<sup>3</sup> (9.4 million acre-feet) in storage. Sheng *et al.* (2001b) state that the volume of recoverable fresh ground water is about 9,250 Mm<sup>3</sup> (7.5 million acre-feet), with 3,700 Mm<sup>3</sup> (3 million acre-feet) in Texas, 4,800 Mm<sup>3</sup> (3.9 million acre-ft) in New Mexico, and 738 Mm<sup>3</sup> (600,000 acre-feet) in Mexico.

As a result of the historic water level decline, the fresh ground water quality has been affected. In particular, in the urban areas of El Paso and Ciudad Juarez the water quality decline is noticeable (Sheng *et al.* (2001), Sheng and Devere (2005)). This is a long-standing problem. Two decades ago, Ashworth (1990) indicated that: "Increased dissolved-solids concentrations in fresh-water zones of both the Hueco Bolson are attributed mainly to downward leakage of brackish water from shallow zones and possibly upconing of brackish water from below. Analyses of water samples from wells completed in the Hueco Bolson show an average annual increase in dissolved solids of about 10 milligrams per liter since the 1950's and 1960's in the United States and about 30 milligrams per liter since the 1970's in Ciudad Juarez. In parts of downtown El Paso and Ciudad Juarez, the dissolved-solids concentration in ground water has increased at rates of 40 to 100 milligrams per liter per year during these periods." (p.7). Thirteen

---

<sup>14</sup>The TDS include calcium, chlorides, nitrates, phosphorus, iron, and sulfur. The U.S. drinking water standards for TDS is 500 milligrams per liter (Forster and Hamlyn, 2005).



years later it was noted by Turner *et al.* (2003) that both Ciudad Juarez and El Paso have taken out approximately 25 wells because saline concentration of the ground water in these wells. That is, as the fresh ground water levels decrease the ground water quality tend to decrease, which translates in higher costs. As a result, it is not possible to recover all fresh ground water. For example, according to Muller and Price (1979), only 75% of storage is available for pumping because of the proximity of *highly* saline ground water.

However, slightly saline water could be used in the near future when the cost of desalination decreases. There is approximately 24,600 Mm<sup>3</sup> (20 million acre-feet) of slightly saline water in the Hueco Bolson aquifer in Texas and similar volumes of slightly saline water exist in New Mexico and Mexico (Sheng *et al.* (2001b)). El Paso is already desalinating ground water to tackle the brackish ground water pollution in cooperation with Fort Bliss (EPWU (2010))<sup>15</sup>.

The aquifer is recharged from different sources. It is recharged by precipitation falling on mountain drainage areas at a rate of approximately 7 Mm<sup>3</sup> (6,000 acre-feet) per year (Meyer (1976)). There is discharge from the Rio Grande River, approximately 41 Mm<sup>3</sup> (33,278 acre-feet) per year from 1968 to 1973, and the Tularosa basin, approximately 4.5 Mm<sup>3</sup> (3,700 acre-feet) per year (Hibbs *et al.* (1997)). The Hueco

---

<sup>15</sup> Turner *et al.* (2003) add: "Beneath the fresh water portion of the Paso del Norte region's aquifers are considerable, though poorly documented, quantities of brackish water. The mineral content of the region's brackish ground water varies from 1,200mg/l to 3,000mg/l. Since 1,000mg/l is the legal upper limit for TDS for municipal water in both Texas and throughout Mexico, brackish water cannot be used without desalination. Permeate, the low-TDS water product from desalination, can be blended with high-TDS well water from the same aquifer that was previously unusable because of its high salinity, to achieve a finished TDS concentration of less than 1,000mg/l. Blending these two waters enhances the yield of usable water." ( p.12)

Bolson aquifer is also recharged by canals and agricultural drains—usually with high salinity, and by reclaimed wastewater by El Paso Water Utilities (Sheng and Devere (2005)). In 1993, recharge by recharge averaged  $4.6 \text{ Mm}^3$  (3,800 acre-feet) (Sheng *et al.* (2001b)).

Nevertheless, induced recharge of the Hueco Bolson aquifer depends on the amount of water pumped. That is, the amount of induced recharge will increase as the water extraction rises. This is because ground water moves from points of higher water level to points of lower water level (i.e. toward cones of depression). Therefore, the discharge from the Rio Grande River and aquifer to the Hueco Bolson aquifer is a function of the ground water pumped. However, the amount of recharge has been reduced not only because of the lining of the Rio Grande River in 1973 and the El Paso-Ciudad Juarez area in 1998, but also because of the urbanization (Pena *et al.* (2005), Sheng and Devere (2005)). This complicates assessing the total amount of recharge that the Bolson aquifer receives.

Furthermore, the flow pattern has changed due to the high rates of pumping, increasing the underflow from Texas to Mexico (Ashworth (1990), Sheng and Devere (2005)). That is, the Mexican part of the aquifer is gaining water from the U.S. part of the aquifer. Unfortunately the water quality is mixed (e.g. the underflow involves both fresh and brackish ground water). Moreover, Sheng and Devere (2005) indicate that not only the underflow between Texas and Mexico has increased because the higher Mexican pumpage—before 1960 the underflow was from Mexico to the U.S., now the underflow is up to  $44 \text{ Mm}^3$  per year from the U.S. to Mexico—but also underflow from

New Mexico to Texas has increased—it has grown from 7.4 Mm<sup>3</sup> (6, acre-feet) to 22.2 Mm<sup>3</sup> (18,000) per year.

Foster and Hamlyn (2005) estimate the amount of recharge (outflow and inflow) using information from Heywood and Yager (2003) and Hutchison (2004). The net flow sub-component for El Paso and Ciudad Juarez are equal to 25.3 Mm<sup>3</sup> (20, 500 acre-feet) and 49.3 Mm<sup>3</sup> (40,000 acre-feet), respectively. We present this estimation in Table 6.

## CONCLUSIONS

Ciudad Juarez is facing a dilemma. On the one hand, it requires cheap water to maintain its social and economic development, on the other, water is becoming scarcer (i.e. more costly) not only because there are more users but also because there is less water of good quality. Having flexible allocation mechanisms across users is an important part of the solution (Nitze (2003), Ganster *et al.* (2003), Mumme and Aguilar (2003)). In this direction, Ciudad Juarez is proposing to use water from Rio Grande River for municipal usage and then treat the municipal wastewater to meet the irrigation water demand (Turner *et al.* (2003)). However, Ciudad Juarez has few options to improve this situation because lacks of political and monetary resources (Turner *et al.* (2003)).

Unfortunately, this situation is similar in many other parts of Mexico where the political and monetary resources are insufficient to implement efficient ground water management strategies. Moreover, there are policies in Mexico that encourage that provide perverse incentives (see Kemper (1999), Asad and Dinar (2006), Asad and Garduno (2006)). For instance,

- 1) Mexican farmers that irrigate with ground water have subsidies equivalent to two-thirds of the electricity cost.
- 2) Approximately 26% of farmers extract water without legal authorization and some farmers extract more water than the quota permitted by the regulator.
- 3) There are cases that the extraction quota is greater than the sustainable yield of the aquifer.

Table 1. Population growth Ciudad Juarez (1950-2005)

YEAR	POPULATION
1950	131,308
1960	276,995
1970	424,135
1980	567,365
1990	798,499
1995	1,011,786
2000	1,218,817
2005	1,313,338

Source: INEGI (2010).

Table 2. Nominal wage per day: maquiladoras and minimal official wages (1993-2006).

YEAR	AVERAGE NOMINAL WAGE IN MAQUILADORAS (PESOS)	MINIMAL NOMINAL OFFICIAL WAGE (PESOS)
1993	35.32	13.06
1994	39.81	13.97
1995	48.51	14.95
1996	60.21	20.40
1997	76.43	24.30
1998	90.44	29.95
1999	105.97	31.91
2000	120.62	35.12
2001	141.35	37.57
2002	155.54	39.74
2003	159.34	41.53
2004	169.91	43.29
2005	175.29	45.24
2006	183.89	47.05

Source: INEGI (2010).

Table 3. Employment and gross production in Ciudad Juarez 1998

	Employment (1998)	Gross production (1998) (thousands of Pesos)
TOTAL	375 191	48 390 320
Agriculture, forestry, fishing and hunting	251 (0.07%)	23 421 (0.05%)
Mining	187 (0.05%)	44 309 (0.09%)
Utilities	1 534 (0.41%)	734 514 (1.52%)
Construction	5 732 (1.53%)	2 155 929 (4.46%)
Manufacturing	239 794 (63.91%)	26 331 081 (54.41%)
Whole and retail trade	55 435 (14.78%)	8 354 984 (17.27%)
Transportation	8 923 (2.38%)	2 329 431 (4.81%)
Information	9 933 (2.65%)	941 575 (1.95%)
Accommodation and food services	17 949 (4.78%)	2 454 578 (5.07%)
Other services except government	11 513 (3.07%)	1 054 279 (2.18%)

Source: INEGI (2010).

Table 4. Water use in Ciudad Juarez by user type (1999)

User	Registered accounts	Annual Volume (m <sup>3</sup> /yr)	Annual volume (af/yr)	Average Consumption	Average consumption (gpcd)
Domestic	232,013	87,373,286	70,835	322 avg l/cap/day	85 gpcd (avg)
Low	80,275	28,308,600		270 liters/capita/day	71 gpcd
Mid/Lower	96,726	36,007,559		339 liters/capita/day	90 gpcd
Upper	35,352	14,851,458		386 liters/capita/day	102 gpcd
Commercial	19,660	8,205,669		521 liters/capita/day	138 gpcd
Industrial	10,553	10,175,108	8,249	88.94 m <sup>3</sup> /user/month	
Public	996	9,364,124	7,553	802.06 m <sup>3</sup> /user/month	
Subtotal	1,087	4,707,198	3,797	402.30 m <sup>3</sup> /user/month	
Unregistered	244,647	111,619,716	90,492		
Accounts/pipes	22,857	20,356,566	16,503		
Losses		18,016,355	14,606		
Total	267,504	149,992,637	121,601		

Source: PNWTF (2001)

Table 5. Projected municipal and industrial water demand for Ciudad Juarez by category (2001) (liter per second).

Year	Domestic	Commercial	Industrial	Public	Total (L/s)	Total (as/yr)
1999	4702.8	362	308.2	168.7	5541.8	141,296
2000	4930.8	472.6	326.1	193.1	5922.7	151,008
2005	6164.9	590.9	407.8	241.4	7404.9	188,799
2010	7453.2	714.4	493	291.8	8952.4	288,254
2015	8711.2	834.9	576.2	341.1	10463.4	266,779
2020	9840.7	943.2	650.9	385.3	11820.2	301,373

Source: PNWTF (2001).



Table 6. Rates of ground water and ground water transfer in 2002 for the El Paso and Ciudad Juarez aquifer sub-components

Flow	El Paso Sub-Component		Ciudad Juarez Sub-Component	
	AF	Mm3	AF	Mm3
Southward Flow	16,000	19.7	0	0
Eastward Flow	5,000	6.2	640	0.8
Westward Flow	9,000	11.1	1,500	1.9
Induced Vertical				
Recharge	22,000	27.1	13,000	16
Rerecharge of				
Treated Wastewater	2,500	3.1	0	0
Flow from El Paso				
to Ciudad Juarez	-32,000	-39.5	32,000	39.5
Net Flow into				
Sub-component	20,500	25.3	40,000	49.3

Source: Foster and Hamlyn (2005).

Table 7. Water demand for Ciudad Juarez and El Paso by category and source

NAME OF INSTITUTION	TEXAS		NEW MEXICO		CHIHUAHUA	
	MUNICIPAL	IRRIGATION	MUNICIPAL	IRRIGATION	MUNICIPAL	IRRIGATION
	El Paso Water Utilities	El Paso County Water Improvement Dist.#1	Las Cruces Water Resources Dept.	Elephant Butte Irrigation District	Junta Municipal de Agua y Saneamiento	Distrito de Riego 009
Area	City of El Paso=158,336 acres (247.4 mi <sup>2</sup> ) (2000)	45,569 irrigated acres (2000); 69,010 acres with water rights; 76,114 acres total area EPCWID	City of Las Cruces=32,294 acres (50.46 mi <sup>2</sup> ) (2000)	73,810 irrigated acres (2000); 90,640 acres with water rights; 133,000 acres total area EBID	Ciudad Juarez=40,880 acres (165.48 km <sup>2</sup> )(1995)	39,796 acres irrigated (2000); 51,436 irrigable, 61,100 acres total area Distrito
Number of water accounts	165,743 accounts (2000)	34,850 accounts (2000) (30,000 tracts<2 acres)	22,549 accounts (2000)	8,000 accounts (2000) (5,000 tracts<2 acres)	265,299 registered accounts (2000)	3,213 accounts (1999) (1,052 tracts<12 acres)
Population	City of El Paso=514,342 (1990 census) 563,662 (2000 census) avg 1.0% annual growth	El Paso County = 591,610 (1990 census) 679,622(2000 census) avg 1.4% annual growth	City of Las Cruces=62,126 (1990 census) 74,267 (2000 census) avg 2% annual growth	Doña Ana County= 135,510 (1990 census) 174,682 (2000 census) avg 2.5% annual growth	Cd. Juarez= 798,499 (1990 census) 1,217,818 (2000 census) avg 4.3% annual growth	
Water Supply	47% Hueco Bolson 20% Mesilla Bolson 33% Rio Grande (2000)	100%Rio Grande; negligible ground water	93% Mesilla Bolson, 7% Jornada del Muerto Bolson (2000)	87% Rio Grande, 13% Mesilla Bolson (2000)	100% Hueco Bolson	34% Rio Grande, 33% Hueco Bolson, 33% wastewater from Cd. Juarez (2000)
Annual Water Use (Total production including losses; gpcd=gallons per capita per day)	122,000 af (1990), 126,420 af (2000) avg 0.4% annual increase; 159 gpcd (2000)	264, 127 af (2000)	16,900 af(1990), 20,680 af(2000) avg 2% annual increase; 246 gpcd (2000)	525,435 af(2000) (including a 1995 estimate of 70,000 af ground water)	97,150 af(1990), 124,000 af(2000) avg 2.5% annual increase; 88 gpcd (1999)	173,500 af from all sources (including 60,000 af Rio Grande per 1906 Treaty) (2000)
Water Quality (TDS<1000 mg/L for drinking water)	Avg TDS 530-800 mg/L, depending on source (2000)	Avg TDS 800-1300 mg/L, depending on location (1999)	Avg TDS 500, range 300-1000, depending on location (1999)	Avg TDS 550-1000 mg/L for surface water, dep. On location (1999)	Avg TDS unknown; 12% of wells tested exceeded limit (1999)	Avg TDS 986 mg/l for mixed sources; range 650-3700 (1990)
Metering & Fees	12% of water pumped is neither	Surface water metered; rates for farm	13% of production is not billed	Surface water metered;	8% of water users are not registered;	Irrigation users pay fees based

---

metered nor billed (1999); rates based on water volume	tracts based on 2 af allotment w/additional charges for more volume; small tract flat rate	(1999); rates based on water volume; rates increase as consumption increases	ground water metered by OSE; farm tract rates use 2 af allotment w/add charges for more volume, small tract price based on quantity over 1 af.	only 59% of registered users have water meters; only 66% of existing meters function properly and are read (1999)	on the number of irrigations
---	---	---	--	--	------------------------------------

---

Source: PNWTF (2001).

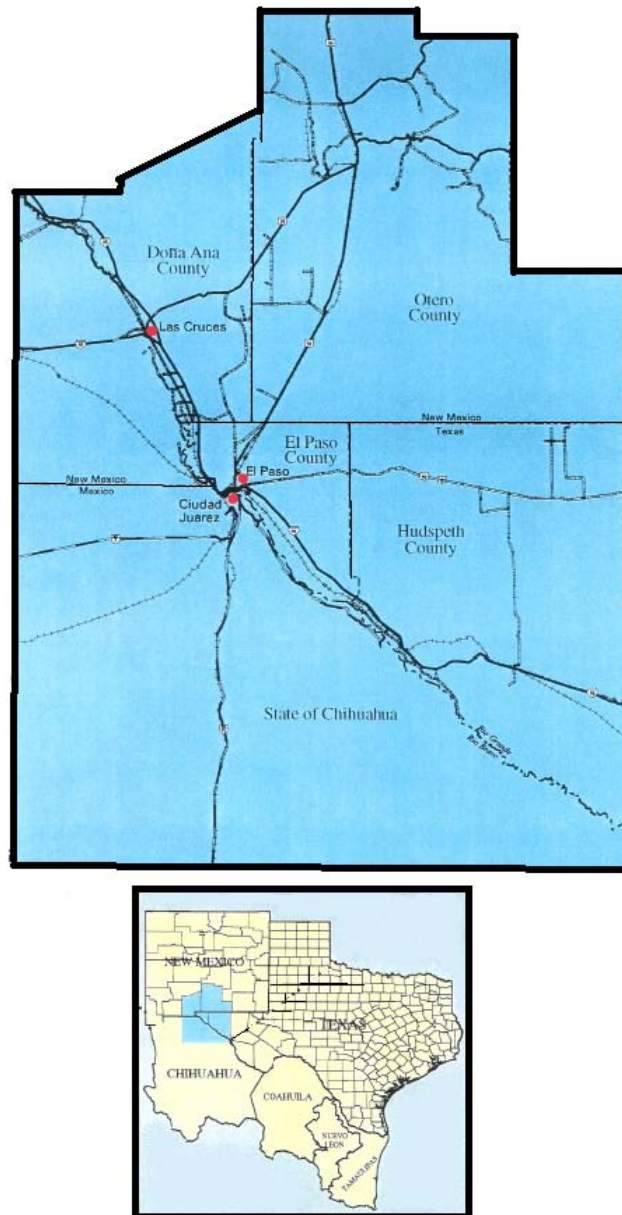


Figure 1. El Paso and Ciudad Juarez.  
Adapted from *Hibbs et al.* (1997).

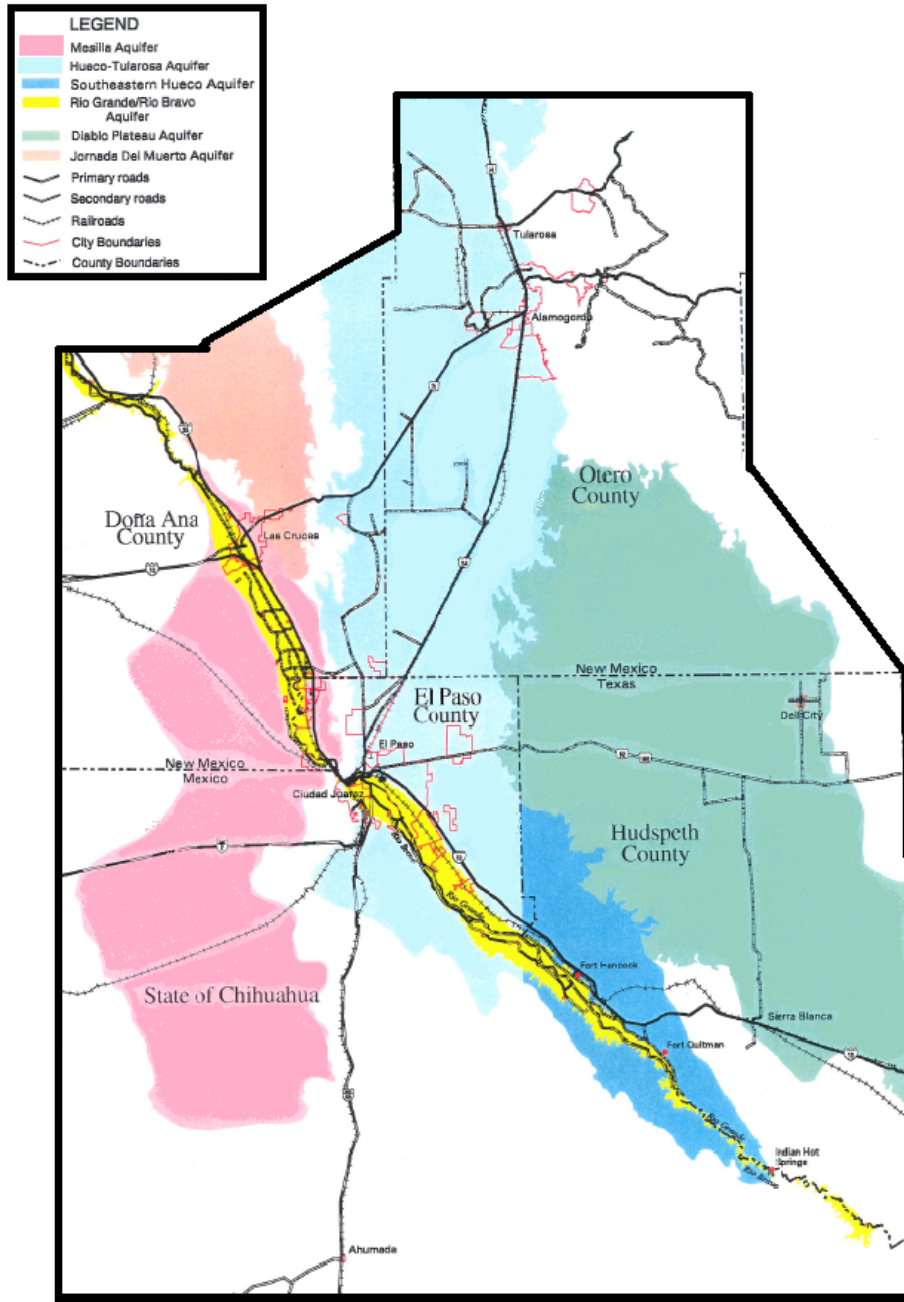


Figure 2. Paso del Norte region's aquifers.  
Adapted from Hibbs et al. (1997).

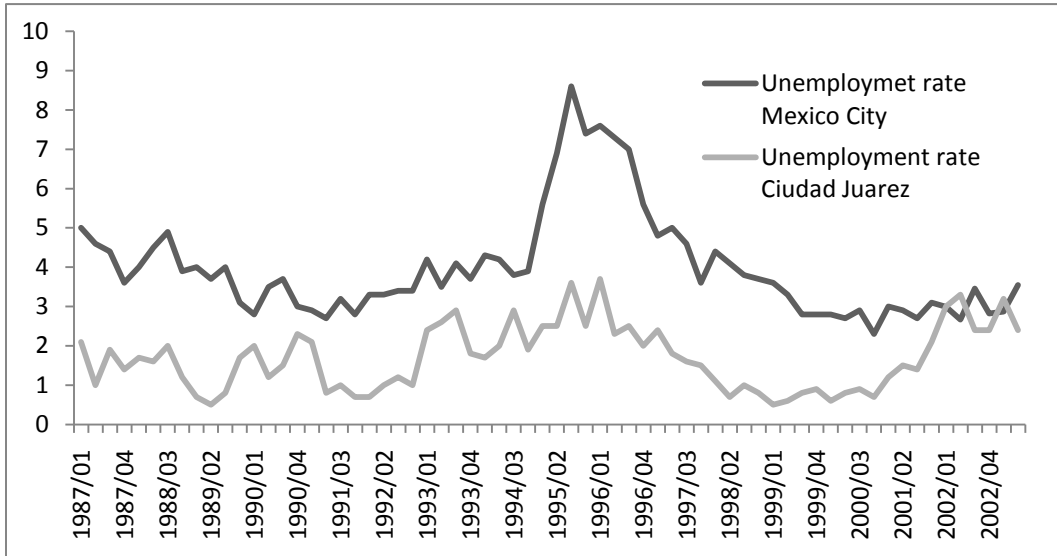


Figure 3. Unemployment rate Mexico City and Ciudad Juarez

Source: INEGI (2010).

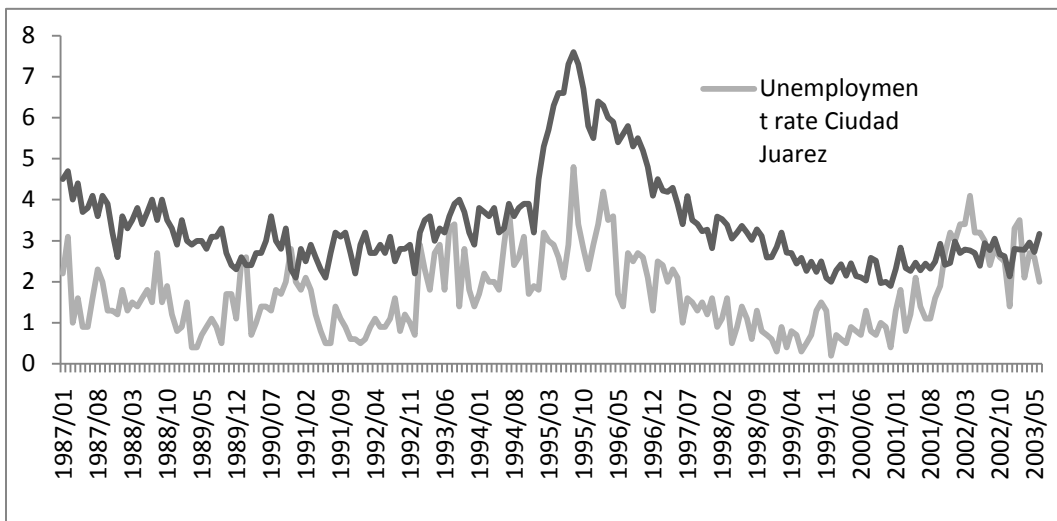


Figure 4. Unemployment rate Mexico and Ciudad Juarez\*

Source: INEGI (2010).

\*Where the unemployment rate of Mexico is equal to the unemployment average rate of 48 Mexican cities.

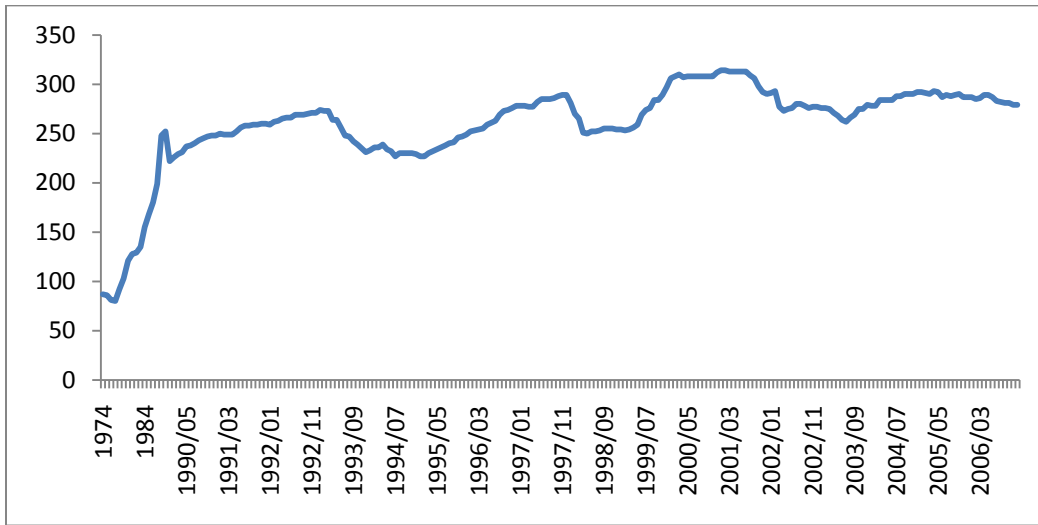


Figure 5. Maquiladora plants in Ciudad Juarez.

Source: INEGI (2010).

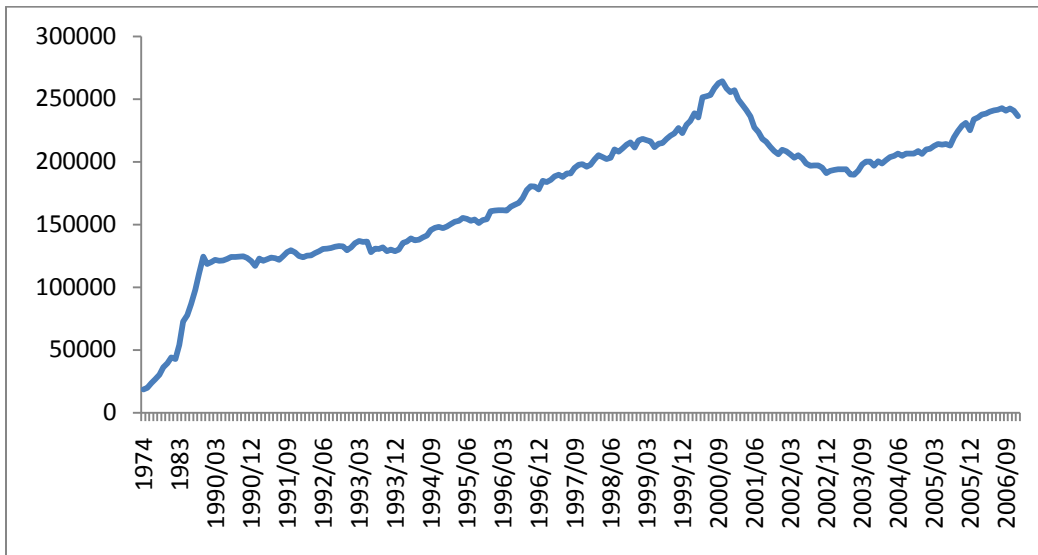


Figure 6. Maquiladora workers in Ciudad Juarez (1974-2006).

Source: INEGI (2010).

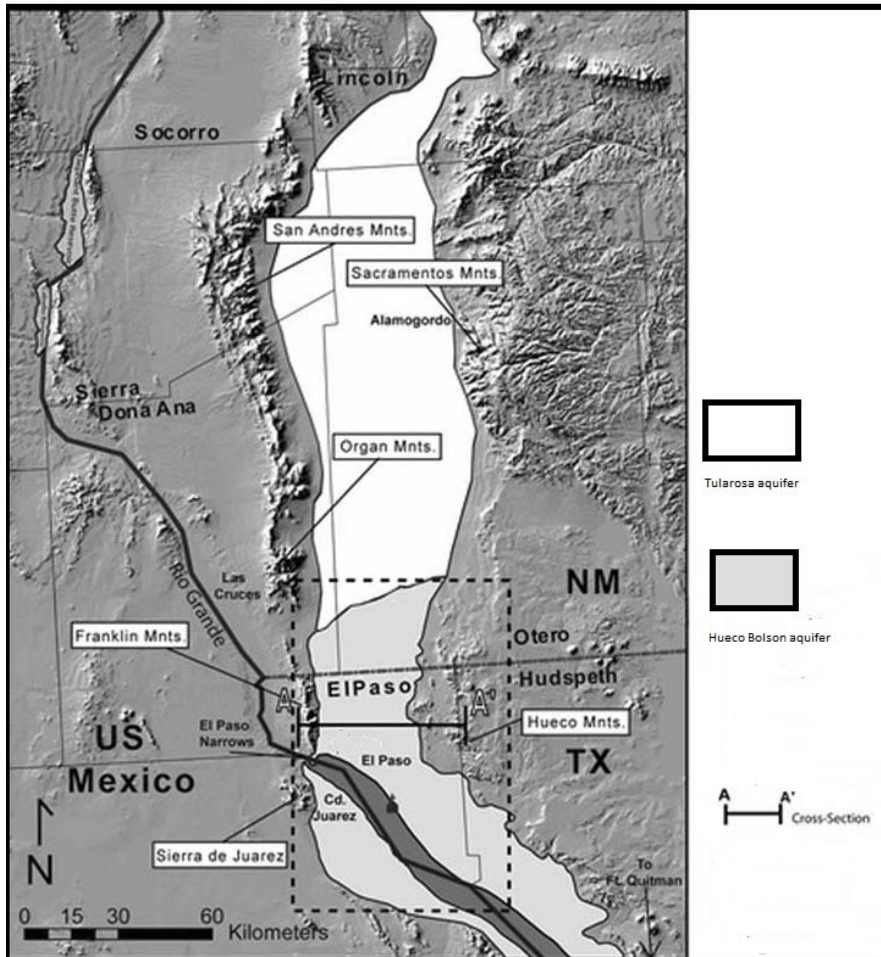


Figure 7. Bolson Hueco Aquifer.

Adapted from Sheng and Devere (2005).



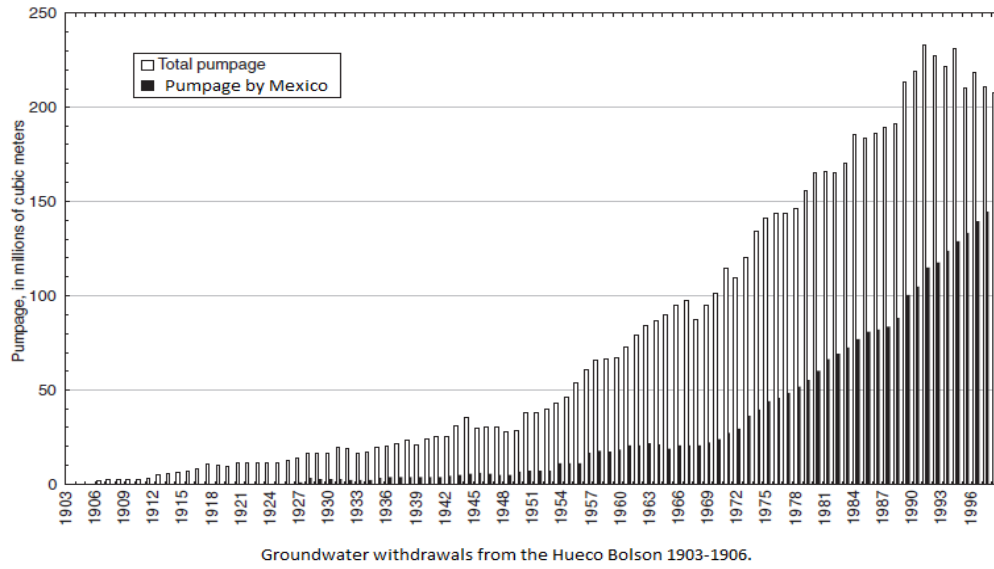


Figure 8. Ground water extraction by Ciudad Juarez and El Paso  
Adapted from Heywood and Yager (2003).

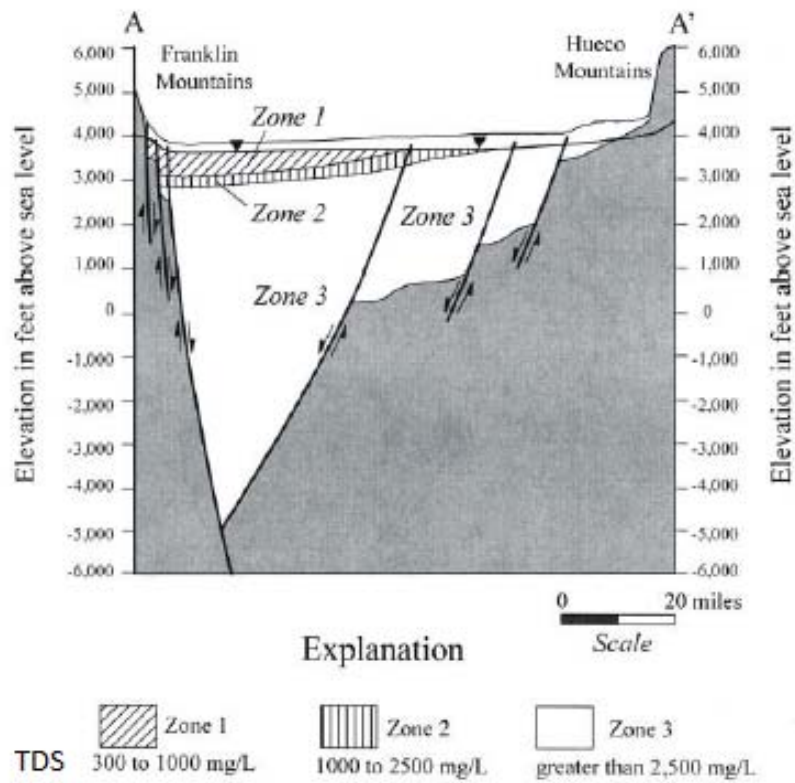


Figure 9. Hueco Bolson aquifer (transversal cross section view)

Adapted from Hutchison (2004).

## CHAPTER 4

### SUSTAINABLE WATER MANAGEMENT

#### INTRODUCTION

In the previous chapter we illustrate how Ciudad Juarez has attracted foreign investment during the last few decades due to relatively low costs. These include low wages supported by low transportation costs and government incentives—i.e., tax incentives and *weak* enforcement of environmental regulations. This has led to economic and population growth, but also to higher demand for public services which leads to congestion and scarcity. In particular, water resources have become more scarce.

If the increasing scarcity of water leads to increased water prices, the nominal wage will need to increase to offset the increasing price of water. As the nominal wage increases, Ciudad Juarez's comparative advantage will decline up to the point where foreign investment stops. If the nominal wage cannot be increased due to competitive pressure, increasing water prices means that the real wage will fall and the incentive for worker to move to Ciudad Juarez will fall. In these conditions, what is the best strategy that Ciudad Juarez can implement to maximize sustainable social welfare?

This chapter examines the role of water scarcity and water management on the economic sustainability of Ciudad Juarez. In the first part we analyze the conditions that lead to the economy to reach a stable steady state with positive levels of capital and population.

In the second part we characterize efficient and sustainable water management strategies in Ciudad Juarez under particular demographic, economic and environmental conditions (a) when the only source of water is an aquifer, or (b) when there is conjunctive use ground and imported water. In both cases, it is concluded that there are efficient water management strategies that lead to positive levels of employment and capital in the long run.

Our model assumes that domestic savings in Ciudad Juarez are insufficient to generate economic growth (i.e. that the marginal propensity to save of wage earners is extremely low). Nonetheless, Ciudad Juarez does have a comparative advantage with respect to other cities deriving from the low cost of labor.

As illustrated in the previous chapter, migration plays an important role in the economy of Ciudad Juarez. In our model, migration fosters economic growth—i.e. increasing foreign investment—by maintaining low wages. At the same time it increases the cost of water by increasing demand on, for example, the ground water stocks of the Bolson del Huevo aquifer. The latter effect causes an external effect (negative) on all inhabitants of Ciudad Juarez that is not *internalized* by the new comer.

Efficient management of an aquifer requires a strategy that optimizes the benefits of extracting an additional unit of water today relative to the benefits of extracting it tomorrow (i.e., recognizing the scarcity rents in the ground water extraction cost). In the literature there are two well-defined cases: the first studies the optimal ground water allocation under different contexts, such as, common property rights, uncertainty, and quality issues (see Dixon (1989), Negri (1989), Provencher and Burt (1993), Roseta-Palma (2002), Rubio and Casino (2003)). The second analyzes the

efficient ground water allocation with conjunctive use of fresh water (with or without uncertainty) (see Burt (1967, 1970), Burness and Martin (1998), Tsur and Graham-Tomasi (1991)). In contrast to this, the models presented here deal with the optimal amount of reclaimed water recharged. In particular, the first models the problem of a utility that aims to maximize its profits by extracting and recharging reclaimed water. In this model, the control variable is the amount of water recharged and the amount of ground water extracted is given and exogenous to the utility. The second model assumes that a utility can import or extract water to cover the water demand. Moreover, the utility can recharge reclaimed water to reduce the cost of pumping water.

We use standard elements and assumptions of economic growth theory, using the migration models of Barro and Sala-i-Martin (1995) and Braun (1993), to examine how migration and foreign capital result in economic growth. Barrow and Sala-i-Martin analyze how migration affects the economic growth using the models of Solow and Ramsey. Migration in these models affects economic growth via an effective depreciation rate that depends on both migration rates and capital. However, in both models the economy is closed to foreign goods and assets.

In Braun's model, migration responds directly to the present value of wage rates in an open economy in which the real interest rates are equal across the world and there is perfect capital mobility. In this model the aggregated production function depends on capital, labor, and on the per capita use of a fixed natural resource. Then, as the population increases due to migration the natural resource usage is congested and, consequently, wages will decrease.

In contrast to other studies that link water and economic growth, economic growth is here explained by interaction of labor migration, foreign investment, and the cost of supplying water. In particular, labor and investment are determined by the impact on rate of return of relative wages, which depends on the price of water, labor productivity, and rate of return on capital respectively.

Barbier (2004, 2005) investigates how water scarcity affects the economic growth of a closed economy where population growth is exogenous. His model presents two scenarios: one where water is not a binding constraint and other where it is binding. In the former case, the economy might not supply water efficiently leading to lower rates of economic growth.

Barbier's model is based on economic growth models that use public infrastructure or natural resources (see, for example, "Congestion Model of Productive Government Services" and "Government and Growth", in Barro and Sala-i-Martin (1992, 1995) and Braun (1993)). These inputs have public goods/ bads characteristics that result in intertemporal misallocation (see Sala-i-Martin (1995)). As Barbier puts it:

"If water has the characteristic of a non-excludable good subject to congestion, then there are essentially two ways in which scarcity may affect economic growth. First, as water becomes increasingly scarce in the economy, the government must exploit less accessible sources of freshwater through appropriating and purchasing a greater share of aggregate economic output, in terms of dams, pumping stations, supply infrastructure, etc. Second, it is also possible that water utilization in an economy may be restricted by the absolute availability of water." (p.245).

This chapter is organized in five sections. The first section presents the model and describes the two critical markets—the labor and water markets. A second section analyzes the conditions that lead to a steady state with positive levels of population and capital in the context of water autarky. A third section examines necessary conditions to maximize the discounted social welfare under water autarky. A fourth section investigates optimal water allocation under water imports. The last section summarizes the main findings and presents conclusions.

## SECTION I

### THE MODEL

In this model there are two markets that interact with each other to support economic growth. These are the labor and water market. The first determines the flow of migrant workers and investment and the other balances the water demand and supply.

This section describes these two markets. The first part of this section presents the equations that govern the migration and investment flows and shows how these equations work together in the labor market. The second describes the elements that determine the water demand and supply when the only source of water is an aquifer and it is possible to recharge water.

The next section analyzes how these two sectors interact and the conditions under which the economy reaches a steady state with positive levels of labor and capital.

### LABOR MARKET

The aggregate production function of Ciudad Juarez at time  $t$ ,  $Y(t)$ , depends on aggregate capital,  $K(t)$ , and labor,  $L(t)$  at time  $t$ . We assume that the production function is characterized by constant returns to scale, decreasing returns to scale in each factor, and that it satisfies the Inada conditions. However, we omit technological change<sup>16,17</sup>,

---

<sup>16</sup> In this case output is a homogeneous good.

<sup>17</sup> Furthermore, it is assumed that the product of these plants is sold elsewhere but Mexico.



$$Y(t) = Y(K(t), L(t)) \quad (4.1.0)$$

Where,

$$\frac{\partial Y}{\partial K} > 0, \quad \frac{\partial^2 Y}{\partial K^2} < 0, \quad \frac{\partial Y}{\partial L} > 0, \quad \frac{\partial^2 Y}{\partial L^2} < 0,$$

and

$$\lim_{K \rightarrow 0} \left( \frac{\partial Y}{\partial K} \right) = \lim_{L \rightarrow 0} \left( \frac{\partial Y}{\partial L} \right) = \infty$$

$$\lim_{K \rightarrow 0} \left( \frac{\partial F}{\partial K} \right) = \lim_{L \rightarrow 0} \left( \frac{\partial F}{\partial L} \right) = 0$$

The wage and rate of return to capital in Ciudad Juarez will be determined by the marginal productivity of each factor. Furthermore, it is assumed that the wage in Ciudad Juarez is lower than in the U.S. and that the nominal rate to return of capital is equal in both countries (see Braun (1993)). As a result, productivity of capital will be higher in Ciudad Juarez than in the U.S.

#### DYNAMIC EQUATION FOR THE CAPITAL STOCK

Foreign investment will depend on the difference between the wage in Ciudad Juarez and the U.S. If this difference becomes smaller, foreign investment will decrease and vice-versa. Transaction costs work the other way around. That is, high transaction costs will decrease foreign investment.

The change in capital stock over time will accordingly be a function of the nominal wage of Ciudad Juarez relative to the U.S. and of transaction costs. This is represented in condition (4.1.1).

$$\frac{\dot{K}(t)}{K(t)} = f\left(S(t)_{(+)}^{US}, S(t)_{(-)}^{CJ}, \Omega_{(-)}\right), \quad (4.1.1)$$

where,

- $K(t)$  is the net stock of capital at time  $t$  (gross capital minus depreciation).
- $\dot{K}(t)$  is the change of net capital with respect to time.
- $S(t)^{US}$  is the net average wage in the United States at time  $t$ .
- $S(t)^{CJ}$  is the net average wage in Ciudad Juarez at dollar units at time  $t$ .
- $\Omega_k$  is the ratio of transformation between monetary units and capital.

Equation (4.1.1) is assumed to have the following specific functional form:

$$\frac{\dot{K}(t)}{K(t)} = \left( \frac{S(t)^{US}}{S(t)^{CJ}} - 1 \right) \Omega_k, \quad (4.1.2)$$

where  $\Omega_k$  is equal to one.

Equation (4.1.2) says that if the number of workers in the economy and the U.S. wage rate are both constant, then the rate of growth of capital in Ciudad Juarez will tend to zero. For instance, if the economy starts with  $L^{SS}$  workers and  $K_1$  units of capital, the wage in Ciudad Juarez will be  $S_1^{CJ}$  where the wage is determined by the marginal productivity of labor as stated above. This is depicted in Figure 10. Since this wage level is lower than the U.S. wage,  $S^{US}$ , the capital stock will increase to  $K_2$ . At this level, the wage will be  $S_2^{CJ}$  and given that this is lower than the  $S^{US}$  investment will increase continue.

This process will continue up to the point at which the wage in Ciudad Juarez is equal to the U.S ( $S^{CJ}(L^{SS}, K^{SS})$  in Figure 10). At this point capital will be equal to  $K^{SS}$ . The rate of growth of capital will be positive (negative) for capital levels lower (higher) than  $K^{SS}$ .

So far we have assumed that foreign investment in Ciudad Juarez is a function of the wage difference between the U.S. and Ciudad Juarez. In reality, there are other countries that compete with Ciudad Juarez for the foreign investment.

Assuming that there is another city, CC, that competes with Ciudad Juarez and has a wage,  $S^{CC}$ , higher than Mexican but lower than the U.S. The dynamic equation for capital is now defined as,

$$\frac{\dot{K}(t)}{K(t)} = \left( \frac{S^{CC}}{S(t)^{CJ}} - 1 \right). \quad (4.1.3)$$

#### DYNAMIC EQUATION FOR THE POPULATION IN CIUDAD JUAREZ

In this model there are two commodities: water and the total money expenditure on other goods. The wage that workers receive is used in buy these goods. Without loss of generality we assume that each individual uses a fixed amount of water,  $E$ , and so pays  $EP(t)^{WR}$ . Their disposable income is equal to the nominal wage minus water expenditure (minus taxes, assumed for simplicity to be zero). Individuals that work do not work in Ciudad Juarez they receive the net average wage in Mexico, equal to  $S(t)^{MX}$ , and their disposable income is equal to average wage because water is free.

Workers from other Mexican cities migrate to Ciudad Juarez if the disposable income they receive in Ciudad Juarez is higher than elsewhere, assuming prices to be equal in Mexico and that disposable income in Ciudad Juarez is defined by the nominal wage  $S(t)^{CJ}$  minus the price of water  $P(t)^{WR}$ . Further, it is assumed that labor supply in Mexico is inelastic.

It follows that the rate of migration to Ciudad Juarez will be a function of the disposable income differential between other cities in Mexico and Ciudad Juarez. This is represented by the differential equation (4.1.3).

$$\frac{\dot{L}(t)}{L(t)} = f\left(S(t)^{CJ}_{(+)}, S(t)^{MX}_{(-)}, E P(t)^{WR}_{(-)}, \Omega_l_{(-)}\right), \quad (4.1.4)$$

where:

- $L(t)$  is the number workers and  $\dot{L}(t)$  is the population growth in Ciudad Juarez.
- $S(t)^{CJ}$  is the average wage in Ciudad Juarez at time  $t$ .
- $S(t)^{MEX}$  is the net average wage in Mexico at time  $t$ .
- $P(t)^{WF}$  is the price that workers pay for water multiplied by the per capita water demand,  $E$ .
- $\Omega_l$  is the ratio of transformation between monetary units and migration.

We assume that the proportional growth rate of the Ciudad Juarez population is described by an equation with the specific functional form,

$$\frac{\dot{L}(t)}{L(t)} = \left( \frac{S(t)^{CJ} - E P(t)^{WR}}{S(t)^{MX}} - 1 \right) \Omega_l, \quad (4.1.5)$$

where  $\Omega_l$  is equal to one.

If capital is constant over time, the price of water is an increasing function of population, and the wage in the U.S. is constant. In this case population growth will tend to zero. In Figure 11, population growth is zero when the population level is equal to  $L^{SS}$ . At this point the wage in Ciudad Juarez (net of the price of water) will be equal to the

average net wage in Mexico. In Figure 11 this wage level is equal to  $S(L^{SS}, K^{SS})^{CJ} = S^{MX} + EP(t)^{WR}$ —where  $K^{SS}$  is the fixed amount of capital in the economy and the price of water is a linear function of population. If the population level is higher than  $L^{SS}$ , then the net wage in Ciudad Juarez will be lower than the net wage in Mexico. In this case, the rate of migration will be negative and vice versa.

#### WATER SECTOR

As stated in the previous chapter, Ciudad Juarez relies on an aquifer to supply water. It is assumed that only households consume water (at a fixed level determined by  $E$ ), so total demand for water,  $TDW$ , at time  $t$  is given by,

$$TDW = L(t)E = E(t) \quad (4.1.6)$$

It will be assumed that the aquifer is like a bathtub or a single cell. Figure 12 depicts this aquifer (taken from Gisser (1983)).

Where  $WT_0$  is the initial water table level,  $R(t)$  is the artificial recharge,  $E(t)$  is the water extracted,  $\alpha E(t)$  is the water that infiltrates again to the aquifer,  $S_L$  is the city elevation, and  $W_n$  is the natural discharge ( $W_n$  and  $\alpha E(t)$  are zero in this case).

#### GROUND WATER RECHARGE<sup>18</sup>

---

<sup>18</sup> "This concept [artificial recharge] uses water of a given quality introduced at a point that is intended to allow water supplies to flow into a wellfield production zone. The aquifer head is raised so that a driving head is created to push water into the aquifer formations, from which the water is pumped via a wellfield that could be many miles away [...] In some instances a surface area is simply flooded to create an artificial aquifer head at the point of recharge." (Bloetscher *et al.* (2005), p.12).

Water authorities in Ciudad Juarez may recharge the aquifer by using treated water (see Figure 13). It is assumed that all waste water has the same quality, that secondary treatment is used, and the aquifer has permeability that allows reclaimed water recharge via a recharge well.

The water stock at time  $t$ ,  $W(t)$  (e.g. the volume of ground water in cubic meters), depends on the rate of water extraction  $E(t)$ , artificial recharge  $R(t)$ , and exogenous (constant) recharge  $\bar{R}$ . This includes the amount of water pumped by El Paso, which is assumed constant.

$$\dot{W}(t) = R(t) - E(t) + \bar{R}. \quad (4.1.7)$$

#### COST FUNCTIONS

The cost of supplying water has two components: the cost of water extraction and cost of water treatment and recharge. The cost of extraction per unit is a decreasing convex function of the stock of ground water at time  $t$ ,  $f(W(t))$ , and some constant price,  $P_E$ , which captures the variable costs per unit of ground water extracted (e.g. energy costs, wages, and well maintenance costs). We represent the ground water pumping cost function as<sup>19</sup>,

$$C(E(t)) = P_E f(W(t)) E(t), \quad (4.1.8)$$

with the following properties,

---

<sup>19</sup> "The total cost of extraction per acre depends on the quantity of water extracted and the depth of the water table. Like most ground water models, costs vary directly with the pumping rate and inversely with the level of the water table (or, equivalently, the stock of water). Marginal pumping costs increase with both the rate of extraction and pumping lift (equivalently, marginal pumping costs vary inversely with the stock of water)." (Negri (1989), p 10).

$$\frac{\partial C(E(t))}{\partial W(t)} = P_E \frac{\partial f(W(t))}{\partial W(t)} E(t) < 0,$$

$$\frac{\partial^2 C(E(t))}{\partial W(t)^2} = P_E \frac{\partial^2 f(W(t))}{\partial W(t)^2} E(t) > 0,$$

$$\lim_{W \rightarrow \infty} (f(W)) = 0,$$

$$\lim_{W \rightarrow 0} (f(W)) = \infty.$$

The economy can treat and recharge a percentage of the water used to counterbalance the loss of water volume in the aquifer. The cost of this process is modeled as an increasing convex function of the water treated and recharged  $R(t)$ . That is,

$$\frac{\partial C(R(t))}{\partial R(t)} > 0, \quad \frac{\partial^2 C(R(t))}{\partial R(t)^2} > 0,$$

given  $E(t) \varphi \geq R(t)$  and  $0 < \varphi < 1$ . (4.1.9)

Total cost is the sum of extraction and recharging costs,

$$TC(t) = C(E(t)) + C(R(t)) \tag{4.1.10}$$

The literature generally ignores sunk and capital costs and considers only variable costs (e.g. the cost of energy required to pump ground water) (see Koundouri (2004), Shaw (2005), Provencher (1995)).

## SECTION II

## WATER AS A CONSTRAINT ON ECONOMIC GROWTH

This section describes the conditions that lead to stable steady state with positive levels of employment and capital. In this case, the economy only relies on ground water, but note that these conditions can be extended to other contexts, such as water imports.

### SUSTAINABLE YIELD

Sustainable yield, or sustainable water extraction, means that the amount of water extracted from the aquifer must equal the amount of natural and artificial recharge. In terms of (4.1.7),

$$R(t) + \bar{R} - E(t) = 0. \quad (4.2.0)$$

Given that extraction is equal to the total water demand,

$$R(t) + \bar{R} = E L(t). \quad (4.2.1)$$

The proportion of water that it is possible to treat and recharge is given by  $0 < \varphi < 1$ , so the maximum level of recharging available sustain a safe yield level is equal to  $E(t)^* \varphi$  (i.e.,  $E(t) \varphi \geq R(t)$ ). Where  $E(t)^*$  is given by,

$$E(t)^* = \frac{\bar{R}}{1 - \varphi}. \quad (4.2.2)$$

Then, we can rewrite condition (4.2.0) as following,

$$R(t) + \bar{R} - E(t) = 0 \quad \text{for } R(t) \in [0, E(t)^* \varphi] \text{ given that } E(t) \leq E(t)^*, \quad (4.2.3)$$

The maximum population level in the economy is given by (using condition (4.1.6))



$$L(t)^* = \frac{\bar{R}}{E(1-\phi)}. \quad (4.2.4)$$

In other words, the economy must have a population level equal or lower than  $L(t)^*$  to reach a steady state.

#### THE ECONOMY

The aggregate production function of the economy is assumed to be Cobb-Douglas, and to satisfy the assumptions stated in section 1 (see condition (4.1.0)). Thus,

$$Y(t) = K(t)^\alpha L(t)^{1-\alpha}, \quad (4.2.5)$$

where  $0 < \alpha < 1$ .

The wage in Ciudad Juarez is determined by the productivity of labor,

$$S(L(t), K(t))^{CJ} = (1 - \alpha) K(t)^\alpha L(t)^{-\alpha}, \quad (4.2.6)$$

Assuming that the net wage in Mexico and the nominal wage in U.S. are fixed, the economy will be described by the following equations (substituting (4.2.5) and (4.2.6) into (4.1.2) and (4.1.4)),

The dynamic equation for the capital stock is:

$$\frac{\dot{K}(t)}{K(t)} = \left( \frac{S^{US}}{S(t)^{CJ}} - 1 \right), \quad (4.2.7)$$

the dynamic equation for the population is:

$$\frac{\dot{L}(t)}{L(t)} = \left( \frac{[S(t)^{CJ} - E P(W(t), R(t))^{WR}]}{S^{MX}} - 1 \right), \quad (4.2.8)$$

and the dynamic equation for ground water is:

$$\dot{W}(t) = R(t) + \bar{R} - E(t), \quad (4.2.9)$$

for  $R(t) \in [0, E(t) \varphi]$ .

#### WATER TARIFFS

It is assumed that the water tariff is an increasing function (of the recharge level and a decreasing function of the ground water stock) with a first derivative ( $C^1$  function). In addition, we require that the water tariff covers the total cost of extracting and recharging water. That is,

$$-\frac{\partial(P(W(t), R(t))^{WR})}{\partial W(t)} > 0, \quad (4.2.10a)$$

$$\frac{\partial(P(W(t), R(t))^{WR})}{\partial R(t)} > 0, \quad (4.2.10b)$$

and,

$$P_E f(W(t))L(t)E + C(R_t) = P(W(t), R(t))^{WR} L(t)E. \quad (4.2.10c)$$

#### STEADY STATE OF THE ECONOMY

The  $\dot{L} = 0$  locus is given by (using (4.2.8))<sup>20</sup>,

$$L = 0, \tag{4.2.11}$$

and,

$$S(L(t), K(t))^{CJ} - EP(W(t), R(t))^{WR} = S^{MX}. \tag{4.2.12}$$

Condition (4.2.12) says that workers will stop migrating when the disposable income in Ciudad Juarez is equal to the disposable income in the rest of Mexico.

The schedule for  $\dot{K}(t) = 0$  is given by (using equation (4.2.7)),

$$K = 0, \tag{4.2.13}$$

and,

$$S^{US} = S(K(t), L(t))^{CJ}. \tag{4.2.14}$$

Condition (4.2.14) indicates that foreign capital will increase up to the point where wages in the United States and Ciudad Juarez are equal.

Under the conditions assumed in the model there is a stable positive steady state (this is showed in the Appendix A). This is steady state is given when the conditions (4.2.3), (4.2.12), and (4.2.14) hold. That is, for positive levels of labor, capital, and the stock of water ( $L^{SS}$ ,  $K^{SS}$ ,  $W^{SS}$ ), the following conditions hold,

---

<sup>20</sup> We are taking non negative values of capital and population.

$$gEL^{SS} + \bar{R} - EL^{SS} = 0, \quad (4.2.15a)$$

$$S(K^{SS}, L^{SS})^{CJ} = S^{MEX} + EP(W^{SS}, gEL^{SS})^{WR}, \quad (4.2.15b)$$

$$S^{US} = S(K^{SS}, L^{SS})^{CJ}, \quad (4.2.15c)$$

$$L^{SS} \leq L^*, \quad (4.2.15d)$$

where  $g$  is a percentage of water that is recycled (e.g.,  $R = gEL$  and  $g \leq \varphi$ ).

It is worth noting that the economy reaches a positive steady state because the water tariff covers the total cost of supplying water and is an increasing function with a first derivative.

The steady state level of labor force will be inversely related to the water recharge capability of Ciudad Juarez ( $\varphi$ ), extraction and recharging costs, the net average wage in Mexico ( $S^{MX}$ ), and the demand for water ( $E$ ). It will be directly related to the real wage in the U.S. ( $S^{US}$ ), and the ground water stock, ( $W^{SS}$ ). The steady state level of capital is directly proportional to employment weighted by the US wage and capital productivity ( $\alpha$ ).

The main conclusion of this section is that the economy will reach a positive steady state at which there is safe (sustainable) yield and at which the incentive to migrate or invest in Ciudad Juarez is zero. This result depends on the existence of a water tariff function with the properties described above. This result can be extended to a situation where Ciudad Juarez can import water from elsewhere, as long as the cost of importing water is increasing and tariffs cover the cost of supply.

## SECTION III

### OPTIMAL RECHARGING POLICY IN ABSENCE OF EXTERNAL WATER SOURCES

This section characterizes the efficient water management strategies that lead both to sustainable (positive) levels of population and capital, and to the use of water at rates no greater than the recharge rate (natural and artificial) in the long run. Two cases are analyzed. The first derives the optimal solution of a cost minimization problem without population growth. The second examines the solution of a private utility that wants to maximize its profits given that population is determined by investment and migration flows and the municipal authority sets the water tariffs.

In both cases it is assumed that some regulator sets up a minimal ground water level  $W^T$  (a “sustainability target”) that the utility must not pass. This ground water level works as climatic variability buffer. In addition, it affects the steady state levels of capital and employment as it was explained in the previous sections.

In the rest of the dissertation it will be assumed that there is a positive steady state given that utility can recharge up to  $\varphi$  percent of the used water in the economy and sustainability target is  $W^T$ .

### ZERO POPULATION GROWTH

In this case we assume that a central planner wants to minimize the cost of providing water on a sustainable basis by recharging and recharging water to some aquifer with adequate permeability. In this economy there is no population growth and water demand is completely inelastic. The water utility can recycle and recharge a proportion

of the water used in the economy,  $\varphi$ , and is required to meet a target ground water,  $W^T$ , in the aquifer at the end of the extraction period.

The problem is the following,

$$\begin{aligned}
 & \text{Min}_{R_t} \sum_{i=0}^T \rho^i (P_E f(W_t) L E + C(R_t)) \\
 & \text{s.t.} \\
 & W_{t+1} = W_t + \bar{R} + R_t - L E, \\
 & 0 \leq R_t \leq \varphi L E, \\
 & W_T \geq W^T, \\
 & W_0 = W,
 \end{aligned} \tag{4.3.0}$$

Where  $\rho$  is the rate discount.

To solve this problem we assume that there is a variable  $y$  such that,

$$\begin{aligned}
 y_t &= \frac{R_t}{\varphi L E}, \\
 y_t &\in [0,1]
 \end{aligned}$$

(4.3.1)

Then, the problem can be rewritten as,

$$\begin{aligned}
 & \text{Max}_{R_t} \sum_{i=0}^T -\rho^i (P_E f(W_t) L E + C(R_t)) \\
 & \text{s.t.} \\
 & W_{t+1} = W_t + \bar{R} + R_t - L E, \\
 & y_t \varphi L E = R_t, \\
 & W_T \geq W^T, \\
 & W_0 = w.
 \end{aligned} \tag{4.3.2}$$

The current value Hamiltonian associated with this problem is given by,

$$H = (-P_E f(W_t)EL - C(y_t \phi LE)) + \eta(W + y_t \phi LE + \bar{R} - EL) \quad (4.3.3)$$

The Maximum principle requires that,

$$\frac{\partial H}{\partial y_t} = -\frac{\partial C(R_t)}{\partial R_t} \phi LE + \eta_t \phi LE = 0, \quad (4.3.4)$$

$$\rho \frac{\partial H}{\partial W_t} = \left[ -P_E EL \frac{\partial f(W_t)}{\partial W_t} \right] \rho + \eta_t \rho = \eta_{t-1}, \quad (4.3.5)$$

These conditions are both necessary and sufficient since the objective function is convex and constraints are concave. Then, there exists an optimal sequence pair  $(\{W^*\}, \{Y_t^*\})$  that solves problem (4.3.2) and a sequence  $\{\eta_t\}$  for  $t \in [0, T]$  such that the following equations are satisfied,

$$\frac{\partial H}{\partial y} (t, W_t^*, y_t^*, \eta_t) = 0, \quad \forall y \in [0,1]$$

$$\rho \frac{\partial H}{\partial W} (t, W_t^*, y_t^*, \eta_t) = \eta_{t-1}, \quad \forall t \in [0, T]$$

Rewriting condition the first order condition,

$$\frac{\partial C(R_t)}{\partial R_t} = \eta_t, \quad (4.3.6)$$

The LHS of equation (4.3.6) is the marginal cost of an additional unit of recharging in period  $t$ . The RHS is the opportunity cost of an additional unit of ground water in period  $t$ . For an optimal recharging trajectory both terms must be equal.

Now, rearranging condition (4.3.5) we obtain,

$$\eta_{t+1}\rho = \eta_t + P_E \frac{\partial f(W_{t+1})}{\partial W_{t+1}} E L \rho. \quad (4.3.7)$$

This condition says that in the optimal solution the discounted opportunity cost of an additional unit of ground water in period  $t+1$  (on the LHS) equals to the opportunity cost of an additional unit of ground water in period  $t$  plus the effect of the stock externality. That is, the last term captures the increase in the total cost of reducing the ground water stock marginally.

If we substitute condition (4.3.6) into (4.3.7) we have that,

$$\rho \frac{\partial C(R_{t+1})}{\partial R_{t+1}} = \frac{\partial C(R_t)}{\partial R_t} + P_E \frac{\partial f(W_{t+1})}{\partial W_{t+1}} E L \rho. \quad (4.3.8)$$

This new condition tell us that at the optimal recharging trajectory the marginal discounted cost of recharging an additional unit of water in period  $t+1$  must be equal to marginal cost of recharge an additional unit of water in period  $t$  plus the stock externality.

If  $T = \infty$ ,  $W_0$  is large enough, and  $W^T$  is free, then at the steady state we have that (using conditions (4.3.6) and (4.3.7) at the steady state),



$$\frac{\partial C(R_{ss})}{\partial R} = -\frac{P_E}{r} \frac{\partial f(W_{ss})}{\partial W} E L, \quad (4.3.9)$$

where  $W_{ss}$  is the ground water level at the steady state,  $R_{ss}$  is the recharging level at the steady state, and  $r$  is the rate of return.

This condition says that in the steady state the marginal cost of recharging is equal to the cost of reducing the stock of ground water marginally which is equal to the social user cost of ground water consumption weighted by the rate of return (Provencher and Burt (1993)).

To illustrate the problem numerically, suppose that:

$$\begin{aligned} W_0 &= 8,000m^3, \\ W_T &= 1,000m^3, \\ L_0 &= 20, \\ \rho &= 0.9, \\ \bar{R} &\in (40m^3, 67.5m^3, 80m^3), \\ f(W_t) &= \frac{1}{(W_t)^2}, \\ P_E &= (5, 15), \\ C(R_t) &= 0.01 (R_t)^2. \end{aligned}$$

Furthermore, suppose that each worker consumes only two  $m^3$  per year, and  $\varphi$  is equal to 90%.

Figures 14 and 15 depict the optimal recharge strategies for different prices of extraction and natural rate of recharge (time is measured on the horizontal axis). Figure 14 describes different optimal recharging strategies for different prices of extraction given that the constant rate of recharge is equal to 40  $m^3$ . We observe in this figure that when the relative extraction cost is lower—i.e., the price of extraction is equal to five,

the economy starts recharging smaller amounts of water (see the green trajectory in Figure 14). However, given that the utility recharges lower amounts of water, the ground water stock decreases at faster rate causing higher relative extraction costs. Therefore, the utility will find optimal recharging more water than when the price of extraction is equal to 15. In the final periods, we see that amount of water recharged is lower, but increasing, when the price of extraction is equal to 15 than when it is equal to five. It is worthy noticing that when the price is equal to five the recharge trajectory reaches the steady state level before.

Figure 15 describes optimal recharging strategies for different natural rates of recharge. When the natural recharge is the largest (equal to  $80\text{m}^3$ ), the utility recharges the lowest amount of water in all periods. When the natural recharge is the smallest (equal to  $40\text{m}^3$ ) the utility is recharging the highest amount of water in all periods. Hence, the recharging trajectory will reach the sustainable yield faster with lower natural rates of recharge.

#### OPTIMAL RECHARGING POLICY

The literature on ground water allocation distinguishes two types of external effects under common property. The first is a stock externality and takes place when by extracting an additional unit of ground water stock in period  $t$ , the user reduces the set of pumping alternatives to other users in period  $t+1$ . The second is a pumping cost externality and arises when withdrawal by one user reduces the stock of ground water, increasing the pumping costs for all users. If there is no intervention or agreement, the resource will be overexploited relative to the surplus maximizing policy (Negri (1989), Provencher and Burt (1993)).

It is assumed that workers are rent seekers and there is perfect mobility across Mexico. This together with the fact that Ciudad Juarez automatically meets demand for water, means that the problem resembles an open access common-pool resource problem of the type much discussed in the ground water literature. When a new worker migrates to Ciudad Juarez they cause a negative effect on the rest of population because as the stock of water gets depleted the marginal cost of supplying water rises for everyone. Today's extraction rates impose an intertemporal externality on the future, which is not internalized by the migrant. The difference between the typical commons problem and this case is that there is a third party that can set prices optimally. Nevertheless, since there is open access the individual surplus will be reduced as new workers arrive to Ciudad Juarez.

The demand for water for each user is given (i.e., the demand is completely inelastic),

$$\left\{ \begin{array}{ll} E & \forall \quad P(W^t, R_t)^{wr} \\ 0 & \text{if } S_t^{CJ} < E P(W^t, R_t)^{wr} \end{array} \right\}. \quad (4.3.10)$$

Assuming that the international capital market adjusts immediately—i.e., that at each period workers receive the U.S. nominal wage; or  $S^{US} = S^{CJ} \quad \forall t \in (0, \infty)$ , the consumer surplus will be defined as the maximum willingness to pay times the water consumption. That is,

$$\left( \frac{S_t^{CJ} - S^{MX}}{E} - P(W_t, R_t)^{wr} \right) E > 0,$$

where the maximum willingness to pay is equal to,

$$\left( \frac{S_t^{CJ} - S^{MX}}{E} - P(W_t, R_t)^{wr} \right).$$

A private utility supplies all water to Ciudad Juarez but after  $T$  years Ciudad Juarez has the authority to implement a safe yield policy and set the water tariffs. Hence, the problem for the private utility is to exploit the aquifer  $T$  years to maximize profits by selling and recharging water. As before, there is a minimum terminal stock of water,  $W^T$ , that must be met.

The problem for the private utility is the following,

$$\begin{aligned} & \text{Max}_{\substack{E \in \mathbb{R}^+ \\ R \in [0, EL(1+n)^T]}} \sum_{t=0}^T \rho^t \left\{ P_t^{wr} EL_t - (P_E f(W_t) EL_t + C(R_t)) \right\} \end{aligned}$$

*s.t.*

$$0 \leq R_t \leq \varphi EL_t,$$

$$\varphi < 1,$$

$$W_{t+1} = W_t + \bar{R} + R_t - EL_t,$$

$$W_T \geq W^T \tag{4.3.11}$$

$$W_0 = W,$$

$$L_0 = L,$$

$$\text{for } t \in (0, T),$$

where  $\rho$  is the rate discount.

Population in each period is determined by dynamic equations of labor and capital, which are the discrete version of the continuous equations (4.2.7) and (4.2.8). Specifically, we use the following differential equation to represent population dynamics

(the addition of a the maximum growth rate “ $n$ ” does not change the results of previous sections),

$$L_{t+1} = L_t + L_t n \left( \frac{\frac{S^{US} - S^{MX}}{E} - P(W_t, R_t)^{wr}}{\frac{S^{US} - S^{MX}}{E}} \right), \quad (4.3.12)$$

where  $n$  is less than the rate of discount. This differential equation has the following important feature: As individual welfare decreases if the water tariff increases, the population growth rate is decreasing in the water tariff. When the water tariff is close to zero the population growth rate is  $n$ ; and when the water tariff equal to  $(S^{US} - S^{MX})/E$  the population growth rate is zero.

To solve this problem we assume that there is a variable  $y$  such that,

$$y_t = \frac{R_t}{\varphi EL_t},$$

$$y_t \in [0,1].$$

Thus, the problem becomes,

$$\underset{\substack{E \in [0, \infty) \\ y_t \in [0,1]}}{\text{Max}} \sum_{t=0}^T \rho^t \left\{ P_t^{wr} EL_t - (P_E f(W_t) EL_t + C(y_t \varphi EL_t)) \right\}$$

s.t.

$$\begin{aligned}
W_{t+1} &= W_t + \bar{R} + y_t \phi E L_t - E L_t, \\
L_{t+1} &= L_t + L_t n \left( \frac{\frac{S^{US} - S^{MX}}{E} - P(W_t, R_t)^{wr}}{\frac{S^{US} - S^{MX}}{E}}} \right), \\
W_T &\geq W^T \\
W_0 &= W, \\
L_0 &= L \\
\text{for } t &\in (0, T).
\end{aligned} \tag{4.3.13}$$

The Hamiltonian associated with (4.3.11) is:

$$\begin{aligned}
H &= \left( P_t^{wr} E L_t - P_E f(W_t) E L_t - C(y_t \phi E L_t) \right) \\
&\quad + \eta_t (W_t + y_t \phi E L_t + \bar{R} - E L_t)
\end{aligned} \tag{4.3.14}$$

The Maximum principle requires that,

$$\frac{\partial H}{\partial E} = P_t^{wr} L_t - P_E f(W_t) L_t - \frac{\partial C(R_t)}{\partial R_t} y_t \phi L_t + \eta_t (y_t \phi L_t - L_t) = 0, \tag{4.3.15}$$

$$\frac{\partial H}{\partial y_t} = - \frac{\partial C(R_t)}{\partial R_t} \phi E L_t + \eta_t \phi E L_t = 0, \tag{4.3.16}$$

$$\rho \frac{\partial H}{\partial W_t} = \left[ - P_E \frac{\partial f(W_t)}{\partial W_t} E L_t \right] \rho + \eta_t \rho = \eta_{t-1}. \tag{4.3.17}$$

Once again, these conditions are both necessary and sufficient because the objective function is convex and constraints are concave—although the latter is true if and only if population changes are smooth and the maximum potential population

growth is lower than the rate of discount. There exist optimal sequences  $(\{W^*\}, \{Y_t^*\}, \{E^*\})$  that solve the problem (4.3.13) and a sequence  $\{\eta_t\}$  for  $t \in [0, T]$  such that the following equations are satisfied,

$$\frac{\partial H}{\partial y}(t, W_t^*, y_t^*, E_t^*, \eta_t) = 0, \quad \forall y \in [0, 1]$$

$$\frac{\partial H}{\partial E}(t, W_t^*, y_t^*, E_t^*, \eta_t) = 0, \quad \forall E \in [0, \infty)$$

$$\rho \frac{\partial H}{\partial W}(t, W_t^*, y_t^*, E_t^*, \eta_t) = \eta_{t-1}, \quad \forall t \in [0, T].$$

By combining conditions (4.3.15) and (4.3.16) we have,

$$P_t^{wr} = P_E f(W_t) + \frac{\partial C(R_t)}{\partial R_t}. \quad (4.3.18)$$

This condition says that the water utility will supply any quantity of water that the market requires if the water tariff is equal to the marginal cost of supplying water, which is equal to marginal cost of pumping plus the marginal cost of recharging water. In equilibrium, the water utility supplies  $EL_t$ .

Equation (4.3.16) provides the optimal condition for recharge. We can rewrite it to aid interpretation, as,

$$\frac{\partial C(R_t)}{\partial R_t} = \eta_t. \quad (4.3.19)$$

The LHS of equation is the marginal cost of an additional unit of recharging in period  $t$ . The RHS is the opportunity cost of an additional unit of ground water in period

$t$ . For a recharging trajectory to be optimal the two terms must be equal. This condition is equal to condition (4.3.6) of the cost minimization problem.

Rearranging condition (4.3.17) and replacing condition (4.3.19) we obtain,

$$\rho \frac{\partial C(R_{t+1})}{\partial R_{t+1}} = \frac{\partial C(R_t)}{\partial R_t} + P_E \frac{\partial f(W_{t+1})}{\partial W_{t+1}} E L \rho. \quad (4.3.20)$$

As in the condition (4.3.8), the LHS is marginal discounted cost of recharging an additional unit of water in period  $t+1$ . The RHS is the marginal cost of an additional unit of recharging in period  $t$  plus the effect of the stock externality or the discounted sum of the marginal damages to each user. This condition is equal to condition (4.3.7) of the cost minimization problem.

If  $T = \infty$  and  $W_0$  is large enough, then at the steady state we have that (using conditions (4.3.13), (4.3.14) and (4.3.15) at the steady state),

$$P_t^{wr} - P_E f(W_{ss}) = -\frac{P_E}{r} \frac{\partial f(W_{ss})}{\partial W} E L_{ss}, \quad (4.3.21)$$

where  $W_{ss}$  is the ground water level at the steady state,  $L_{ss}$  is the population level at the steady state—i.e. there is no migratory flows, and  $r$  is the rate of return.

This condition says that in the steady state the marginal benefits are equal to the foregone benefits of an additional unit of ground water weighted by the rate of return. Another interpretation of equation (4.3.21) is that

$$r (P_t^{wr} - P_E f(W_{ss})) = -P_E \frac{\partial f(W_{ss})}{\partial W} E L_{ss}. \quad (4.3.22)$$



In this case, the return on the marginal benefit has to be equal to the cost of reducing the stock of ground water marginally which is equal to the social user cost of ground water consumption (Provencher and Burt (1993)).

When the planning horizon is infinite,  $T=\infty$ , the economy will reach a positive steady state because the optimal tariff is equal to the marginal cost of supplying water, which is a convex function with a first derivative and covers the total cost (see conditions (4.2.10) and (4.2.15)).

One again, to illustrate this numerically, we suppose that:

$$W_0 = 7,388,000m^3,$$

$$W_T = 10,000m^3,$$

$$L_0 = 1,500,$$

$$\rho = 0.9,$$

$$\bar{R} = 4,930m^3,$$

$$f(W_t) = \frac{1}{(W_t)},$$

$$C(R_t) = 0.001(R_t)^2,$$

$$S^{CC} - S^{MX} = \$4,502.$$

Furthermore, each worker consumes  $100 m^3$  per year and  $\varphi$  is equal to 89%. That is, the economy can recycle up to 89% of the water consumed in the economy. Figure 16 depicts the water consumed and recharged through time ( $T=40$  years). We see in this figure that the utility starts recharging low levels of water in the early periods but later increases as time passes.

We can summarize the main finding so far in the following points: First, the utility will manage the aquifer efficiently by taking into account not only the scarcity

rents but also internalizing the “social user cost” of ground water consumption (Provencher and Burt (1993)). Second, the profit maximization solution minimizes the cost of providing water along the planning horizon—we can see this by comparing the first order conditions of the maximization problem with those of the minimization problem<sup>21</sup>. Third, given that the water tariff is equal to the marginal cost of supplying water, the economy reaches a positive steady state.

Hence, by setting the water tariff equal to marginal cost, the utility will minimize the cost of supplying water and the economy will reach a positive steady state. But, does the utility’s solution maximize the social welfare?

#### WELFARE

The problem for the Ciudad Juarez utility is: to maximize social welfare in a sustainable way (reaching a positive steady state). We claim that the utility’s solution will maximize social welfare and result in a positive steady state when the planning horizon is infinite. There are three reasons that lead to this result:

- (a) Given that the utility is minimizing costs, the water tariff is lowest for any planning horizon if it is equal to the marginal cost of supplying water. Hence, welfare will be maximized for any planning horizon.
- (b) Given that marginal cost is an increasing and convex function, the economy will converge to a positive steady state when the planning horizon is infinite.
- (c) The population trajectory will converge smoothly and continuously to the steady state given that the water tariff is an increasing and convex function.

---

<sup>21</sup> This is a result well established in economic theory.

Hence, the best strategy to maximize the social welfare and reach a positive steady state is by setting water tariffs equal to marginal cost, and leaving the utility to choose the amount of water that will be recharged.

## SECTION IV

### LOOKING INTO THE FUTURE: IMPORTING WATER

As was mentioned in the last chapter, Ciudad Juarez is now considering importing water from elsewhere to maintain its economic growth and mitigate the overdraft of the Bolson del Huevo aquifer. In this case, the economy is no longer limited by aquifer's natural rate of recharge, but by the relative cost of importing water from elsewhere. Therefore, given that the parameters that determine the importing and extracting costs are exogenous to Ciudad Juarez, the best policy option is to implement efficient prices and leave the market to work.

This section analyzes the optimal water allocation between water imports and extraction from the aquifer (pumping). In addition, we illustrate how the optimal solution leads to the highest social welfare. We first consider the choice of how much water to import and to pump to cover water demand, distinguishing between cost-minimization and profit maximization outcomes. We then consider the impact of water recharge. In both cases, the planning horizon is infinite.

### ASSUMPTIONS

The cost of importing water is an increasing and convex function of the amount of water bought. We are going to represent this function as,

$$C(E_{2,t}) = P_I \left( E_{2,t}^\lambda \right), \quad (4.4.0)$$

where  $P_I$  is the price of the imported water in cubic meters,  $E_{2,t}$  is the amount of water bought, and  $\lambda$  measures how fast the cost of importing water increases.

The per unit pumping cost is a decreasing convex function of the stock of ground water at time  $t$ ,  $f(W_t)$ , and some constant price,  $P_E$  as in condition (4.1.10).

As in the previous section, there is a private utility that supplies water and minimum ground water stock,  $W_T$ . In addition, the population growth is given by (as condition (4.3.12))

$$L_{t+1} = L_t + L_t n \frac{\left( S^{US} - S^{MX} / E - P(W_t, E_{2,t})^{wr} \right)}{S^{US} - S^{MX} / E}, \quad (4.4.1)$$

where  $P(W_t, E_{2,t})^{wr}$  is the price that users pay for water.

Contrary to the previous section we assume that the planning horizon is infinite.

#### COST MINIMIZATION

The problem for Ciudad Juarez is minimizing the cost of supplying the demand of water by choosing how much water import and extract. This problem is given by,

*Min Total Cost :*

$E_t \in \infty$

$$\sum_{t=0}^{\infty} \rho^t \left( P_E f(W_t) E_{1,t} + P_I (E_{2,t})^\lambda \right)$$

*s.t.*

$$E_t = EL_t$$

$$E_t = E_{1,t} + E_{2,t} \quad (4.4.2)$$

$$W_{t+1} = W_t + \bar{R} - E_{1,t},$$

$$L_{t+1} = L_t + L_t n \frac{\left( S^{US} - S^{MX} / E - P(W_t, E_{2,t}) \right)}{S^{US} - S^{MX} / E},$$

$$\begin{aligned}
E_{1,t} &\geq 0, \\
E_{2,t} &\geq 0, \\
W_0 &= W \\
\lim_{t \rightarrow \infty} W_t &\geq W^T \\
L_0 &= L \\
\forall t,
\end{aligned}$$

where  $E_{1,t}$  is the water pumped from the aquifer and  $E_t$  is the total water demand.

Writing the Lagrangian function corresponding to this problem:

$$\begin{aligned}
l_t &= \sum_{t=0}^{\infty} \rho^t \left( P_E f(W_t) E_{1,t} + P_I (E_t - E_{1,t})^\lambda \right) \\
&+ \eta_{t+1} \rho^{t+1} (W_t + R_t - E_{1,t} - W_{t+1})
\end{aligned} \tag{4.4.3}$$

The first order necessary conditions include,

$$\frac{\partial l_t}{\partial W_t} = \rho^t P_E \frac{\partial f(W_t)}{\partial W_t} E_{1,t} + \eta_{t+1} \rho^{t+1} - \eta_t \rho^t = 0, \tag{4.4.4}$$

$$\frac{\partial l_t}{\partial E_{1,t}} = \rho^t P_E f(W_t) - \lambda P_I (E_t - E_{1,t})^{\lambda-1} - \eta_{t+1} \rho^{t+1} = 0, \tag{4.4.5}$$

$$\frac{\partial l_t}{\partial \eta_{t+1}} = \rho^{t+1} (W_t + \bar{R} - E_{1,t} - W_{t+1}) = 0, \tag{4.4.6}$$

$$\forall t \in \infty.$$

The suppose that the sequence  $\{E_{1,t}^*, W_t^*, \eta_t\}$  satisfies conditions (4.4.4), (4.3.5), and (4.4.6) for  $t \in [0, \infty)$  and the objective function is convex and constraints are concave given the initial conditions  $W_0 = W$  and  $L_0 = L$ . Then,  $\{E_{1,t}^*, W_t^*, \eta_t\}$  is optimal provided that the transversality condition is satisfied:

$$\lim_{t \rightarrow \infty} n_t (W_t - W^T) \geq 0.$$

We can rewrite conditions (4.4.4) and (4.4.8) as<sup>22</sup>,

$$-\eta_{t+1}\rho = -\eta_t + P_E \frac{\partial f(W_t)}{\partial W_t} E_{1,t}, \quad (4.4.7)$$

$$P_E f(W_t) - \rho \eta_{t+1} = \lambda P_t (E_t - E_{1,t})^{\lambda-1}. \quad (4.4.8)$$

Condition (4.4.7) says that the optimal solution requires that the discounted opportunity cost of an additional unit of ground water in period  $t+1$  (on the LHS) equals the opportunity cost of an additional unit of ground water in period  $t$  plus the effect of the stock externality—this term captures the increase in the total cost of reducing the ground water stock marginally<sup>23</sup>.

The LHS of condition (4.4.8) is the marginal cost of ground water extraction in period  $t$  plus the discounted cost of reducing an additional unit of the ground water in period  $t+1$ . That is, the LHS not only takes into account the marginal cost of pumping an

---

<sup>22</sup> We assume that  $E_{1,t} > 0, \forall t \in [0, \infty)$ .

<sup>23</sup> In this case  $\eta$  is negative.

additional unit today but also the future cost that results from pumping that extra unit today. The RHS is the marginal cost of importing one unit of water in period  $t$ .

#### PROFIT MAXIMIZATION.

The problem for the private utility is maximizing profits by pumping and importing water. That is,

*Max profits :*

$$\begin{aligned} & \begin{matrix} E_t \in \infty \\ E_{1,t} \in \infty \end{matrix} \\ & \sum_{t=0}^{\infty} \rho^t \left( P_t^{wr} E_t - P_E f(W_t) E_{1,t} - P_I (E_{2,t})^{\lambda} \right) \\ & s.t. \tag{4.4.9} \\ & E_t = E L_t, \\ & E_t = E_{1,t} + E_{2,t}, \\ & W_{t+1} = W_t + \bar{R} - E_{1,t}, \end{aligned}$$

$$L_{t+1} = L_t + L_t n \frac{\left( S^{US} - S^{MX} / E - P(W_t, E_{2,t})^{wr} \right)}{S^{US} - S^{MX} / E},$$

$$E_{1,t} \geq 0,$$

$$E_{2,t} \geq 0,$$

$$W_0 = W,$$

$$\lim_{t \rightarrow \infty} W_t \geq W^T,$$

$$L_0 = L,$$

$$\forall t \in \infty.$$

The water tariff sets by the municipal authority. Hence, the utility takes the water tariff as given. The Lagrangian function corresponding to this problem is:



$$l_t = \sum_{i=0}^{\infty} \rho^i (P_i^{wr} E_t - P_E f(W_t) E_{1,t} - P_l (E_t - E_{1,t})^\lambda) + \eta_{t+1} \rho^{t+1} (W_t + \bar{R} - E_{1,t} - W_{t+1}), \quad (4.4.10)$$

The first order necessary conditions are,

$$\frac{\partial l_t}{\partial W_t} = -\rho^t P_E \frac{\partial f(W_t)}{\partial W_t} E_{1,t} + \eta_{t+1} \rho^{t+1} - \eta_t \rho^t = 0, \quad (4.4.11)$$

$$\frac{\partial l_t}{\partial E_{1,t}} = -\rho^t P_E f(W_t) + \rho^t \lambda P_l (E_t - E_{1,t})^{\lambda-1} - \eta_{t+1} \rho^{t+1} = 0, \quad (4.4.12)$$

$$\frac{\partial l_t}{\partial E_t} = \rho^t P_l^{wr} - \rho^t \lambda P_l (E_t - E_{1,t})^{\lambda-1} = 0, \quad (4.4.13)$$

$$\frac{\partial l_t}{\partial \eta_{t+1}} = \rho^{t+1} (W_t + \bar{R} - E_{1,t} - W_{t+1}) = 0, \quad (4.4.14)$$

$$\forall t \in (0, \infty).$$

These conditions are both necessary and sufficient because the objective function is convex and constraints are concave and the transversality condition is satisfied<sup>24</sup>. Hence, there exists an optimal sequence  $\{E_{1,t}^*, W_t^*, \eta_t\}$  for  $t \in [0, \infty)$  that solves problem (4.4.9) such that equations (4.4.11), (4.4.12), (4.4.13) and (4.4.14) are satisfied for  $t \in [0, \infty)$  along with the values  $W_0 = W$  and  $L_0 = L$ .

---

<sup>24</sup> The transversality condition is,  $\lim_{t \rightarrow \infty} \eta_t (W_t - W^T) \geq 0$ .

We can rewrite conditions (4.4.2) and (4.4.3) to aid interpretation<sup>25</sup>,

$$P_t^{wr} = \lambda P_t (E_t - E_{1,t})^{\lambda-1}, \quad (4.4.15)$$

$$\eta_{t+1} \rho - P_E \frac{\partial f(W_t)}{\partial W_t} E_{1,t} = \eta_t, \quad (4.4.16)$$

$$P_E f(W_t) + \rho \eta_{t+1} = \lambda P_t (E_t - E_{1,t})^{\lambda-1}. \quad (4.4.17)$$

Condition (4.4.15) indicates that if the water tariff is equal to the marginal cost of supplying water, the utility will sell any quantity demanded by the market.

The following condition (4.4.16) says that the opportunity cost of an additional unit of ground water in period  $t$  (on the RHS) is equal to the discounted opportunity cost of an additional unit of ground water in period  $t + 1$  minus the effect of the stock externality, as in condition (4.4.7).

Finally, the LHS of condition (4.4.17) is the *net* marginal cost of ground water extraction in period  $t$ . This term is divided into the marginal cost of pumping an additional unit of ground water in period  $t$ ,  $P_E f(W_t)$ , and discounted foregone benefits of pumping an additional unit of ground water in period  $t$ ,  $\rho \eta_{t+1}$ . The RHS is the marginal cost of importing one unit of water in period  $t$ .

It is worth noting that conditions (4.4.16) and (4.4.17) are equivalent to conditions (4.4.7) and (4.4.8) in the cost minimization problem.

As  $T$  goes to  $\infty$ , we have that (by substituting (4.4.18) and (4.4.19) in (4.4.20)),

---

<sup>25</sup> We assume that  $E_{1,t} > 0, \forall t \in [0, \infty)$ .

$$P_{ss}^{wr} - P_E f(W_{SS}) = -\frac{P_E}{r} \frac{\partial f(W_{SS})}{\partial W_{SS}} E_{1,SS}. \quad (4.4.18)$$

That is, in the steady state the marginal benefits are equal to the foregone benefits of extracting an additional unit of ground water which are equal to the social user cost of ground water consumption (Provencher and Burt (1993)) weighted by the rate of return. This condition is equal to condition (4.3.21).

As in the previous section, when the planning horizon is infinite,  $T=\infty$ , the economy reaches a positive steady state because, the price is equal to marginal cost of supplying water which is a convex function with a first derivative and covers the total cost (see conditions (4.2.10) and (4.2.15)); and the cost of importing water is an increasing convex function (see Section II).

## RECHARGE

As in the previous section, there is a private utility that supplies water and Ciudad Juarez sets water prices equal to the marginal cost. The problem for the private utility is maximizing profits by pumping and importing water. That is,

*Max profits :*

$$\begin{aligned} E_t &\in \infty \\ E_{1,t} &\in \infty \\ R_t &\in [0, \infty) \end{aligned}$$

$$\sum_{t=0}^{\infty} \rho^t \left( P_t^{wr} E_t - P_E f(W_t) E_{1,t} - C(R_t) - P_I (E_{2,t})^2 \right)$$

*s.t.*

$$E_t = E L_t$$

$$E_t = E_{1,t} + E_{2,t},$$

$$W_{t+1} = W_t + \bar{R} + R_t - E_{1,t},$$

$$L_{t+1} = L_t + L_t n \frac{\left( S^{US} - S^{MX} / E - P(W_t, E_{2,t}) \right)}{S^{US} - S^{MX} / E},$$

(4.4.19)

$$E_{1,t} \geq 0,$$

$$E_{2,t} \geq 0,$$

$$0 \leq R_t \leq E_t$$

$$W_0 = W,$$

$$\lim_{t \rightarrow \infty} W_t \geq W^T,$$

$$L_0 = L,$$

$$\forall t \in \infty.$$

To solve this problem we assume that there is a variable  $y$  such that,

$$y_t = \frac{R_t}{\varphi E_t},$$

$$y_t \in [0,1]$$

The Hamiltonian associated with (4.3.19) is:

$$H = \left( P_t^{wr} E_t - P_E f(W_t) E_{1,t} - C(y_t \varphi E_t) - P_I (E_t - E_{1,t})^\lambda \right) + \eta_t (W_t + y_t \varphi E_t + \bar{R} - E_{1,t}), \quad (4.4.20)$$

and the first order necessary conditions include,

$$\frac{\partial H}{\partial E_t} = P_t^{wr} - \frac{\partial C(R_t)}{\partial R_t} y_t \varphi - \lambda P_I (E_t - E_{1,t})^{\lambda-1} + \eta_t y_t \varphi = 0, \quad (4.4.21)$$

$$\frac{\partial H}{\partial E_{1,t}} = -P_E f(W_t) + \lambda P_I (E_t - E_{1,t})^{\lambda-1} - \eta_t = 0, \quad (4.4.22)$$

$$\frac{\partial H}{\partial y_t} = -\frac{\partial C(R_t)}{\partial R_t} \varphi E_t + \eta_t \varphi E_t = 0, \quad (4.4.23)$$

$$\rho \frac{\partial H}{\partial W_t} = \left[ -P_E \frac{\partial f(W_t)}{\partial W_t} E_{1,t} \right] \rho + \eta_t \rho = \eta_{t-1}, \quad (4.4.24)$$

Once again, these conditions are both necessary and sufficient because the objective function is convex and constraints are concave—although the latter is true if and only if population changes are smooth and population growth is lower than the rate of discount, and the transversality condition is satisfied<sup>26</sup>. Then, there are optimal sequences  $(\{W^*\}, \{Y_t^*\}, \{E_t^*\}, \{E_{1,t}^*\}, \{R_t^*\})$  that solve the problem (4.4.19) and a sequence  $\{\eta_t\}$  for  $t \in [0, \infty)$  such that the following equations are satisfied,

$$\frac{\partial H}{\partial y} (t, W_t^*, y_t^*, E_t^*, E_{1,t}^*, R_t^*, \eta_t) = 0, \quad \forall y \in [0, 1]$$

$$\frac{\partial H}{\partial E_t} (t, W_t^*, y_t^*, E_t^*, E_{1,t}^*, R_t^*, \eta_t) = 0, \quad \forall E_t^* \in [0, \infty)$$

$$\frac{\partial H}{\partial E_{1,t}} (t, W_t^*, y_t^*, E_t^*, E_{1,t}^*, R_t^*, \eta_t) = 0, \quad \forall E_{1,t}^* \in [0, \infty)$$

$$\frac{\partial H}{\partial R_t} (t, W_t^*, y_t^*, E_t^*, E_{1,t}^*, R_t^*, \eta_t) = 0, \quad \forall R_t^* \in [0, \infty)$$

$$\rho \frac{\partial H}{\partial W} (t, W_t^*, y_t^*, E_t^*, E_{1,t}^*, R_t^*, \eta_t) = \eta_{t-1}, \quad \forall t \in [0, \infty)$$

Rewriting and organizing these conditions we have the following:

---

<sup>26</sup> The transversality condition is,  $\lim_{t \rightarrow \infty} n_t (W_t - W^T) \geq 0$ .

$$P_t^{wr} = \lambda P_t (E_t - E_{1,t})^{\lambda-1}, \quad (4.4.25)$$

$$P_E f(W_t) + \frac{\partial C(R_t)}{\partial R_t} = \lambda P_t (E_t - E_{1,t})^{\lambda-1}, \quad (4.4.26)$$

$$\frac{\partial C(R_t)}{\partial R_t} = \eta_t, \quad (4.4.27)$$

$$\left[ -P_E \frac{\partial f(W_{t+1})}{\partial W_{t+1}} E_{1,t+1} \right] \rho + \frac{\partial C(R_{t+1})}{\partial R_{t+1}} \rho = \eta_t, \quad (4.4.28)$$

These conditions must hold along the optimal trajectory.

The difference between these conditions and the previous ones is that the marginal cost of recharge is equal to shadow cost.

When the planning horizon is infinite,  $T=\infty$ , the economy reaches a positive steady state because the price is equal to marginal cost of supplying water which is a convex function with a first derivative and covers the total cost (see conditions (4.2.10) and (4.2.15)).

## WELFARE

As in the previous section, it was shown that: (1) the utility will manage the aquifer efficiently by taking into account not only the scarcity rents but also internalizing the “social user cost” of ground water consumption (Provencher and Burt (1993)); (2) the profit maximization solution minimizes the cost of providing water along the planning horizon; (3) finally, given that the optimal water tariff is equal to marginal cost of supplying water, the economy reaches a positive steady state.

We claim that the private utility's solution will maximize social welfare and result in a positive steady state when the planning horizon is infinite. So the best strategy to maximize the social welfare and reach a positive steady state is setting prices equal to marginal cost.

## SECTION V

### CONCLUSIONS

The model used in this chapter describes an economy that depends on foreign investment for economic growth. The comparative advantage of the economy rests in its low wages, which are a function of the cost of supplying water among other things (e.g. labor productivity). Given that water sources are limited, the cost of supplying water is increasing in the level of employment. So, comparative advantage will be lost gradually as workers migrate to Ciudad Juarez looking for better economic opportunities. We show that Ciudad Juarez will converge to a stable steady state with positive levels of employment and capital given that the water tariff covers in each period the total cost of supplying water and it is smooth increasing function. This conclusion applies both to the water autarky model and to the water imports model<sup>27</sup>.

We also show that by implementing the water tariff derived from the profit maximization problem over an infinite horizon, real wages (and hence social welfare) will be at a maximum for any given level of employment.

If the only source of water is an aquifer, we show that the optimal water management strategy includes a sequence of water prices equal to the marginal cost of supplying water along with a planning horizon, and that this maximizes real wages without jeopardizing the groundwater stock in the long run.

---

<sup>27</sup> This result can be extended to a situation where Ciudad Juarez can import water from elsewhere, if the cost of importing water is increasing and the prices cover the total cost.



If water imports are possible, the sustainability of Ciudad Juarez will be constrained by the relative cost of importing water in terms of pumping groundwater. It is optimal use groundwater and to price water equal to the marginal cost of supplying water.

There are three main lessons derived from this chapter that can be applied to places with limited surface and ground water resources: (1) that prices should take into account the water scarcity and investment in water infrastructure and operation; (2) that water reclamation and recharge is an efficient option for enhancing groundwater-constrained economic growth; and (3) that safe yield may be implemented efficiently.

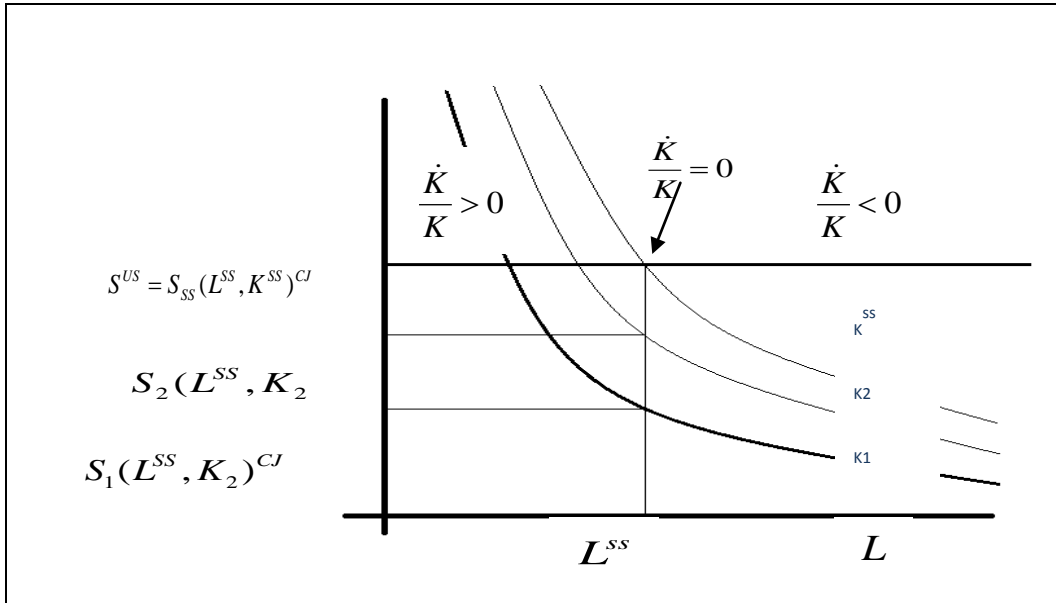


Figure 10. Behavior of the dynamic equation for the capital stock.

Notes. This figure represents the behavior of the dynamic equation for the capital stock when the number of workers in the economy and the U.S. wage rate are both constant.

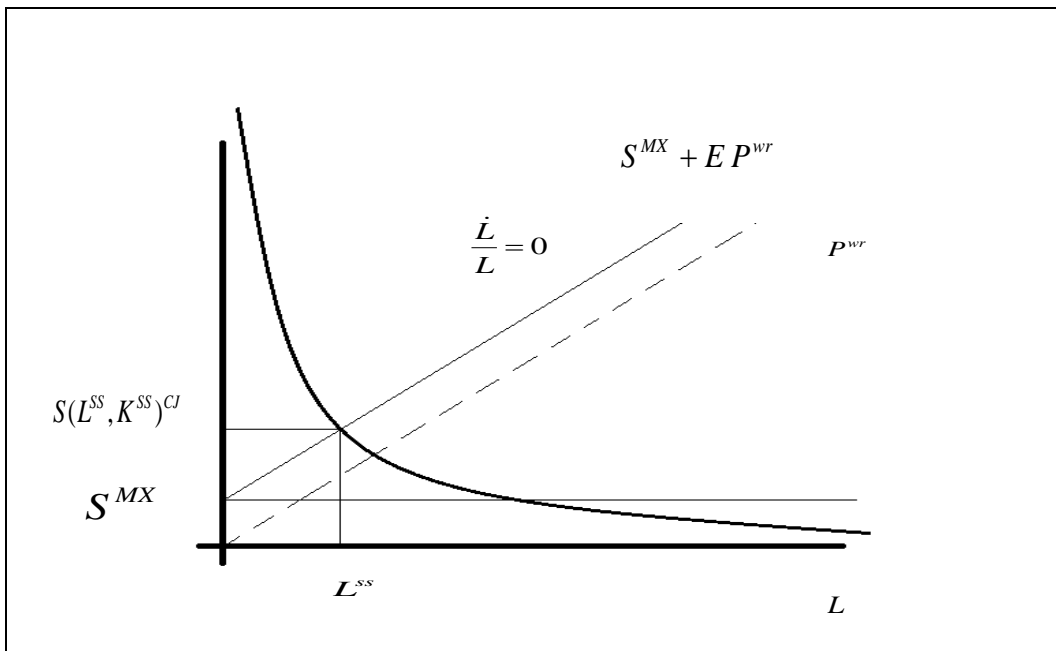


Figure 11. Behavior of the dynamic equation for the population.

Notes. This figure depicts the behavior of the dynamic equation for the population when the capital is constant over time.

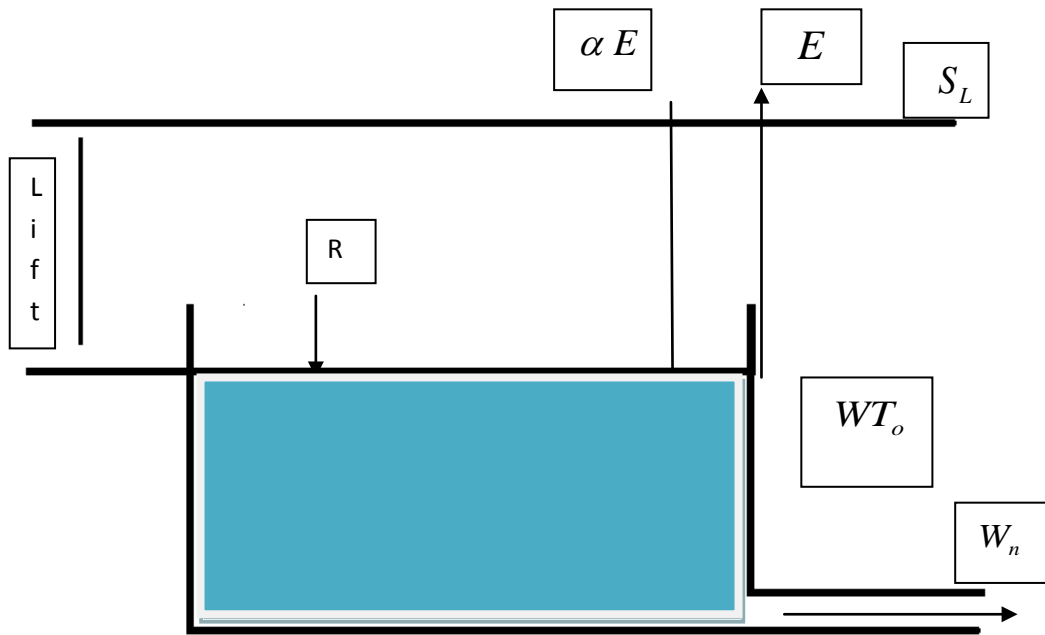


Figure 12. Ground water model.

Notes. This figure represents the aquifer model used in this dissertation.

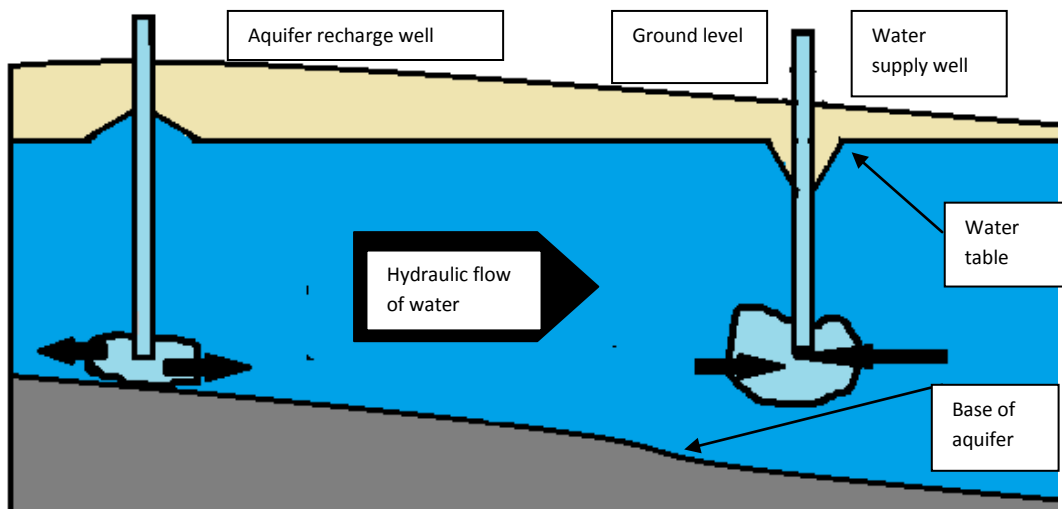


Figure 13. Ground water recharge model. *Notes.* This figure represents the ground water recharge model used in this dissertation (adapted from Bloetscher *et al.* (2005)).



Figure 14. Recharge trajectories. *Notes.* This figure depicts the optimal recharge trajectories when the price of extraction is 15 and 5 given that the natural rate of recharge is constant.

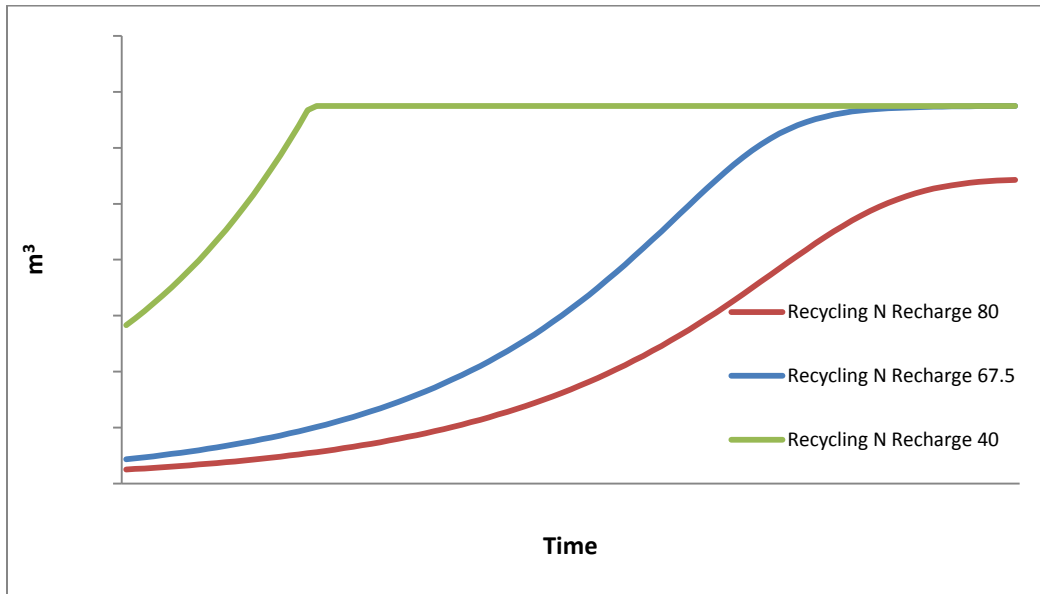


Figure 15. Recharge trajectories. *Notes.* This figure depicts the optimal recharge trajectories when the natural rate of recharge varies from 80, 67.5, to 40 m<sup>3</sup> given that price of extraction is equal to 15.

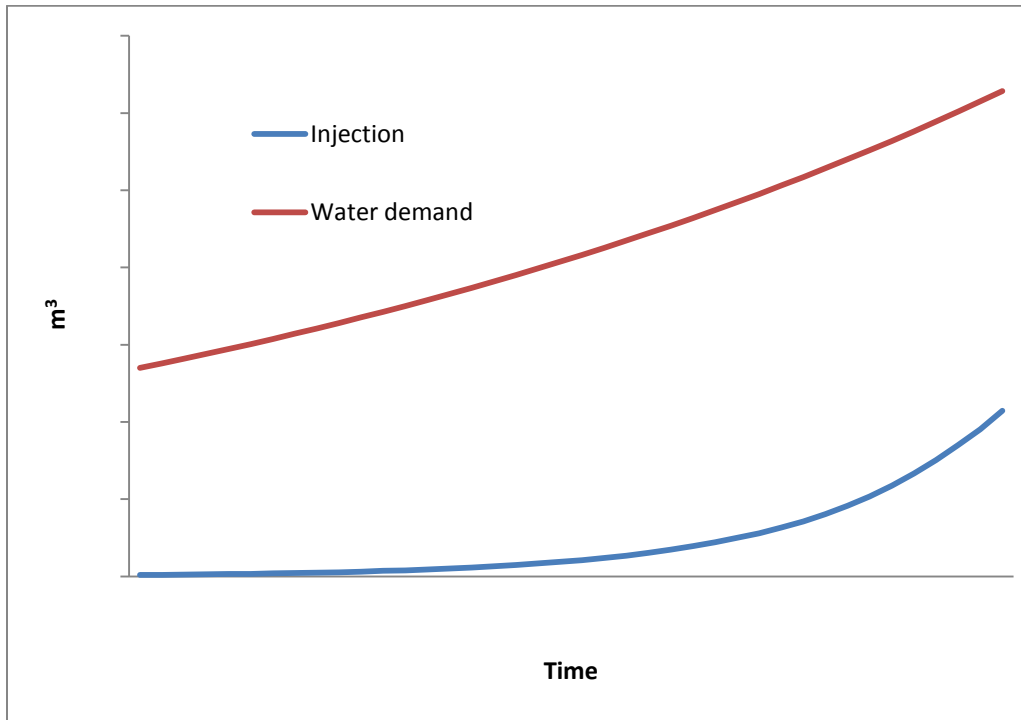


Figure 16. Recharge trajectories. *Notes.* This figure depicts the optimal artificial recharge trajectory given that the natural rate of recharge is constant.

## CHAPTER 5

### MODEL ANALYSIS

#### INTRODUCTION

This dissertation is motivated by the fact that Ciudad Juarez, like most of the Mexican cities located on the U.S.-Mexican border, faces water scarcity problems. As economic growth continues, increasing demand for finite stocks of water will aggravate those problems. Hence, the problem for Ciudad Juarez and the region is to implement an efficient, equitable and *sustainable* strategy for the management of the water resources. Efficient prices are an essential part of such a strategy. In Chapter 4 we showed that by implementing the optimal price mechanisms the cost of providing water could be minimized in a sustainable way. In this chapter we discuss two models, one that deals with a situation where Ciudad Juarez depends only on the Bolson del Hueco aquifer to meet its water demand. The other model assumes that the economy can meet its water demand either by extracting water or importing water.

The objective of this chapter is to understand how these water regimes work when Ciudad Juarez faces a range of costs, water demand levels, planning horizons, and recharge capabilities. The parameters were calibrated using data from the national bureau of statistics of the Mexican government (INEGI) and the literature. Contrary to assumptions of the last chapter, population growth is now assumed to be constant (i.e. it is not dependent only the real wage differential). We calibrate population growth on information obtained from both the Mexican government and literature. The assumption of constant population growth leads to non-convexities, compromising the

results of the last chapter—that a profit maximizing water utility will maximize the real wage for any given level of employment when the planning horizon is infinite. Therefore, some type of government intervention might be needed. The reason for adding the assumption of constant population growth is to capture the fact that there is a positive (natural) rate of increase in the resident population of Ciudad Juarez. We believe that this enriches the conclusions of the dissertation by exploring the implication of the model when migration is not the only source of population growth. We use the simulation software developed by Frontline Systems to model both water regimes to deal with the non-convexities associated with the calibration.

It is important to make the following clarification with respect to our measure of welfare. Individual welfare is measured by the difference in the real (disposable) income received in Ciudad Juarez and the average real wage received elsewhere in Mexico. That is, it is a relative measure of welfare. If this measure is positive then the individual worker is better off by working in Ciudad Juarez than elsewhere in Mexico. In particular, the representative worker will be better off by the amount equal to (see Chapter 4).

$$\left( \frac{S_t^{CJ} - S^{MX}}{E} - P(W_t, R_t)^{wr} \right) E > 0.$$

However, when it is negative, the representative worker is *losing money* by working in Ciudad Juarez. This amount is equal to,

$$\left( \frac{S_t^{CJ} - S^{MX}}{E} - P(W_t, R_t)^{wr} \right) E < 0.$$



This chapter consists of five sections. The first three focus on the closed (autarkic) water management regime. The first section calibrates the autarky model and illustrates the steady state population levels for different recharge capabilities.

The second examines how the optimal recharge trajectory changes when relative costs, recharge capabilities, and the planning horizon vary. The third analyzes how welfare depends on costs and the planning horizon. In particular, this section analyzes the relationship between relative costs—i.e. the relation between extraction and recharge costs —and welfare levels. In addition, we explain the relationship between the planning horizon and welfare levels.

Section four analyzes the open water regime. In particular, we examine how the importing and pumping trajectories are affected by changes in relative costs. Moreover, we show how population and welfare levels behave when the water tariffs vary. The last section presents a set of conclusions.

## SECTION I

### WATER AUTARKY

In this section, we calibrate the autarkic water management regime, and show the steady state population levels associated to different recharge capabilities. The analysis starts in 1996 with a population level equal to 1,033,944 and population growth rate equal to 2.19% (PNWTF (2001))<sup>28,29</sup>. Wages in Ciudad Juarez are bounded from below by the expected probability of finding a job in a Maquildora plant, and from above by international competition which, for convenience we refer to as competition with Brazil.

The fresh groundwater stock in 1996 was equal to 738 Mm<sup>3</sup> (see Chapter 3), and we assume that in the long run the economy must end with a groundwater stock equal to 184.5 Mm<sup>3</sup> (i.e.,  $W^T = 184.5$ ), or the 25% of the initial fresh groundwater level. That is, the “sustainability target” adopted by the planning authority equal to 184.5 Mm<sup>3</sup>. This may be interpreted as the minimum fresh groundwater required to protect Ciudad Juarez from future climatic variability. As it was stated in Chapter 3, the estimated water recharge is 49.3 Mm<sup>3</sup> (this includes the water pumped and recharged by El Paso). Furthermore, on average each inhabitant consumes 115.92 m<sup>3</sup> per year<sup>30</sup>.

We assumed in Chapter 4 that the groundwater extraction cost function has the following form (using (4.1.7)):

---

28 In 1995, Ciudad Juarez had 1,011,786 inhabitants (see Chapter 3). Then, with a population growth rate of 2.19%, the population level in 1996 is 1,033,944.

29 According to the El Paso del Norte Task Force by 2020 there will be 2,517,708 inhabitants in Ciudad Juarez with a population growth rate of 2.19% (PNWTF (2001)).

30 We are assuming that the daily consumption of water in Ciudad Juarez was equal to the 1999 level, which was equal to 322 liters (see Chapter 3).

$$C(E(t)) = P_E f(W(t)) E(t) = \frac{P_E E(t)}{(W(t))^\phi}, \quad (5.1.0)$$

where  $W(t)$  is the volume of groundwater. The parameter  $\phi$  reflects how fast the pumping cost increases and it takes only positive values.  $P_E$  is a constant that includes the costs of well reparation and wages and electricity (e.g., the operational and maintenance costs).

The cost of extraction function is convex because as the groundwater stock diminishes it becomes polluted with brackish water, and also because extraction costs increase as the groundwater level decreases.

According to Turner *et al.* (2003) the groundwater production costs for EPWU (El Paso Water Utilities) was \$0.10 per cubic meter in real terms in 1995—this includes pumping and well replacement costs. Thus, the cost for extraction at time  $t$  is, t

$$C(E(t)) = \frac{P_E E(t)}{(W(t))^\phi} = \frac{(0.10)(738 * 10^6)^\phi E(t)}{W(t)^\phi}. \quad (5.1.1)$$

Recharge costs depend on the type of technology implemented (e.g., recharge well or basin recharge), the quality of water recharged (e.g., primary or advanced secondary wastewater treatment), and location of the recharge facilities (Bloetscher *et al.* (2005), Sheng (2005b)). The recharge cost is represented as follows (see Chapter 4),

$$C(R(t)) = P_R R(t)^\gamma, \quad (5.1.2)$$

the parameter  $\gamma$  measures the increase in recharge costs when an additional unit is recharged in the aquifer. This parameter is higher than one.  $P_R$  represents the price of

one cubic meter of water. The price of reclaimed water in El Paso was 0.33 Dollars in 2010 (EPWU (2010)). We are going to use this price as a substitute for  $P_R$ . In Dollars of 1996 this price is equal to \$0.241<sup>31</sup>, implying that (4.1.3) is equal to:

$$C(R(t)) = 0.241 R(t)^\gamma \quad (5.1.3)$$

In the case of wages, we assume that wages in Ciudad Juarez are bounded from above by the competition with Brazil and from below by average wages elsewhere in Mexico. The reference to Brazil reflects the fact that Brazil is the main rival of Mexico in the region for production of commodities of the type manufactured in the Mexican maquiladoras (Dussel (2007))<sup>32</sup>.

We further assume that the expected wage to migrants to Ciudad Juarez is the expected probability of having a job in a Maquiladora plant<sup>33</sup>, multiplied by the wage paid in a Maquiladora plant plus the average remuneration received in Mexico multiplied by the probability of not finding a job in the Maquiladora industry. That is,

*(Maquiladora wage)(Probability of finding a job in the maquiladora industry)+(Average remuneration in Mexico)(Probability of not finding a job in the maquiladora industry)=Expected wage in Ciudad Juarez.*

According to the Bureau of Labor Statistics (BLS (2009)), the hourly compensation costs for production workers in manufacturing in 1996 for Mexico and

---

<sup>31</sup> We are using the CPI from the BLS (2010).

<sup>32</sup> We can add that data availability is much better for Brazil than for other countries that compete with Mexico.

<sup>33</sup> We assume that there are no price differences between Ciudad Juarez and the other Mexican cities but in the price of water.

Brazil were 1.58 and 5.76 U.S. Dollars, respectively<sup>34,35</sup>. The monthly average remuneration in Mexico was 290.34 U.S. Dollars for the same year<sup>36</sup>.

In Chapter 3 we saw that 46% of total workers were employed in the maquiladora industry. Hence, the probability of having a job in a maquiladora plant is equal to 0.46.

Hence, the maximum possible wage in Ciudad Juarez, if wages in the Maquiladoras were driven to equality with those in Brazil, would be:

$$(\$1,105.92)(0.46) + (\$290.34)(0.54) = \$665.5. \quad (5.1.4)$$

In fact, the monthly expected wage in Ciudad Juarez, when wages are determined by actual wages in the Maquiladora industry (the *status quo* hereafter), is

$$(\$303.36)(0.46) + (\$290.34)(0.54) = \$296.2. \quad (5.1.5)$$

Therefore, using condition (4.3.13), we have that the maximum willingness to pay for water if wage rates were driven to equality with Brazil, would be:

$$(\$1,105.92)(0.46) + (\$290.34)(0.54) - \$290.34 = \$375.16, \quad (5.1.6)$$

and for the status quo,

---

<sup>34</sup> To obtain the monthly value we multiply first the salary per hour by eight hours and then multiplied by 24 to obtain the monthly remuneration.

<sup>35</sup> For the Bureau of Labor Statistics the Hourly compensation costs include (1) hourly direct pay and (2) employer insurance expenditures and other labor taxes (BLS (2009)).

<sup>36</sup> The average remuneration in Mexico was 79,500 Pesos in 2004 (INEGI, 2004). We converted this amount into Pesos of 1996 using the CPI provided by the Banco de México (Banco de México (2010)). This amount is converted into U.S. Dollars of 1996 (IMF (2010)).

$$(\$303.36)(0.46) + (\$290.34)(0.54) - \$290.34 = \$5.9. \quad (5.1.7)$$

The water tariff implemented is equal to the marginal cost of extraction and recharge as it was stated in Chapter 4. That is,

$$P(t)^{WR} = P_E f(W_t) E + \gamma P_R (R_t)^{\gamma-1} \left( \frac{R_t}{L_t} \right). \quad (5.1.8)$$

#### STEADY STATES

In the next part of this section we derive the steady state population levels corresponding to different recharge capabilities (these are illustrated in Table 8). After, we show the parameters associated to some of these steady state population levels.

We show in the tables 9 and 10, the associated values  $\phi^*$  and  $\gamma^*$  for the steady state values when  $\phi$  equals 78%, 72%, and 65%. Table 9 depicts the case when wages are determined by Brazil. Table 10 depicts the case when wages are at current levels<sup>37</sup>.

The parameters  $\phi$  and  $\gamma$  are defined in the following intervals: (0, 4.4) and (1,2.5), respectively<sup>38</sup>. However, for some  $\phi$ , the steady state is not defined for higher or lower values.

The information from Tables 9 and 10 will be used in the next two sections to run sensitive analysis and policy experiments.

---

<sup>37</sup> In the Appendix B, we show how to derive the steady state values.

<sup>38</sup> These values are valid for population values higher than one person.

## SECTION II

### WATER AUTARKY: SENSITIVITY ANALYSIS

In this section we examine how the relative cost of extraction, the planning horizon, recharge capability, and the sustainability target affect the optimal recharging/recharge trajectory.

We analyze five cases taking the case where wages are at the highest possible level (set by the competition with Brazil), and therefore when population stress on the resource is at a maximum. For all these six cases, population grows continuously (e.g., the time horizon in each case is chosen to allow population growth). In the next section we deal with negative population growth. We present these cases in Table 11:

It is important to notice that relative costs depend on the recharge and extraction technology—i.e.,  $\phi$  and  $\gamma$ , the groundwater stock, the amount of water recharged, and the operational and maintenance costs. Relative costs are manipulated in this chapter by varying the technological parameters  $\phi$  and  $\gamma$ .

These five cases cover a range of possibilities and give us a good understanding of the role of recharging/recharge at high levels of stress on the system.

For each case we illustrate with two figures the recharge and groundwater stock trajectories along the planning horizon.

#### CASE 1: THE COST OF WATER RECHARGE IS 'LOW'

In this case the initial opportunity cost of recharging is lower when  $\phi$  equals 0.5 than when  $\phi$  equals 3. In Figure 17 we see that it is optimal to recharge lower amounts of

water in the first few periods when  $\phi$  equals 0.5. This is because the relative cost is lower when  $\phi$  equals 0.5. As a result, the groundwater level decreases at a higher rate, which leads to higher relative extraction cost. This is shown in Figure 18. Hence, the economy starts to recharge higher amounts of water than when  $\phi$  equals 3—around the period 20 of the simulation (see figures 17 and 18).

As stated in Chapter 4, the recharging/recharge trajectories are determined by both the relative cost of pumping groundwater and by the final groundwater stock  $W^T$ . Therefore, when  $\phi$  equals 0.5 the utility has to recharge even more water in the latter periods because the groundwater level is lower than  $W^T$ . Whereas, when  $\phi$  equals 3, the economy decreases the amount of water recharged in the latter periods given that the groundwater stock is higher than  $W^T$ . In the final period, we see that in both cases the groundwater level is driven to the target minimum,  $W^T$ .

#### CASE 2: THE COST OF WATER ABSTRACTION IS 'HIGH'

This time we reduce  $\gamma$  from 1.2564 to 1.247 leaving the rest of parameters unchanged (i.e.,  $\phi=3$ ,  $\varphi=80\%$ ,  $W^T=185.5 \text{ Mm}^3$ , planning horizon=35 years). This increases the relative extraction cost from  $3/1.2564$  to  $3/1.247$ . As a consequence, the utility will optimally recharge more water in the initial periods when  $\gamma$  equals 1.247, we illustrate this in Figure 19.

As before, the groundwater level will decrease resulting in higher relative extraction costs (see Figure 20). This will, in turn, lead the utility to increase the water recharged. In particular, the utility recharges more water when  $\gamma$  equals 1.2564 because



the groundwater reaches lower levels in this case (see Figure 20). In the later periods recharge trajectories decrease because the groundwater levels are higher than  $W^T$ .

It is worth noticing that recharge trajectories in this case are closer to each other than in Case 1. This is because the difference in the relative costs is smaller in this case. Moreover, in both cases the groundwater level is higher than  $W^T$  for all periods.

#### CASE 3: THE PLANNING HORIZON IS 'SHORT'

We want see how the model behaves when the planning horizon is reduced—i.e., 20 periods instead of 35—using the same parameters as in Case 1. Figure 23 shows the difference between optimal water recharge trajectories for cases 1 and 3 through time. We see in this figure that in the first few periods recharge trajectories are very similar in the two cases. However, in later periods the utility recharges more water in Case 3 than in Case 1 when  $\phi$  equals 0.5. This is because it has less time to satisfy the “sustainable” groundwater level  $W^T$  (in Figure 22 we see that the groundwater level is almost zero when  $\phi$  equals 0.5). When  $\phi$  equals 3, the utility recharges less water in later periods in Case 3 than in Case 1. This is because the groundwater level is higher than in Case 1. In other words, because there are more periods to reach the “sustainable” groundwater level  $W^T$  in case 1, the utility slows water recharge in that case. In conclusion, when the planning horizon is longer, and when the sustainability target is a restriction on the terminal value of stocks and not the current value of stocks, the utility is able to smooth the recharge trajectory over the whole planning horizon.

#### CASE 4: THE PLANNING HORIZON IS 'LONG'

We aim in this case to analyze how the recharge trajectory changes when  $\phi$  decreases from 80% to 70% leaving the rest of parameters the same (i.e.,  $\phi=3$ ,  $\gamma=1.2564$ ,  $W^T=185.5$   $\text{Mm}^3$ , planning horizon=35 years). In Figure 24, we observe that when  $\phi$  equals 70% the utility recharges higher amounts of water in the first few periods than when  $\phi$  equals 80%. This is explained by the fact that the utility needs to recharge water as much as possible when  $\phi$  equals 70% to satisfy the water demand and to reach the groundwater level  $W^T$  at the end of the planning horizon.

Given that the utility recharges less water when  $\phi$  equals 80% in the first periods, the groundwater level reaches lower levels. Thus, the relative extraction cost increases causing higher recharge around period 20.

In later periods, the utility reduces the water recharged because the groundwater level is higher than the minimal level required  $W^T$  when  $\phi$  equals 80%. But when  $\phi$  equals 70% the utility cannot reduce the recharge levels even when the groundwater stock is higher than  $W^T$ ; if the utility reduces the amount of water recharged, it will not meet the water demand (see Figure 25)

#### CASE 5: THE SUSTAINABILITY TARGET IS REDUCED

In this last case, we compare two recharge trajectories: one constrained by a sustainability target,  $W^T$  not less than 185  $\text{Mm}^3$ , and the other with no sustainability target, i.e.,  $W^T$  is constrained only be non-negative. The rest of parameters are unchanged (i.e.,  $\phi=3$ ,  $\gamma=1.2564$ ,  $\phi =80\%$ , planning horizon=35 years). Under these conditions we notice that recharge and groundwater trajectories are equal except in the

final periods (see figures 26 and 27). This is because, in the absence of a sustainability target, it is optimal to exhaust the resource when  $W^T \geq 0$ .

We can summarize this section in the following four points:

- 1) The relative extraction cost of ground water in terms of recharge determines the amount of water optimally recharged by the utility, given everything else equal. If the relative extraction costs of ground water at the period zero are high, the utility will recharge more water in the first periods than when the relative extraction costs are low.
- 2) The recharge capability plays an important role on the optimal recharge trajectory. It is showed that the utility will recharge more water in the first periods as the recharge capability is reduced. This is because the lower the recharge capability, the less flexibility the utility has to meet sustainability target,  $W^T$ , at the end of the period.
- 3) The planning horizon also affects the optimal recharge trajectory. We conclude that if the planning horizon increases the utility can smooth out the amount of water recharged through the planning horizon.
- 4) The optimal recharge trajectory is strongly affected by the sustainability target. As  $W^T$  decreases, the utility will reduce the water optimally recharged in later periods to reach  $W^T$ . However, recharge trajectories may not be affected over the rest of the planning horizon.
- 5) Finally, the results coincide with those presented in the last chapter.

## SECTION III

### WATER AUTARKY: COSTS AND WELFARE

The objective of this section is to understand the impact of relative costs and planning horizons on the welfare levels. In Chapter 4 we saw that the utility maximizes the social welfare when the planning horizon is infinite and the water tariffs are equal to marginal costs. However, this conclusion might not be valid, given non-convexities that can be derived from assuming constant population growth rates.

We show that costs affect the social welfare in two ways: directly by increasing the total cost of supplying water; and indirectly by affecting the transition to the steady state. The latter effect is a direct consequence of the non-convexities derived from the constant population growth rate.

In tables 12 and 13 we present the welfare levels associated with different planning horizons and parameter vectors when wages are determined by Brazil. These tables report nine cases, each consisting of different vector of parameters  $(\varphi^*, \phi^*, \gamma^*)$ . These vectors are associated with the different steady states that correspond to Table 9.

In tables 14 and 15 we present welfare levels associated with different planning horizons and parameter vectors when wages are determined by the status quo. These tables are divided in three cases, each consisting of different vector of parameters  $(\varphi^*, \phi^*, \gamma^*)$ . These vectors are associated with different steady states that correspond to Table 10.

### DIRECT IMPACTS ON WELFARE

We consider, first, the direct effect of costs on the welfare (ignoring for the moment differences in the length of the planning horizon), and taking the case where wages are at a maximum (see tables 12 and 13).

When we compare two parameter vectors with same recharge costs but different extraction costs, we see that welfare will be higher the lower the cost of extraction. This explained by the following argument: We know from the last section that the utility will optimally recharge more water in the early periods if the relative cost of extraction is high. As a consequence, social welfare will be lower given that the utility uses more resources for recharge. So what determines welfare levels in this case is the relative extraction cost at time zero (e.g.,  $\phi/\gamma$ ).

This argument explains the following parameter order in terms of welfare in Table 12 for planning horizon equal to 55 years:  $(\phi=0.1, \gamma=1.267, \phi/\gamma=0.08) > (\phi=0.5, \gamma=1.267, \phi/\gamma=0.4) > (\phi=1, \gamma=1.266, \phi/\gamma=0.8) > (\phi=1.5, \gamma=1.266, \phi/\gamma=1.18) > (\phi=2, \gamma=1.265, \phi/\gamma=1.58)$ ; and, the parameter order in Table 13:  $(\phi=0.1, \gamma=1.277, \phi/\gamma=0.08) > (\phi=0.5, \gamma=1.277, \phi/\gamma=0.4) > (\phi=1, \gamma=1.276, \phi/\gamma=0.8) > (\phi=1.5, \gamma=1.276, \phi/\gamma=1.17) > (\phi=2, \gamma=1.275, \phi/\gamma=1.57) > (\phi=2.5, \gamma=1.272, \phi/\gamma=2)$ . In all these cases, we see that as the relative extraction cost increases, the welfare decreases (in all these vectors the recharge costs,  $\gamma$ , is almost constant).

This argument can be better understood using a particular example. The parameter vectors  $(\phi=1.5, \gamma=1.266, \rho=78.74\%, \phi/\gamma=1.185)$  and  $(\phi=0.1, \gamma=1.267, \rho=78.74\%, \phi/\gamma=0.0789)$  are associated with the welfare levels, after 55 years, equal to 29,315.7 and 31,340.2, respectively (see Table 12). In figures 28 and 29 we describe the recharge and welfare trajectories for both parameter vectors, respectively. These

figures are divided in two regions: Region A illustrates the time period at which the welfare level is higher for the second parameter vector (from 1996 to 2006). The second, B, describes the interval over which the second parameter vector obtains more welfare (from 1996 to 2027).

In Figure 28 we see that the utility recharges less water in part A when  $\phi$  equals 0.1 because the relative extraction cost is lower. As a result, welfare levels are higher in region A when  $\phi$  equals 0.1, Figure 29.

In region B the previous situation is inverted. Now, the utility starts recharging higher amounts of water when  $\phi$  equals 0.1, which reduces the welfare level (see Figure 29). While, when  $\phi$  equals 1.5 the utility reduces the amount of water recharged, which translates into higher welfare levels (see Figure 29).

When we sum the real wage differentials of regions A and B, we find that real wage differentials are higher for the second parameter because: (1) the difference between the real wage differential trajectories in the first region are higher than in the second; (2) given that the social welfare is in present value, the region B has lower weight in the total welfare level.

However, this claim might not hold if two parameter vectors have different recharge costs. For example, the welfare levels for the parameter vectors ( $\phi=0.5$ ,  $\gamma=1.267$ ,  $\varphi=78.74\%$ ,  $\phi/\gamma=0.4$ ) and ( $\phi=4$ ,  $\gamma=1.213$ ,  $\varphi=78.74\%$ ,  $\phi/\gamma=3.3$ ) are, after 55 years, 31,236.40 and 37,014.20, respectively. The second parameter vector has higher relative extraction cost but yields higher welfare. We represent the recharge, real wage differentials, and groundwater trajectories for these parameter vectors in figures 30, 31, and 32, respectively. As before, we divide each figure in two regions, A and B.

In region A the welfare level is lower for the second parameter vector, as it illustrated in Figure 31, because the utility recharges higher amounts of water (see Figure 30). In addition, extraction costs are higher (shown in Figure 32).

In region B the welfare level is higher for the second parameter vector as shown in Figure 31. On top of that, the difference between the welfare trajectories is also higher. This is because the utility recharges lower amounts of water and the pumping cost is lower—this is because the groundwater level is higher, see Figure 32—than for the first parameter vector.

Given that region B covers a longer period, and that the real wage differential between both trajectories is larger than region A—even when this part is discounted at higher rate of discount, total welfare is larger for the second parameter vector.

Hence, if the recharge cost is low enough, it can compensate for the relative extraction cost effect. This explains why in Table 12 there is the following order with respect to real wage differentials :

$(\phi=4, \gamma=1.21, \phi/\gamma=3.3) > (\phi=3.5, \gamma=1.24, \phi/\gamma=2.82) > (\phi=0.1, \gamma=1.267, \phi/\gamma=0.08) > (\phi=0.5, \gamma=1.267, \phi/\gamma=0.4) > (\phi=1, \gamma=1.266, \phi/\gamma=0.8) > (\phi=1.5, \gamma=1.266, \phi/\gamma=1.18) > (\phi=2, \gamma=1.265, \phi/\gamma=1.58),$

and,

$(\phi=0.1, \gamma=1.267, \phi/\gamma=0.08) > (\phi=0.5, \gamma=1.267, \phi/\gamma=0.4) > (\phi=1, \gamma=1.266, \phi/\gamma=0.8) > (\phi=1.5, \gamma=1.266, \phi/\gamma=1.18) > (\phi=3, \gamma=1.258, \phi/\gamma=2.38) > (\phi=2.5, \gamma=1.263, \phi/\gamma=2) > (\phi=1.5, \gamma=1.266, \phi/\gamma=1.185) > (\phi=2, \gamma=1.265, \phi/\gamma=1.6).$

That is, the vectors  $(\phi=4, \gamma=1.21, \phi/\gamma=3.3)$  and  $(\phi=3.5, \gamma=1.24, \phi/\gamma=2.82)$  are associated with higher real wage differentials than other vectors even though they have high relative extraction costs.

For Table 13 we have the order:

$(\phi=4, \gamma=1.22, \phi/\gamma=3.27) > (\phi=3.5, \gamma=1.256, \phi/\gamma=2.8) > (\phi=0.1, \gamma=1.277, \phi/\gamma=0.08) > (\phi=0.5, \gamma=1.277, \phi/\gamma=0.4) > (\phi=1, \gamma=1.276, \phi/\gamma=0.8) > (\phi=1.5, \gamma=1.276, \phi/\gamma=1.17) > (\phi=2, \gamma=1.275, \phi/\gamma=1.57) > (\phi=3, \gamma=1.268, \phi/\gamma=2.365) > (\phi=2.5, \gamma=1.272, \phi/\gamma=2)$ .

In this case, the vectors  $(\phi=4, \gamma=1.22, \phi/\gamma=3.27)$  and  $(\phi=3.5, \gamma=1.256, \phi/\gamma=2.8)$  have the highest welfare levels and the lowest recharge costs.

#### INDIRECT IMPACTS ON WELFARE

Real wage differentials are also affected by relative prices and by the assumption of constant population growth rate independent of the wage rate. When the relative extraction cost is low at the initial period (i.e.,  $\phi/\gamma$  lower than 1.3), real wage differentials rise at a decreasing rate as the planning horizon increases. In this case, the regulator does not need to set a terminal period because the water utility minimizes water supply costs (and hence maximizes real wages) at the safe yield. However, if the relative extraction cost is high at the initial period (i.e.,  $\phi/\gamma$  higher than 1.3), welfare levels will decrease at some point for planning horizons larger than 30 years, and the regulator needs to implement a sustainability target.

This argument can help us to understand why in tables 12 and 13 we have that:



- (1) for the parameter vectors ( $\phi=4, \gamma=1.213, \phi/\gamma=3.3$ ), ( $\phi=3.5, \gamma=1.247, \phi/\gamma=2.8$ ), ( $\phi=3, \gamma=1.25, \phi/\gamma=2.4$ ), ( $\phi=2.5, \gamma=1.26, \phi/\gamma=2$ ), and ( $\phi=2, \gamma=1.26, \phi/\gamma=1.6$ ) of the Table 12, and the parameter vectors ( $\phi=4, \gamma=1.22, \phi/\gamma=3.27$ ), ( $\phi=3.5, \gamma=1.25, \phi/\gamma=2.8$ ), ( $\phi=3, \gamma=1.26, \phi/\gamma=2.3$ ), ( $\phi=2.5, \gamma=1.27, \phi/\gamma=1.96$ ), and ( $\phi=2, \gamma=1.275, \phi/\gamma=1.56$ ) of Table 13, the real wage differentials decrease for planning horizons longer than 55 years.
- (2) for the parameter vectors ( $\phi=0.1, \gamma=1.26, \phi/\gamma=0.08$ ), ( $\phi=0.5, \gamma=1.26, \phi/\gamma=0.4$ ), ( $\phi=1, \gamma=1.26, \phi/\gamma=0.8$ ), and ( $\phi=1.5, \gamma=1.266, \phi/\gamma=1.18$ ) of the Table 12 and the vectors ( $\phi=0.1, \gamma=1.277, \phi/\gamma=0.078$ ), ( $\phi=0.5, \gamma=1.277, \phi/\gamma=0.4$ ), ( $\phi=1, \gamma=1.276, \phi/\gamma=0.78$ ), and ( $\phi=1.5, \gamma=1.276, \phi/\gamma=1.17$ ) of Table 13, real wage differentials increase as the planning horizon increases.

We illustrate the aforementioned argument by carrying out experiments over 66 years for different cost structure. We start by showing how the population trajectories behave for different planning horizons when initial extraction costs are 'low'. We use the parameter vector ( $\phi=4, \gamma=1.213, \phi/\gamma=3.3, \phi=78.74\%$ ) (see Table 12).

In Figure 33 we depict the population trajectories for each of the planning horizons presented in Table 12. We use population trajectories because they track the changes in real wage differentials. The population trajectories that result from these planning horizons tend to grow constantly up to the year 2030. After this year, the population trajectory fluctuates. For instance, we see that change is the most drastic when the planning horizon is equal to 66 years; and the least drastic is when the planning horizon is equal to 45 years. When the planning horizon is equal to 66 years, real wage differential changes tend to be the greatest (implying the lowest welfare levels). When

the planning horizon is equal to 45 years, the real wage differential changes tend to be the least (implying the highest welfare level).

In Figure 34 we represent the real wage differential trajectories for all planning horizons from 1996 to 2029. As was mentioned before, since there is positive population growth in all periods, welfare is positive although decreasing in this period—e.g., the rate of discount and water tariffs increase through time.

Figure 35 depicts the real wage differential trajectories from 2030 to 2060. In this figure we see that when the real wage differential trajectory is equal to 66 years there is the greatest reduction in welfare (which translates as the highest population decrease). When the planning horizon equals 45 years, the real wage differentials are higher or equal than the others real wage differential trajectories. As a result, under this planning horizon Ciudad Juarez obtains the highest welfare levels.

This behavior is explained by the fact that higher relative extraction costs result in higher recharge levels. After the first three decades the groundwater level is higher than the minimal groundwater level  $W^T$ . This results in lower water tariffs than in economies with lower relative extraction costs and higher recharge costs. As a result, population growth will continue. The utility will need to recharge more water to meet the higher water demand causing higher prices. With time, the higher prices will decrease the real wage differentials until the population starts to out-migrate. The population will grow again only when the groundwater stock increases again and the amount of water recharged decreases; thus, allowing lower water tariffs. This process will continue iteratively, and at every iteration the process will be smoother until the economy reaches the steady state.

Now consider the case where the relative extraction costs is low at the initial period. For the parameter vector ( $\phi = 0.1$ ,  $\gamma = 1.26714$ ,  $\phi/\gamma = 0.08$ ,  $\rho = 78.74\%$ ), we see in Figure 36 that all population trajectories coincide and that they smoothly fluctuate around the population steady state level of 2 million after the year 2026. Hence, the utility reaches the safe yield level and the population a steady state. We show in Figure 37 how groundwater stocks converge on the safe yield target.

In figures 38 and 39 we represent the real wage differential trajectories for each planning horizon. The first figure corresponds to a horizon of 30 years (from 1996 to 2026), the second to a horizon of 66 years (from 2027 to 2062). In Figure 38 we see that real wage differentials are positive and monotonically decreasing along these first 30 years. In addition, all real wage differential trajectories coincide. In Figure 39, we see that all trajectories fluctuate from positive to negative levels. But, in every iteration the real wage differential values become smaller because the rate of discount increases. As in the previous figure, all the real wage differential trajectories coincide.

According to our model this behavior is given because after the first three decades, the utility faces lower groundwater levels (lower than  $W^T$ ) and higher water demand. Hence, the utility needs to rely on higher water recharge to increase the groundwater levels and, at the same time, it needs to extract more water to meet the water demand. This will increase the total cost of supplying water, which translates in higher water prices slowing down the population growth before the economy reaches the steady state population level. Consequently, as the planning horizon increases the economy reaches the steady state in a smooth manner.

From the previous analysis we can conclude the following:

- (1) When we compare two parameter vectors with same recharge costs but different extraction costs, the real wage differentials will be higher for the parameter vector with the lowest extraction costs.
- (2) If there are different recharge costs and if they are low enough, the last conclusion will not hold.
- (3) When the relative extraction cost at the initial period is low, real wage differentials will rise at a decreasing rate as the planning horizon increases. The regulator does not need to intervene because the utility reaches both the maximum welfare level and sustainability target.
- (4) When the relative extraction cost at the initial period is high, real wage differentials will decrease at some point for planning horizons longer than 30 years. The regulator will need to intervene to guarantee welfare.

Note that, these conclusions do not apply to tables 14 and 15 where wages are at current levels. In this case, small changes in water tariffs bring about great changes in social welfare. Figures 40 and 41 illustrate the population trajectories that result from the parameter vectors used in tables 14 and 15, respectively.

## SECTION IV

### WATER IMPORTS

Ciudad Juarez is starting to import water from the Mesilla aquifer to mitigate the effects of groundwater decline in the Bolson del Hueco aquifer. Under these circumstances, the opportunity cost of groundwater pumping depends on the cost of importing water. Hence, the limiting factor in the development of Ciudad Juarez will not be the cost of local groundwater, the cost of importing water.

This chapter analyzes how relative costs affect the amount of water imported, welfare, and population levels. As in the previous sections, the conclusions obtained in Chapter 4 might no longer valid because of the non-convexities derived from the constant population growth rate.

Ciudad Juarez plans to buy water in early 2010 from a private company (Grupo Carso) that pumps water from the Mesilla Bolson aquifer (Carrasco (2009)). The price contracted between Grupo Carso and Ciudad Juarez was 0.48 U.S. (in U.S Dollars of 2008) per cubic meter. Since Grupo Carso is pumping water from an aquifer, the cost function of pumping water is increasing and convex. Thereby, the price that Ciudad Juarez pays for water can be represented by the following increasing function,

$$C(E_{2,t}) = P_I(E_{2,t})^\lambda = 0.48 \left( E_{2,t}^\lambda \right), \quad (5.3.0)$$

where  $E_{2,t}$  is the amount of water bought at time  $t$  and measured in cubic meters, and  $\lambda$  is a positive constant in the interval  $(1, \infty)$ . In particular, the parameter  $\lambda$  represents how fast the cost of importing water increases.

The marginal cost of pumping water in 2008 was 0.56 U.S. Dollars (Carrasco (2009)). Using the values of the first section, in 2008 there were 628.5 Mm<sup>3</sup> in the Hueco Bolson aquifer<sup>39</sup>. Therefore, the cost for extraction at time  $t$  is

$$C(E_{1,t}) = \frac{P_E E_{1,t}}{(W_t)^\phi} = \frac{(0.58)(628.5 * 10^6)^\phi E_{1,t}}{W_t^\phi}, \quad (5.3.1)$$

where  $E_{1,t}$  is the amount of water extracted measured in cubic meters at time  $t$ ;  $W_t$  is the volume of water at time  $t$ ; the parameter  $\phi$  reflects how fast the pumping cost increases and it takes only positive values; and finally,  $P_E$  is a constant that includes well reparation and wages and electricity (e.g., the operational and maintenance costs).

The analysis starts in 2008 with a population level equal to 1,370,270 and a population growth rate of 2.19%. As in the previous section, on average each inhabitant consumes 115.92 m<sup>3</sup> per year<sup>40</sup>. Once again, we are going to assume that there is a sustainable target for groundwater stocks of no less than 184.5 Mm<sup>3</sup> (i.e.,  $W^T = 184.5$ ). This can be thought of as a sufficient stock to provide insurance *both* against future climate change *and* against the failure of water imports.

---

<sup>39</sup> The parameter values are: 738 Mm<sup>3</sup> of water in the Hueco Bolson aquifer in 1996, 49.3 Mm<sup>3</sup> of recharge per year, the estimated population was approximately one million, the daily consumption per year is 115.92 m<sup>3</sup>, and the population growth rate is 2.19%.

<sup>40</sup> We are assuming that the daily consumption of water in Ciudad Juarez was equal to the 1999 level, which was equal to 322 liters (see Chapter 3).

In the case of wages, as before, are bounded from below by the expected probability of finding a job in a maquiladora plant, and from above by international competition—again styled competition with Brazil<sup>41</sup>.

As in the water autarky model, the expected wage depends on the probability of finding a job in a maquiladora plant. That is,

*(Maquiladora wage)(Probability of finding a job in the maquiladora industry)+(Average remuneration in Mexico)(Probability of not finding a job in the maquiladora industry)=Expected wage in Ciudad Juarez.*

According to the Bureau of Labor Statistics (BLS (2010)) the hourly compensation costs for production workers in manufacturing for Mexico and Brazil were 4.04 (775.68 monthly) U.S. Dollars and 8.28 (1589.76 monthly) U.S. Dollars, respectively, in 2008. The monthly average remuneration in Mexico was 399.4 U.S. Dollars for the same year<sup>42</sup>.

In Chapter 3 we saw that 46% of total workers were employed in the maquiladora industry. Hence, the probability of having a job in a maquiladora plant is equal to 0.46.

Water tariff is equal to the marginal cost of extraction and recharge as it was stated in Chapter 4. That is,

---

<sup>41</sup> We might add that data availability is much better for Brazil than for other countries that compete with Mexico.

<sup>42</sup> The average remuneration in Mexico was 79,500 Pesos in 2004 (INEGI (2004)). We converted this amount into Pesos of 2008 using the CPI provided by the Banco de México (Banco de México (2010)). This amount is converted into U.S. Dollars of 2008 by using currency exchange series of the IMF (IMF (2010)).

$$P(t)^{WR} = P_E f(W_t) \frac{E_{1,t}}{L_t} + \lambda P_t C(E_{2,t})^{\lambda-1} \frac{E_{2,t}}{L_t} \quad (5.3.2)$$

Using the above data, we conclude that the maximum willingness to pay for water monthly in Ciudad Juarez if wages were driven to the level of those in Brazil would be:

$$(\$1589.76)(0.46) + (\$399.4)(0.54) - \$399.4 = \\ \$547.75 = P(W^T, R_T)^{wr}, \quad (5.3.3)$$

while, the maximum willingness to pay for water under the status quo would be:

$$(\$775.7)(0.46) + (\$399.4)(0.54) - \$399.4 = \\ \$173.3 = P(W^T, R_T)^{wr}. \quad (5.3.4)$$

It is difficult to provide a table like Table 8 that shows all the possible steady states levels because the parameters are defined over a larger interval. However, we can reduce all the possible parameter combinations to just four cases; these are described in Table 16. Each of these cases converges to some positive steady state level of economic activity and population. For the two first cases the steady state population levels are: 781,460.75 and 696,927.88, respectively—lower than the current population level. The other two cases are associated with steady state population levels significantly above the current population level.

We simulate these cases using a time horizon of 55 years, and once again consider both the status quo and the *high stress* case, when wages converge on Brazilian levels.

CASE 1:  $\phi=1.5, \lambda=1.3, \phi/\lambda=1.15$ .



In the next two cases we assume that the cost of imported water is the highest with respect to Table 16. In this case the relative extraction cost is low ( $\phi/\lambda=1.15$ ), which translates in higher ground water extraction to cover the demand in the first years. As a result, the groundwater stock will decrease rapidly in these first years. This is shown in figures 42 and 43.

As the groundwater decreases the extraction cost will increase leading to the utility to import more water up to the point that water imports cover most of the water demanded. This transition takes place around the year 2015. All this process is accompanied by higher water tariffs which will be reflected in negative welfare levels and population growth regardless of the wage level. The welfare trajectory for both wage levels are depicted in figures 48 and 49; the population trajectories are illustrated in figures 50 and 51.

Given that the economy relies even more and more on imported water and that the water demand is lower, the groundwater level tends to rise. This results in less water imported and more ground water extraction over time. When wages are determined by the competition with Brazil this happens around the year 2029 and for the status quo case in 2019. In the latter periods, the economy covers most of its water demand by extracting ground water.

In short, regardless of the wage level, the economy will experience negative real wage differentials, and negative population growth as figures 48 and 49 illustrate.

The next cases are similar to the previous one. That is, in the earlier periods, the utility will rely mostly on ground water to meet water demand. When the groundwater

stock level is *low* the utility starts substituting ground water by imported water. The difference between each case lies in relative costs that translate as different population and welfare levels.

CASE 2:  $\phi=3, \lambda=1.3, \phi/\lambda=2.3$ .

In this case, relative extraction cost is higher than the previous case resulting in higher water imports. We show in figures 44 and 45 the different importing and extracting trajectories for this and the former case. In both cases the utility imports more water in the first periods, when the relative extraction cost is higher, regardless of wage levels.

However, the utility uses mostly ground water to meet the water demand in the first years as in the previous case. As a result, the groundwater stock is reduced causing more water importation around 2014. This can be seen in figures 46 and 47.

After 2014 the economy imports more water to meet the demand. Given that the recharge cost is the highest according to Table 16 relying in water imports raises even more the cost of supplying water than the previous case. This will eventually reduce the water demand causing a reduction in the cost of supplying water and an increase in the groundwater level. As this process continues, the utility will start increasing water extraction. We see in figures 46 and 47 that around 2039 water imports decline in favor of ground water. In later periods, the utility relies mostly in ground water.

When wages are set at Brazilian levels we see in Figure 48 that around the year 2014 welfare level passes from positive to negative. Moreover, Ciudad Juarez presents negative welfare levels for all the time that uses more imported water to cover the

water demand. As a result, the population will decrease for this time period as it is illustrated in figures 46 and 50.

When wages are set at Brazilian levels we see in Figure 48 that around the year 2014 real wage differential passes from positive to negative. Moreover, Ciudad Juarez presents negative real wage differentials for all the time that it uses imported water to cover the water demand. As a result, the population will decrease for this time period as illustrated in figures 46 and 50.

When wages are determined by the status quo we see in Figure 47 that water demand is decreasing for the all except the last couple of periods in the planning horizon. This is because the population level is higher than the steady state population level. In Figure 49 we see that the real wage differentials are negative for most of the planning horizon. As a result the population will decrease for the same time period (see Figure 51).

Since both abstraction and recharge costs are high, the cost of supplying water is higher than the previous case. Therefore, the economy will experience more strongly negative real wage differentials than in other case (see 48 and 49). This is results in lower population levels. This is represented in figures 50 and 51.

CASE 3:  $\phi=1.5, \lambda=1.1, \phi/\lambda=1.36$ .

In the next two cases, we are interested to analyze how the ground water extraction, water imports, welfare levels and population levels change as we decrease the importing cost to 1.1. In this case, given that the relative extraction cost is low, the utility uses more ground water to cover the demand in the first periods.

In fact the utility uses more ground water than Case 2 in the first periods. We show this in figures 52 and 53, where we compare the importing and ground water extraction trajectories for these two cases. However, this is not true when it is compared with Case 1 because the relative extraction cost is higher. This can be seen in figures 54 and 55 which also compare the importing and ground water extraction trajectories for these cases.

Contrary to the previous cases, water demand increases and uses mostly water imported to cover the demand. This is shown in figures 56 and 57. This is because the utility can substitute *expensive* ground water by *cheap* imported water allowing low water tariffs. In other words, population growth is sustained by low importing costs.

For instance, when we compare this case with Case 1, the volume of imported water is higher for the entire planning horizon regardless of the wage level (see figures 54 and 55). Moreover, if we compare this case with Case 2 we obtain a similar result (see figures 52 and 53).

CASE 4:  $\phi=3, \lambda=1.1, \phi/\lambda=2.72$ .

We increase the relative extraction cost by raising the value of  $\phi$  and leaving  $\lambda$  constant, which leads to higher imports in the first periods. Given that the utility faces the highest costs relative to other cases at time zero, the amount of water imported will be higher than in the other cases. This is shown in Figure 60 (this figure compares this case with the other cases).

As in the previous cases, the utility will substitute ground water for imported water as the groundwater level decreases (shown in figures 58 and 59). This allows the

utility to maintain low water tariffs resulting in continued population growth and, therefore, higher water demand.

One of the important effects of having low importing costs is continued population growth and positive welfare levels. Figures 61 and 62 show the population growth for different wage levels; and figures 63 and 64 show the real wage differentials corresponding to different wage levels. In these figures we see that there is constant population growth while real wage differentials are positive but decreasing along the planning horizon regardless of the initial wage level.

In this section we have manipulated the initial extraction and importing costs by changing the technological parameters  $\phi$  and  $\lambda$ , to understand how costs determine the population growth and welfare changes. How population and welfare behaves depends on the water importing and extracting trajectories. There are two main lessons to take away from this section:

- 1) The relative extraction cost determines how much water is imported. For instance, if the extraction cost is relatively high, then the utility will increase the amount of water imported. If the extraction cost is relatively low, then the utility will increase the amount of water abstracted from the aquifer.
- 2) The development of Ciudad Juarez depends of the cost of importing water. If this is high, the utility will rely on expensive ground water leading to low levels of population growth, and low real wage differentials. For example, in cases 1 and 2 there is negative population and welfare growth. Contrary to this, in cases

3 and 4 there is constant population growth and positive or zero real wage differentials.

## CONCLUSIONS

The aquifer Bolson de Hueco is the most important water resource for the municipality of Ciudad Juarez. The opportunity cost of extracting an additional unit of water from this aquifer is determined by relative prices, technology, wages, water availability (e.g., the natural recharge rate), water demand, and the cost of importing water. If this opportunity cost is high, the development of Ciudad Juarez will be constrained. This conclusion corresponds to the findings of Chapter 4.

Nevertheless, the water utility might not maximize real wage differentials when the planning horizon is infinite as concluded in Chapter 4. This is caused by the non-convexities associated with the assumption of real wage independent population growth presented in this chapter. Hence, some type of government intervention might be needed in the case that Ciudad Juarez relied solely on ground water. However, it is shown that in some cases the best policy option may still be to leave the market to work without intervention.

In particular, we find that in the autarkic water management regime the optimal recharge trajectory is affected by the relative costs, water demand, the planning horizon, recharge capabilities and the terminal sustainability target adopted by the planning authority. If either relative extraction costs or water demand increases (decreases), this will increase (decrease) recharge levels. Moreover, if recharge capability increases (decreases), the utility will optimally decrease (increase) recharge levels for any planning horizon. These results coincide with the findings of Chapter 4.

Moreover, we show in the autarkic model that costs affect the real wage differentials in two ways: directly by increasing the total cost of supplying water; and indirectly by affecting the transition to the steady state. The latter effect is a direct consequence of the non-convexities derived from the constant population growth rate and it has a higher impact when the relative extraction costs are high. In such a case, real wage differentials will decrease at some point for planning horizons larger than 30 years. Hence, the regulator needs to intervene. However, if the relative extraction cost is low, real wage differentials will rise as the planning horizon increases. Therefore, the regulator does not need to intervene.

When Ciudad Juarez can import water to cover the water demand it is shown that higher importing costs result in higher use of ground water and *vice versa*. These results coincide with the findings of Chapter 4 even when non-convexities are present. This section also examines the role of relative costs on population and real wage differentials. We find that if the importing cost is relatively high, Ciudad Juarez will rely on ground water leading to declining population and real wage differentials. On the contrary, if the importing cost is relatively low, Ciudad Juarez will rely on water imports leading to higher population and real wage differentials. Thus, importing water from elsewhere can advance the economic development of Ciudad Juarez if the importing cost is low with respect to income of the inhabitants of Ciudad Juarez.

Even when the effect of the non-convexity was not examined as in the first case, we presume that this effect exists and some type of government intervention will be needed.



Table 8. Steady state population levels and recharge capabilities.

$\phi$	Steady State Population Level	$\phi$	Steady State Population Level	$\phi$	Steady State Population Level	$\phi$	Steady State Population Level
99.00%	42,529,330.57	73.00%	1,575,160.39	47.00%	802,440.20	21.00%	538,345.96
98.00%	21,264,665.29	72.00%	1,518,904.66	46.00%	787,580.20	20.00%	531,616.63
97.00%	14,176,443.52	71.00%	1,466,528.64	45.00%	773,260.56	19.00%	525,053.46
96.00%	10,632,332.64	70.00%	1,417,644.35	44.00%	759,452.33	18.00%	518,650.37
95.00%	8,505,866.11	69.00%	1,371,913.89	43.00%	746,128.61	17.00%	512,401.57
94.00%	7,088,221.76	68.00%	1,329,041.58	42.00%	733,264.32	16.00%	506,301.55
93.00%	6,075,618.65	67.00%	1,288,767.59	41.00%	720,836.11	15.00%	500,345.07
92.00%	5,316,166.32	66.00%	1,250,862.66	40.00%	708,822.18	14.00%	494,527.10
91.00%	4,725,481.17	65.00%	1,215,123.73	39.00%	697,202.14	13.00%	488,842.88
90.00%	4,252,933.06	64.00%	1,181,370.29	38.00%	685,956.94	12.00%	483,287.85
89.00%	3,866,302.78	63.00%	1,149,441.37	37.00%	675,068.74	11.00%	477,857.65
88.00%	3,544,110.88	62.00%	1,119,192.91	36.00%	664,520.79	10.00%	472,548.12
87.00%	3,271,486.97	61.00%	1,090,495.66	35.00%	654,297.39	9.00%	467,355.28
86.00%	3,037,809.33	60.00%	1,063,233.26	34.00%	644,383.80	8.00%	462,275.33
85.00%	2,835,288.70	59.00%	1,037,300.75	33.00%	634,766.13	7.00%	457,304.63
84.00%	2,658,083.16	58.00%	1,012,603.11	32.00%	625,431.33	6.00%	452,439.69
83.00%	2,501,725.33	57.00%	989,054.20	31.00%	616,367.11	5.00%	447,677.16
82.00%	2,362,740.59	56.00%	966,575.69	30.00%	607,561.87	4.00%	443,013.86
81.00%	2,238,385.82	55.00%	945,096.23	29.00%	599,004.66	3.00%	438,446.71
80.00%	2,126,466.53	54.00%	924,550.66	28.00%	590,685.15	2.00%	433,972.76
79.00%	2,025,206.22	53.00%	904,879.37	27.00%	582,593.57	1.00%	429,589.20
78.00%	1,933,151.39	52.00%	886,027.72	26.00%	574,720.68		
77.00%	1,849,101.33	51.00%	867,945.52	25.00%	567,057.74		
76.00%	1,772,055.44	50.00%	850,586.61	24.00%	559,596.45		
75.00%	1,701,173.22	49.00%	833,908.44	23.00%	552,328.97		
74.00%	1,635,743.48	48.00%	817,871.74	22.00%	545,247.83		

*Notes.* The steady state population levels for different recharge capabilities,  $\phi$ . For instance, if Ciudad Juarez wants to maintain the current population level (around 1.5 millions) it will require recharging the 70% of the water used.

Table 9. Steady state parameters when wages are determined by Brazil.

Population Level	2,000,000	Population Level	1,500,000	Population Level	1,200,000
$\varphi$	0.787354	$\varphi$	0.716471	$\varphi$	0.64559
$\phi$	$\gamma$	$\phi$	$\gamma$	$\phi$	$\gamma$
0.1	1.26714	0.1	1.277249	0.1	1.287459
0.5	1.267029	0.5	1.277134	0.5	1.287272
1	1.266767	1	1.27686	1	1.287072
1.5	1.29	1.5	1.27633	1.5	1.286524
2	1.265166	2	1.275239	2	1.28541
2.5	1.262949	2.5	1.272974	2.5	1.2311
3	1.258202	3	1.268133	3	1.278182
3.5	1.247113	3.5	1.256822	3.5	1.266675
4	1.213007	4	1.222035	4	1.23128
4.2	1.164566	4.2	1.172631	4.2	1.181015

*Notes.* Steady state values when  $\varphi$  equals 78%, 72%, and 65%.  
In this case,  $\phi$  is not defined for higher values than 4.3.

Table 10. Steady state parameters when wages are determined by current levels.

Population Level	2,000,000	Population Level	1,500,000	Population Level	1,200,000
$\varphi$	0.787354	$\varphi$	0.716471	$\varphi$	0.64559
$\phi$	$\gamma$	$\phi$	$\gamma$	$\phi$	$\gamma$
0.1	1.049068	0.1	1.054841	0.1	1.06118
0.5	1.039854	0.5	1.045444	0.5	1.05163
1	1.007642	1	1.012596	1	1.018208
1.02	1.005034	1.02	1.009937	1.02	1.015503

*Notes.* Steady state values when  $\varphi$  equals 78%, 72%, and 65%.  
In this case,  $\phi$  is not defined for higher values than 1.035.

Table 11. Sample cases.

	$\phi$	$\gamma$	$\varphi$	Time Horizon	$W^T$ (sustainability target)
Case 1	3	1.2564	80%	35	185.5
	0.5	1.2564	80%	35	185.5
Case 2	3	1.247	80%	35	185.5
	3	1.2564	80%	35	185.5
Case 3	3	1.2564	80%	20	185.5
	0.5	1.2564	80%	20	185.5
Case 4	3	1.2564	80%	35	185.5
	3	1.2564	70%	35	185.5
Case 5	3	1.2564	80%	35	185.5
	3	1.2564	80%	35	$\geq 0$

Table 12. Welfare levels when  $\varphi$  equals 78.74% and wages are determined by Brazil.

$\varphi$	78.74%	Welfare (Millions of Dollars)			
$\phi$	$\gamma$	30 years	45 year	55 years	66 years
0.1	1.26714	31,313.5	31,313.7	31,340.2	31,340.3
0.5	1.267029	31,213.5	31,213.7	31,236.4	31,284
1	1.266767	30,882.5	30,876.8	30,898.3	30,931
15	1.266239	29,308	29,309.5	29,315.7	29,339
2	1.26566	29,316.5	28,386.1	28,386	28,385.7
2.5	1.262949	29,438.8	29,347.2	29,085.7	28,338.4
3	1.258202	29,987.1	28,973.2	28,911	28,873
3.5	1.247113	32,072	31,754	31,729.3	31,698.6
4	1.213007	38,225	38,473.3	38,332	36,864

*Notes.* In this table, we show the steady state values for different parameter vectors given that  $\varphi$  equals 78.74% and wages are determined by the competition with Brazil.

Table 13. Welfare levels when  $\varphi$  equals 71.65% and wages are determined by Brazil.

$\varphi$	71.65%	Welfare (Millions of Dollars)			
$\phi$	$\gamma$	30 years	45 years	55 years	66 years
0.1	1.77249	26,827.2	26,834.1	26,842.7	26,869.4
0.5	1.277134	26,812.6	26,820	26,828.4	26,854.8
1	1.276869	26,600.4	22,622.7	26,799.3	26,824.5
1.5	1.276334	26,744.4	26,745.1	26,752.2	26,774.2
2	1.275239	26,689.1	26,543	26,543.4	26,543.4
2.5	1.272974	26,614.9	26,282.3	26,281.9	26,281.9
3	1.268133	26,634	26,602.7	26,589.3	26,589.3
3.5	1.256822	27,066.2	26,972.3	26,840.5	26,846.7
4	1.222035	36,852.50	33,772.68	32,832	28,294.70

*Notes.* In this table, we show the steady state values for different parameter vectors given that  $\varphi$  equals 71.65% and wages are determined by the competition with Brazil.

Table 14. Welfare levels when  $\varphi$  equals 78.74% and wages are determined by current levels.

$\varphi$	78.74%	Welfare (Millions of Dollars)			
$\phi$	$\gamma$	30 years	45 years	55 years	66 years
0.1	1.049068	376.3	332.4	277.6	277.6
0.5	1.039854	347	346	346	346.1
1	1.007642	151.2	154.5	155.1	155.2

*Notes.* In this table, we show the steady state values for different parameter vectors given that  $\varphi$  equals 78.74% and wages are determined by the status quo.

Table 15. Welfare levels when  $\phi$  equals 78.74% and wages are determined by current levels.

$\phi$	71.65%	Welfare (Millions of Dollars)			
$\phi$	$\gamma$	30 yeas	45 years	55 years	66 years
0.1	1.054841	318	321.1	321.5	320.8
0.5	1.045444	327.5	328.	328.4	328.4
1	1.012596	404.4	351.3	351.7	51.9

*Notes.* In this table, we show the steady state values for different parameter vectors given that  $\phi$  equals 71.65% and wages are determined by the status quo.

Table 16. Sample cases.

	Relative cost of extraction $\phi/\lambda$	Importing Cost $\lambda$	Extraction Cost $\phi$
Case 1	<i>Low incentive to import</i> ( $\phi/\lambda=1.15$ )	High ( $\lambda=1.3$ )	Low ( $\phi=1.5$ )
Case 2	<i>High incentive to import</i> ( $\phi/\lambda$ $=2.3$ )	High ( $\lambda=1.3$ )	High ( $\phi=3$ )
Case 3	<i>Low incentive to import</i> ( $\phi/\lambda$ $=1.36$ )	Low ( $\lambda=1.1$ )	Low ( $\phi=1.5$ )
Case 4	<i>High incentive to import</i> ( $\phi/\lambda=2.72$ )	Low ( $\lambda=1.1$ )	High ( $\phi=3$ )

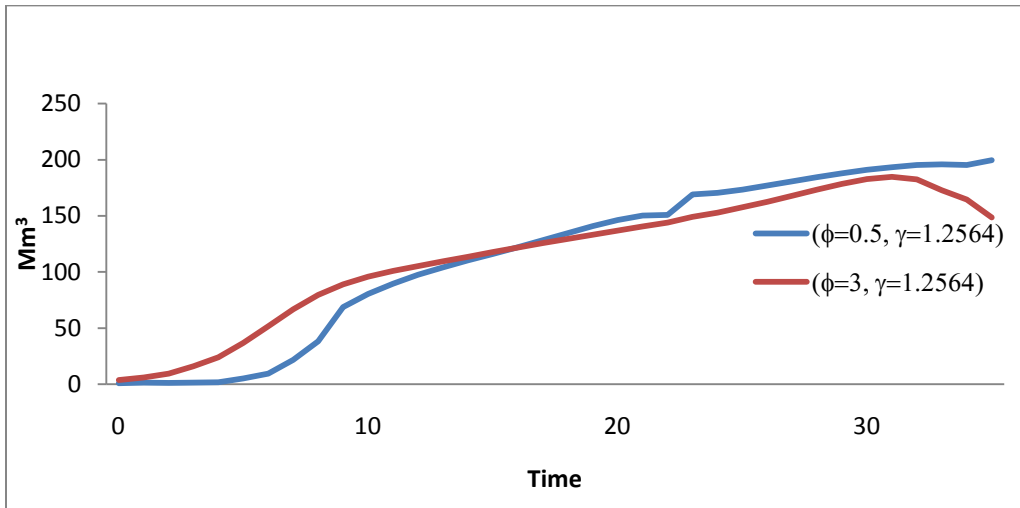


Figure 17. Water recharge Case 1.

*Notes.* This figure depicts the optimal recharge trajectories for the parameter vectors  $(\phi=0.5, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3, \text{planning horizon}=35)$  and  $(\phi=3, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3, \text{planning horizon}=35)$ .

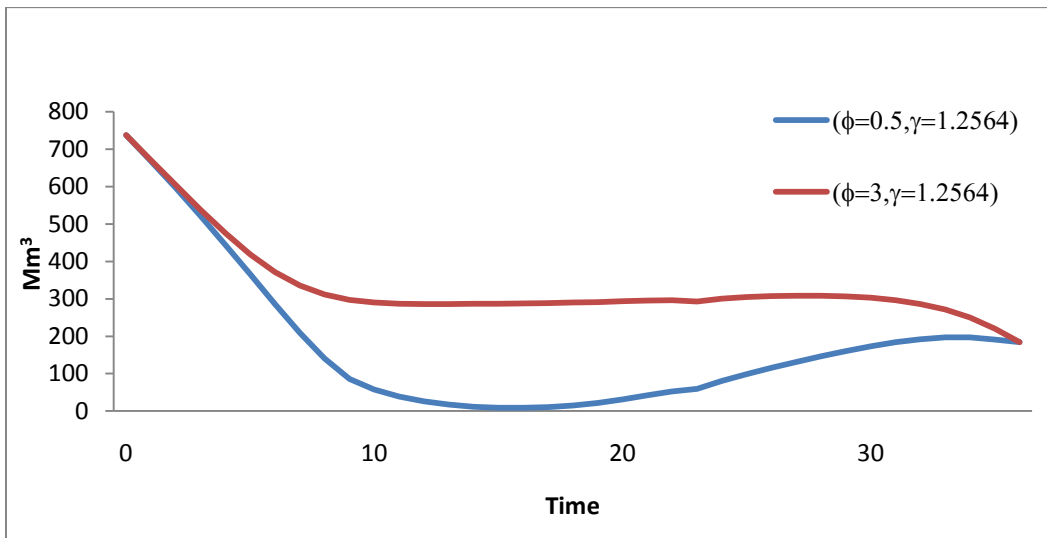


Figure 18. Ground water stock Case 1.

*Notes.* This figure depicts the groundwater trajectories for the parameter vectors  $(\phi=0.5, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3, \text{planning horizon}=35)$  and  $(\phi=3, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3, \text{planning horizon}=35)$ .

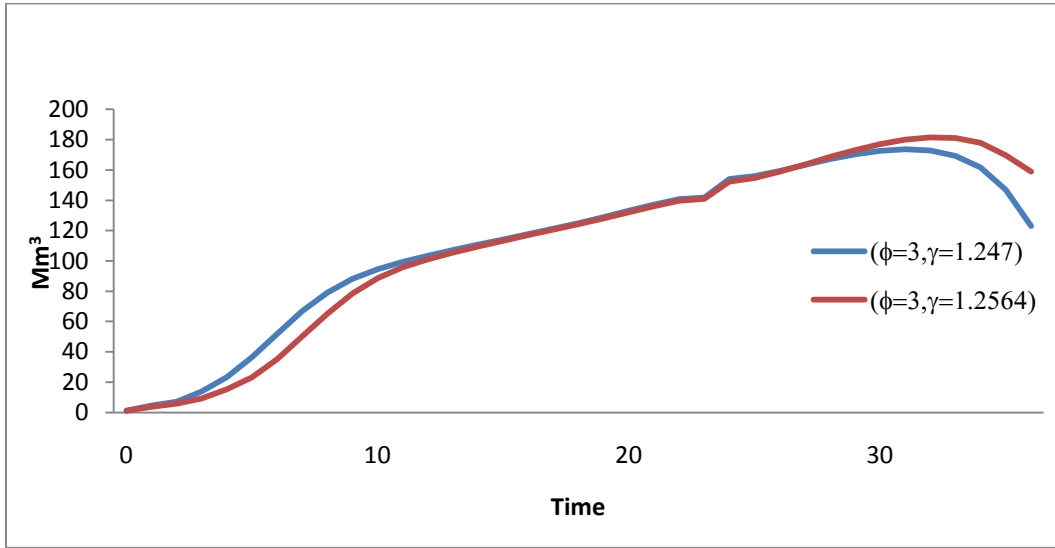


Figure 19. Water recharge Case 2.

*Notes.* This figure depicts the optimal recharge trajectories for the parameter vectors  $(\phi=3, \gamma=1.247, \varphi=80\%, W^T=185\text{Mm}^3, \text{planning horizon}=35)$  and  $(\phi=3, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3, \text{planning horizon}=35)$ .

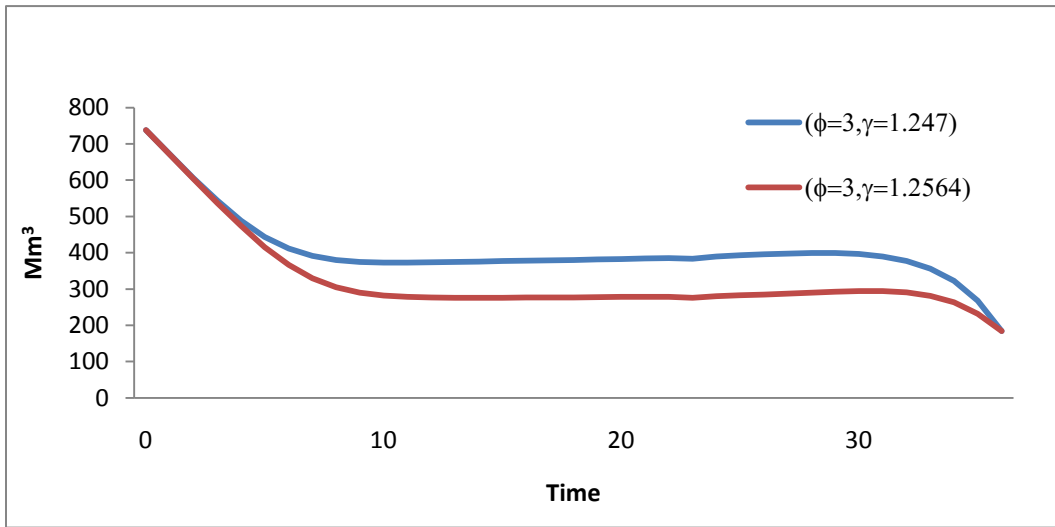


Figure 20. Ground water stock Case 2.

*Notes.* This figure depicts the groundwater trajectories for the parameter vectors  $(\phi=3, \gamma=1.247, \varphi=80\%, W^T=185\text{Mm}^3, \text{planning horizon}=35)$  and  $(\phi=3, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3, \text{planning horizon}=35)$ .

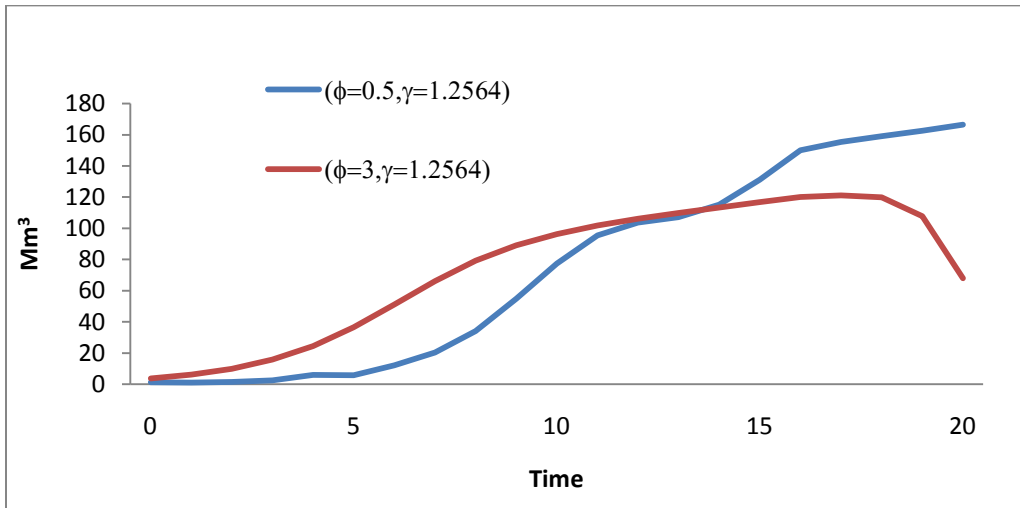


Figure 21. Water recharge Case 3.

*Notes.* This figure depicts the optimal recharge trajectories for the parameter vectors ( $\phi=0.5, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3$ , planning horizon=20) and ( $\phi=3, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3$ , planning horizon=20).

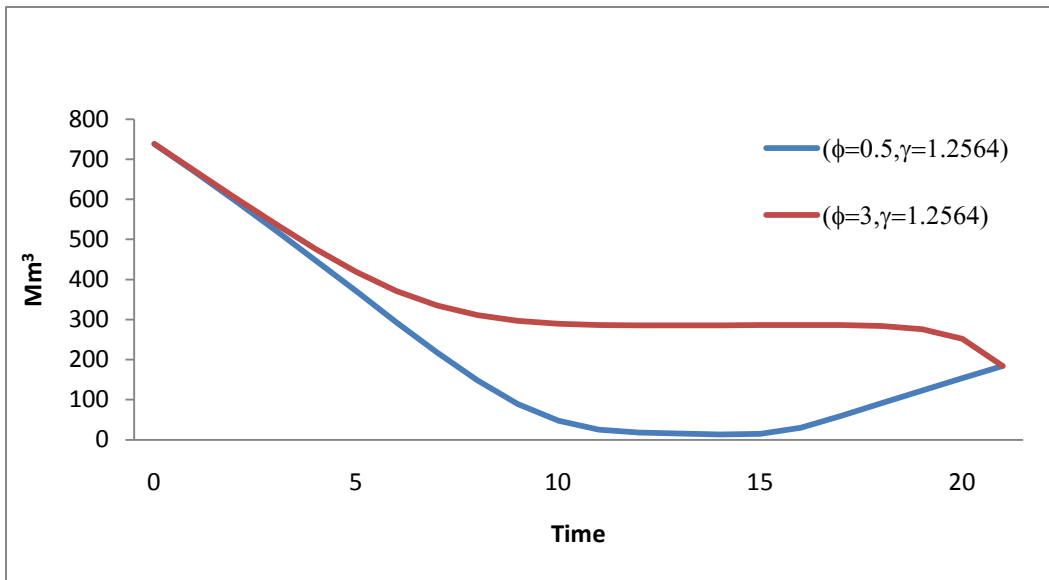


Figure 22. Ground water Case 3.

*Notes.* This figure depicts the groundwater trajectories for the parameter vectors ( $\phi=0.5, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3$ , planning horizon=20) and ( $\phi=3, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3$ , planning horizon=20).



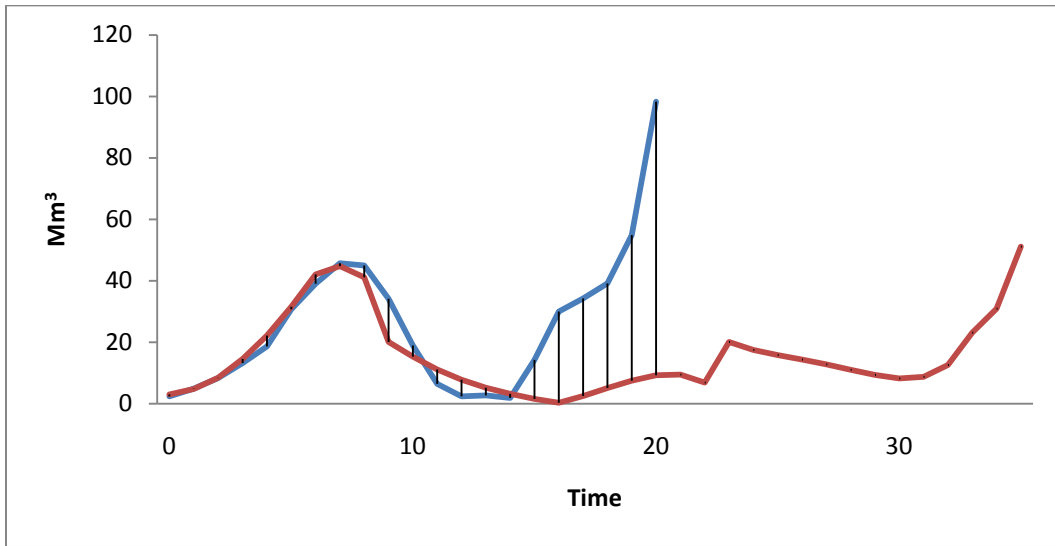


Figure 23. Differences between recharge trajectories.

*Notes.* This figure depicts the absolute difference between the water recharge trajectories for case 1 and 3 through time.

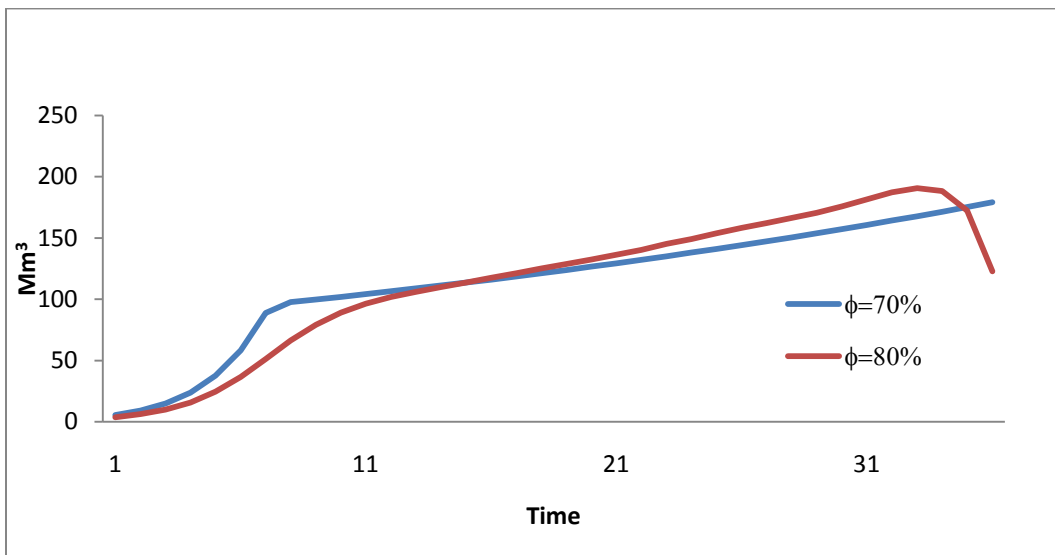


Figure 24. Water recharge Case 4. *Notes.* This figure depicts the optimal recharge trajectories for the parameter vectors  $(\phi=3, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3, \text{planning horizon}=35)$  and  $(\phi=3, \gamma=1.2564, \varphi=70\%, W^T=185\text{Mm}^3, \text{planning horizon}=35)$ .

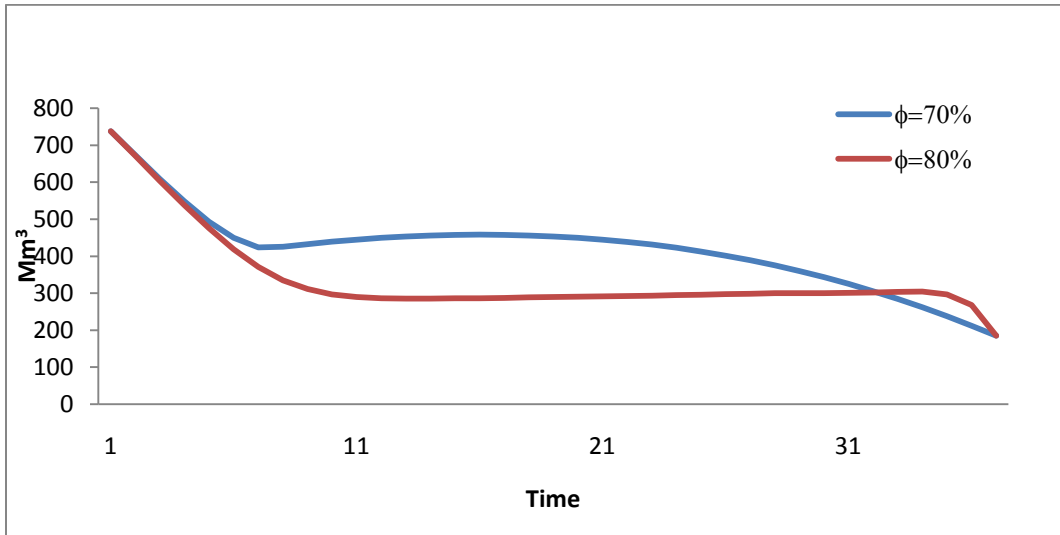


Figure 25. Ground water Case 4. *Notes.* This figure depicts the groundwater trajectories for the parameter vectors ( $\phi=3$ ,  $\gamma=1.2564$ ,  $\phi=80\%$ ,  $W^T=185\text{Mm}^3$ , planning horizon=35) and ( $\phi=3$ ,  $\gamma=1.2564$ ,  $\phi=70\%$ ,  $W^T=185\text{Mm}^3$ , planning horizon=35).

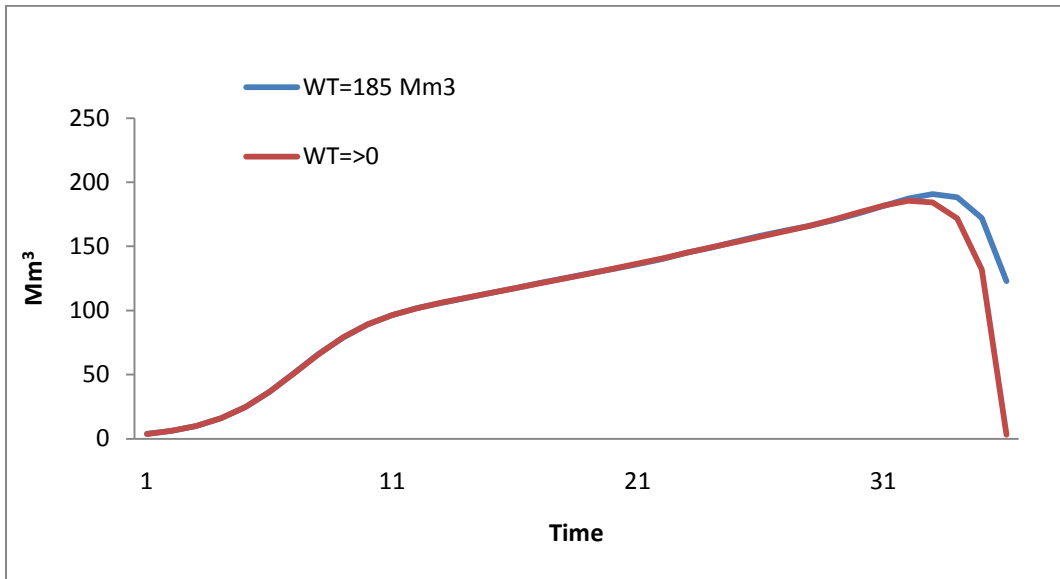


Figure 26. Water recharge Case 5. *Notes.* This figure depicts the optimal recharge trajectories for the parameter vectors ( $\phi=3$ ,  $\gamma=1.2564$ ,  $\phi=80\%$ ,  $W^T=185\text{Mm}^3$ , planning horizon=35) and ( $\phi=3$ ,  $\gamma=1.2564$ ,  $\phi=80\%$ ,  $W^T \geq 0$ , planning horizon=35).

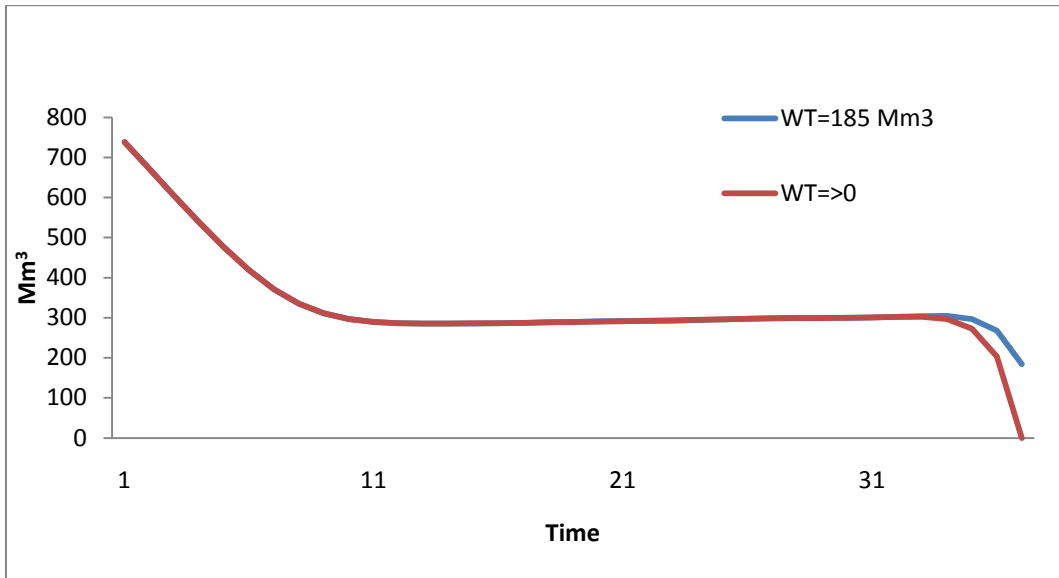


Figure 27. Ground water Case 5. *Notes.* This figure depicts the groundwater trajectories for the parameter vectors ( $\phi=3, \gamma=1.2564, \varphi=80\%, W^T=185\text{Mm}^3$ , planning horizon=35) and ( $\phi=3, \gamma=1.2564, \varphi=80\%, W^T \geq 0$ , planning horizon=35).

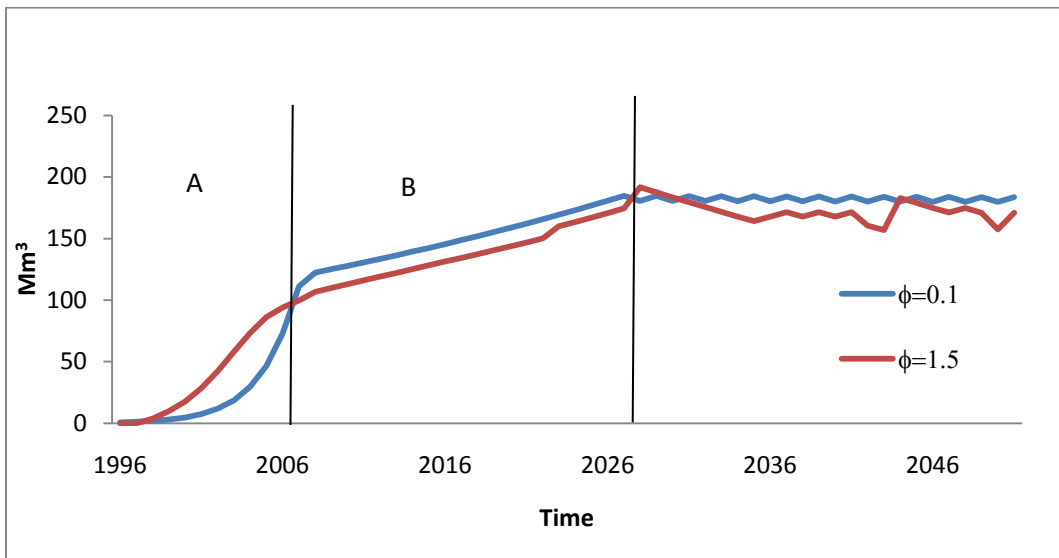


Figure 28. Water Recharge levels. *Notes.* This figure depicts the optimal recharge trajectories for the parameter vectors ( $\phi=1.5, \gamma=1.266, \varphi=78.74\%, \phi/\gamma=1.185$ ) and ( $\phi=0.1, \gamma=1.267, \varphi=78.74\%, \phi/\gamma=0.0789$ ).

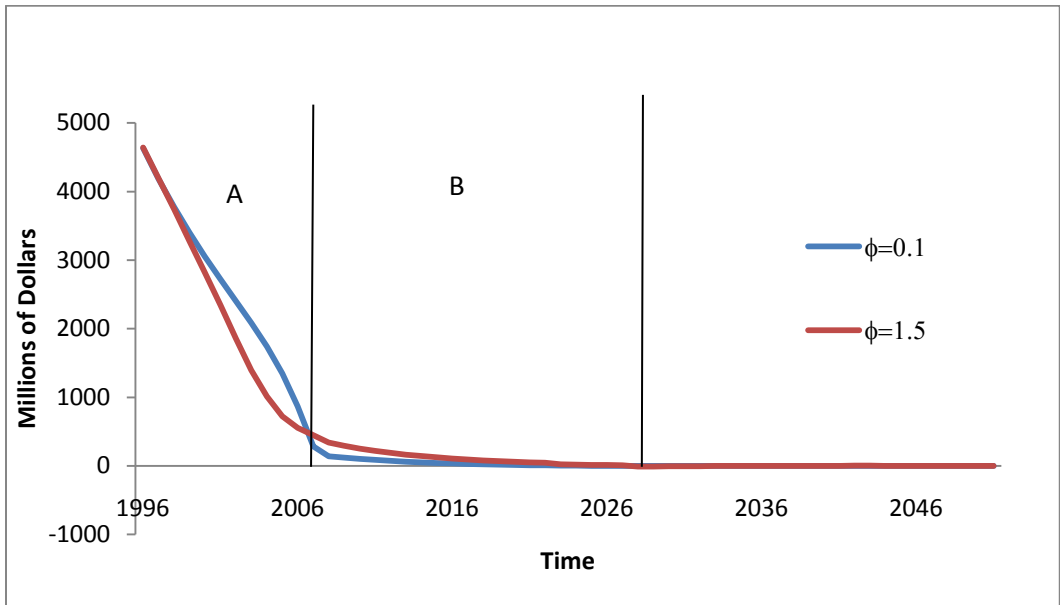


Figure 29. Welfare levels. *Notes.* This figure depicts the welfare trajectories for the parameter vectors  $(\phi=1.5, \gamma=1.266, \rho=78.74\%, \phi/\gamma=1.185)$  and  $(\phi=0.1, \gamma=1.267, \rho=78.74\%, \phi/\gamma=0.0789)$ .

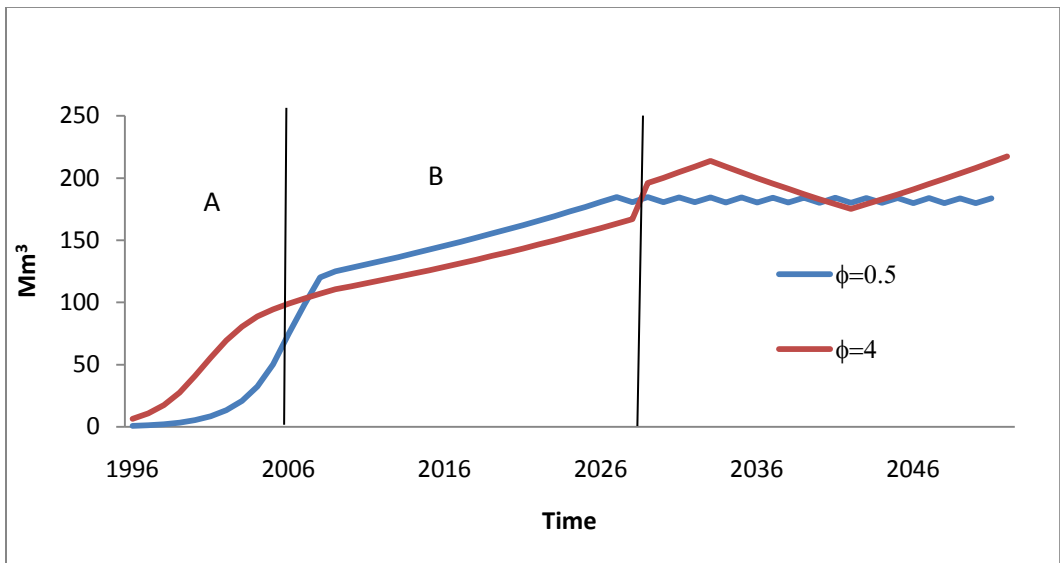


Figure 30. Recharge levels. *Notes.* This figure depicts the optimal recharge trajectories for the parameter vectors  $(\phi=0.5, \gamma=1.267, \rho=78.74\%, \phi/\gamma=0.4)$  and  $(\phi=4, \gamma=1.213, \rho=78.74\%, \phi/\gamma=3.3)$ .

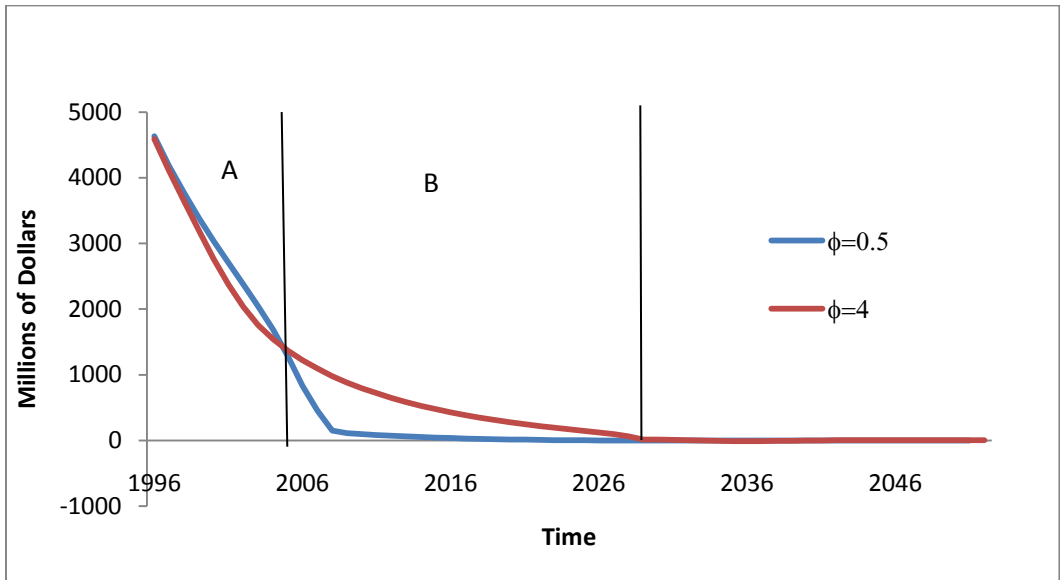


Figure 31. Welfare levels. *Notes.* This figure depicts the welfare trajectories for the parameter vectors  $(\phi=0.5, \gamma=1.267, \varphi=78.74\%, \phi/\gamma=0.4)$  and  $(\phi=4, \gamma=1.213, \varphi=78.74\%, \phi/\gamma=3.3)$ .

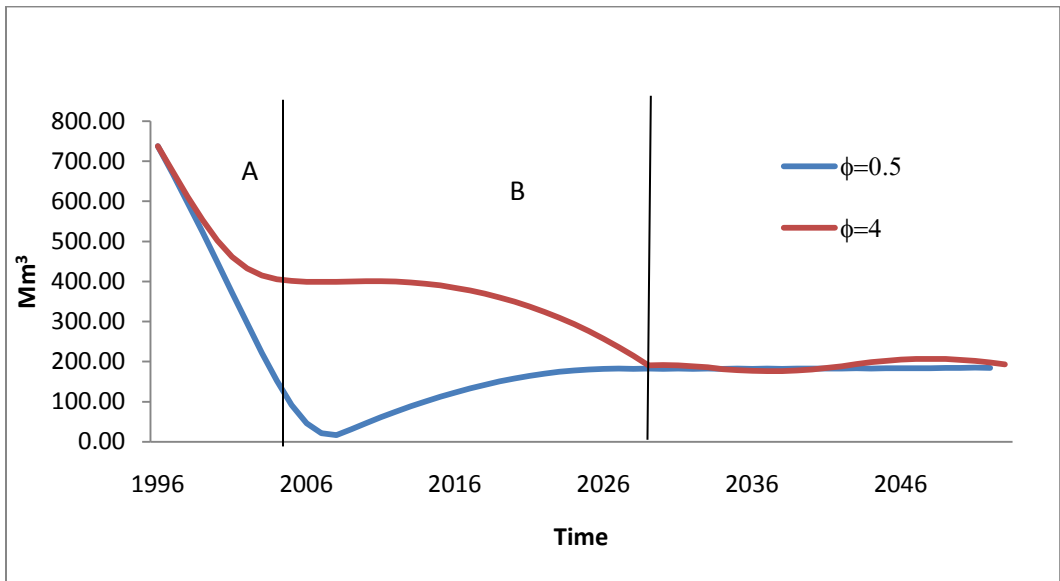


Figure 32. Ground water stock levels. *Notes.* This figure depicts the groundwater trajectories for the parameter vectors  $(\phi=0.5, \gamma=1.267, \varphi=78.74\%, \phi/\gamma=0.4)$  and  $(\phi=4, \gamma=1.213, \varphi=78.74\%, \phi/\gamma=3.3)$ .

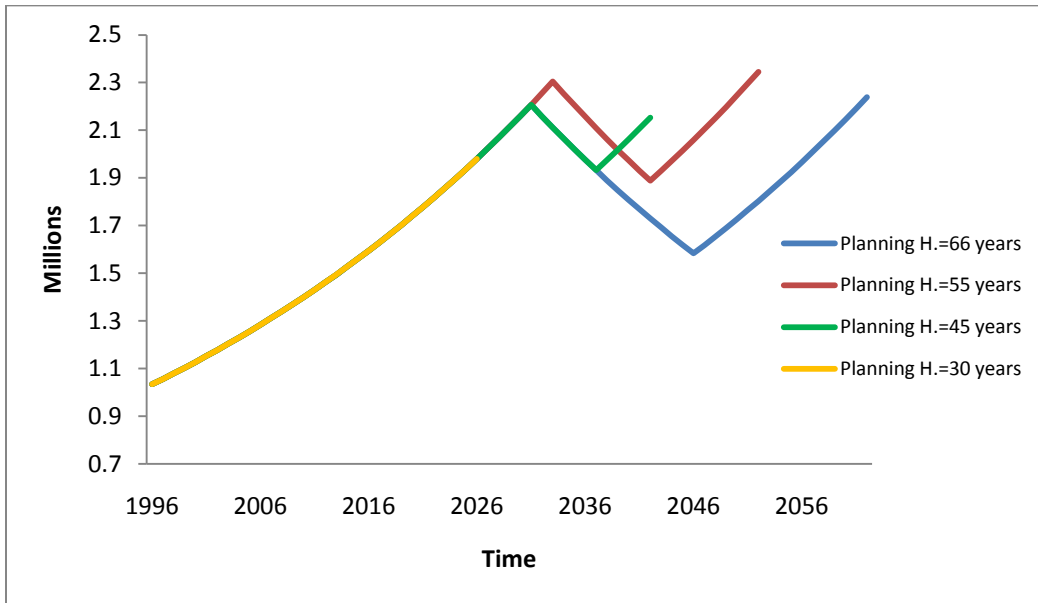


Figure 33. Population trajectories. *Notes.* This figure depicts the population trajectories for different planning horizons when the parameter vector is equal to  $(\phi=4, \gamma=1.213, \varphi =78.74\%)$ .

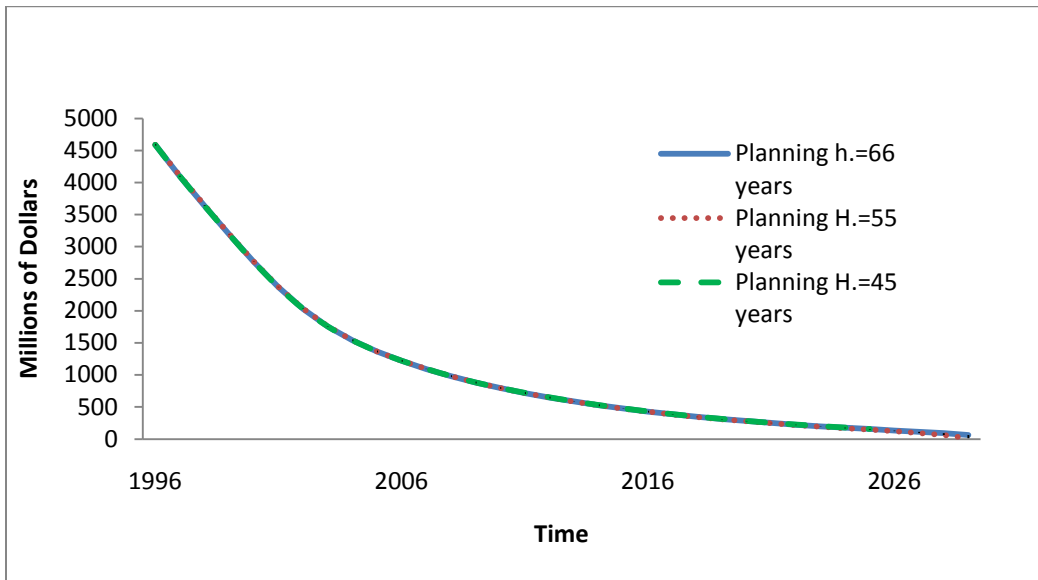


Figure 34. Welfare levels (1996-2029). *Notes.* This figure depicts the welfare trajectories for different planning horizons when the parameter vector is equal to  $(\phi=4, \gamma=1.213, \varphi =78.74\%)$ .

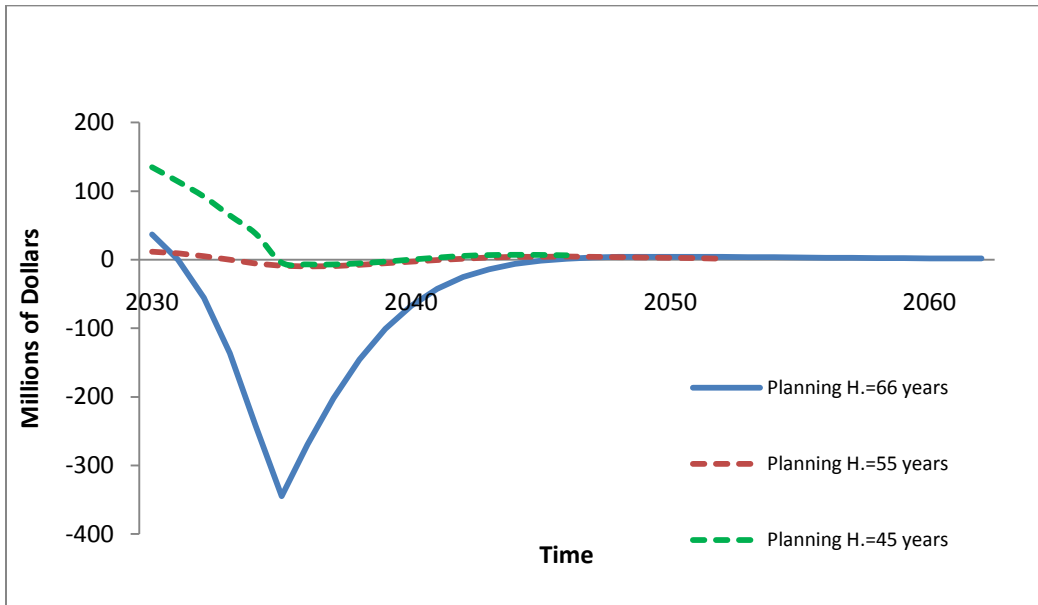


Figure 35. Welfare levels (2030-2060). *Notes.* This figure depicts the welfare trajectories for different planning horizons when the parameter vector is equal to  $(\phi=4, \gamma=1.213, \varphi=78.74\%)$ .

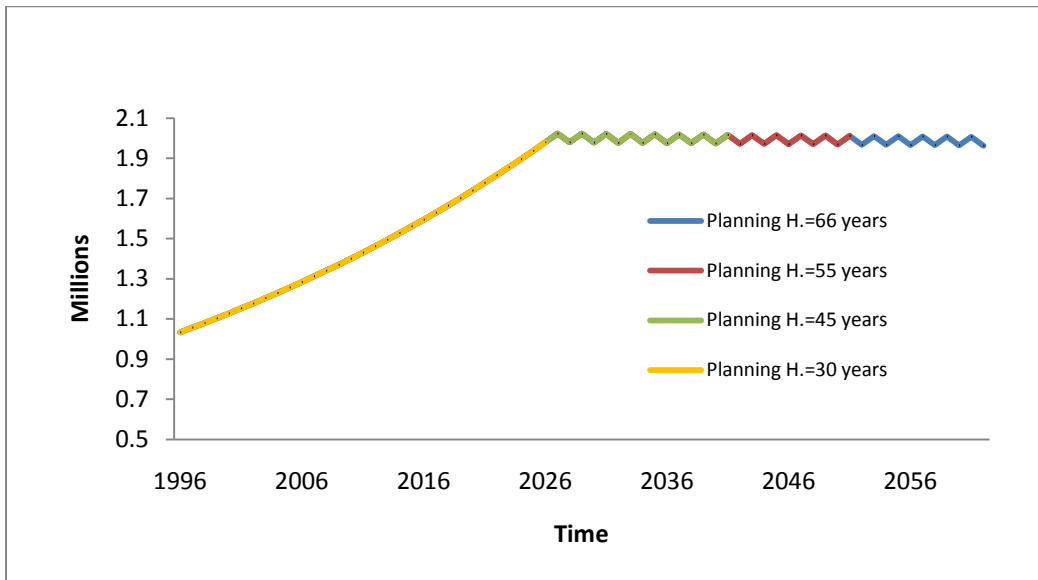


Figure 36. Population trajectories. *Notes.* This figure depicts the population trajectories for different planning horizons when the parameter vector is equal to  $(\phi=0.1, \gamma=1.26714, \varphi=78.74\%)$ .

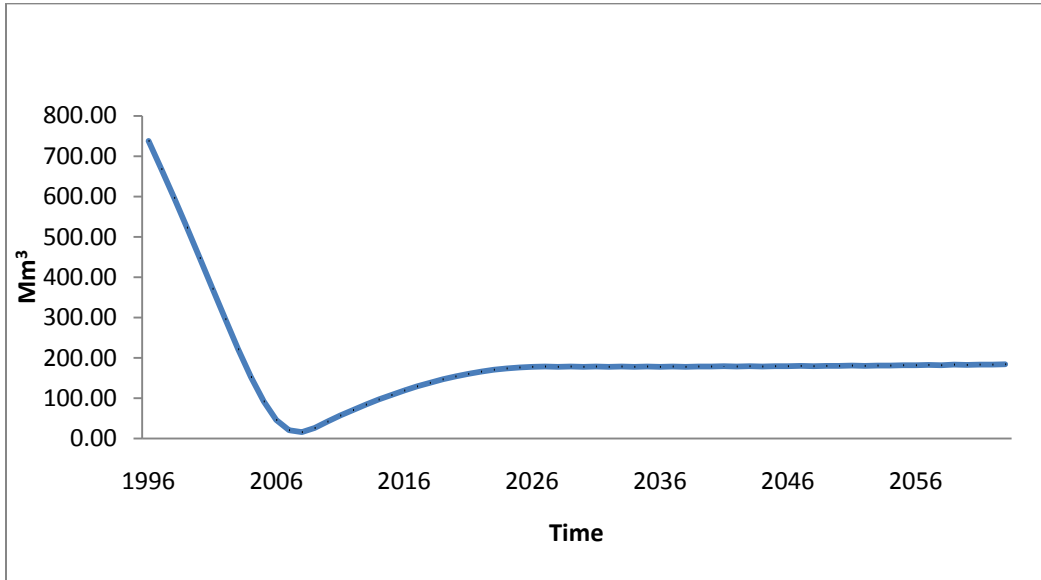


Figure 37. Groundwater stock trajectory.

Notes. This figure depicts the groundwater trajectory when the parameter vector is equal to ( $\phi = 0.1$ ,  $\gamma = 1.26714$ ,  $\rho = 78.74\%$ ).

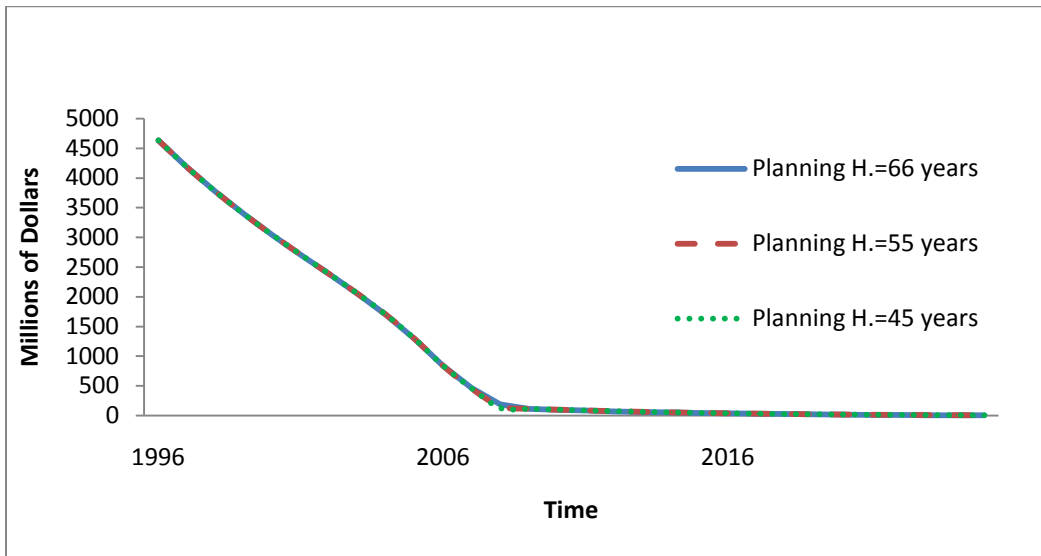


Figure 38. Welfare levels (1996-2025).

Notes. This figure depicts the welfare trajectories for different planning horizons when the parameter vector is equal to ( $\phi = 0.1$ ,  $\gamma = 1.26714$ ,  $\rho = 78.74\%$ ).



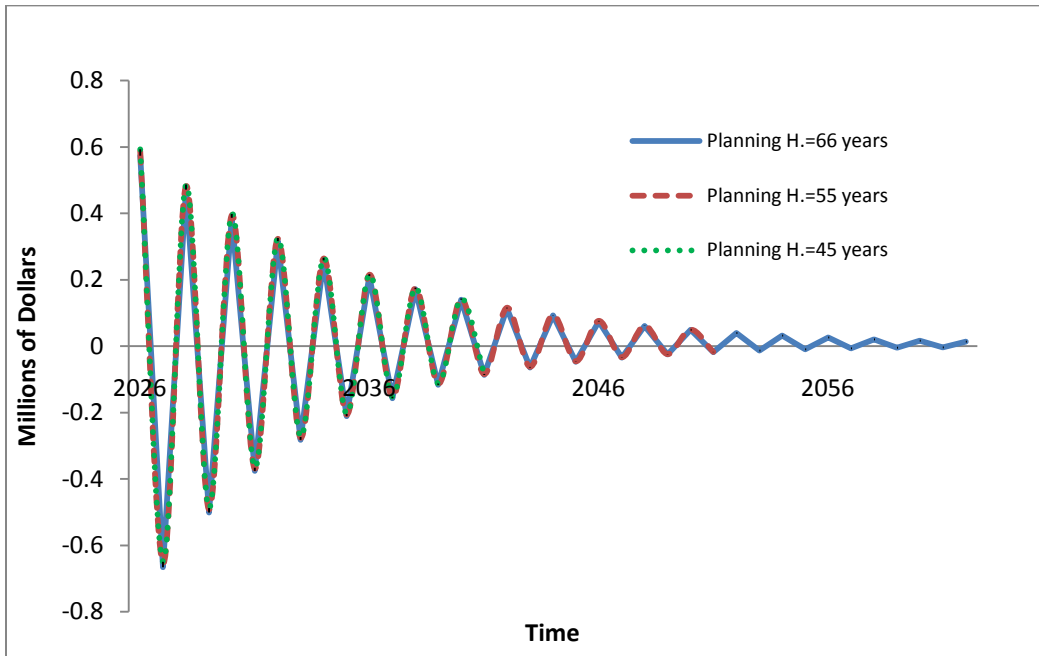


Figure 39. Welfare levels (2026-2060).

*Notes.* This figure depicts the welfare trajectories for different planning horizons when the parameter vector is equal to  $(\phi=0.1, \gamma=1.26714, \varphi=78.74\%)$ .

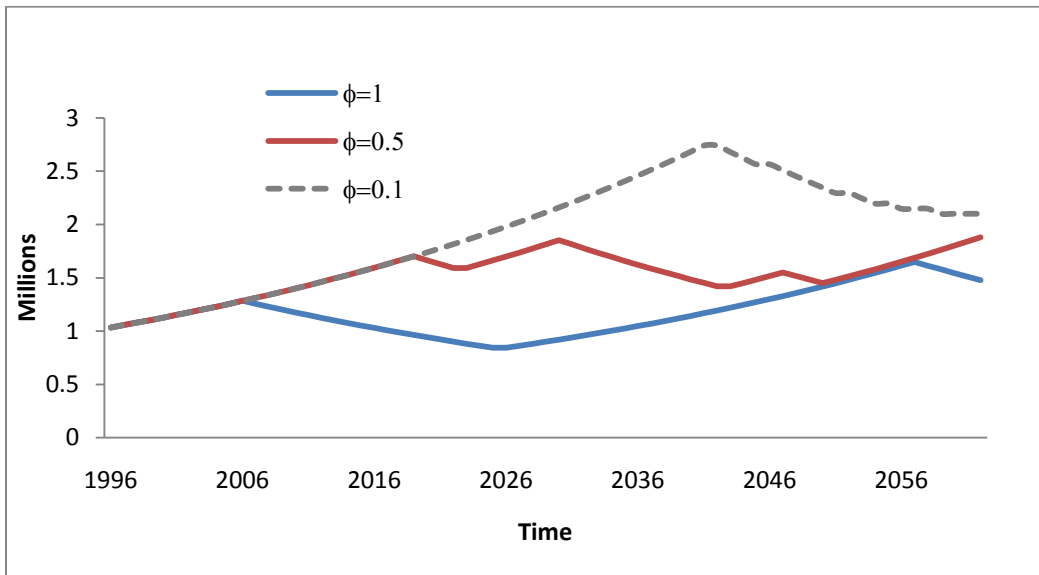


Figure 40. Population trajectories.

*Notes.* The population trajectory when the parameter vectors are:  $(\phi=0.1, \gamma=1.049068, \varphi=78.74\%)$ ,  $(\phi=0.5, \gamma=1.039854, \varphi=78.74\%)$ , and  $(\phi=1, \gamma=1.007642, \varphi=78.74\%)$ .

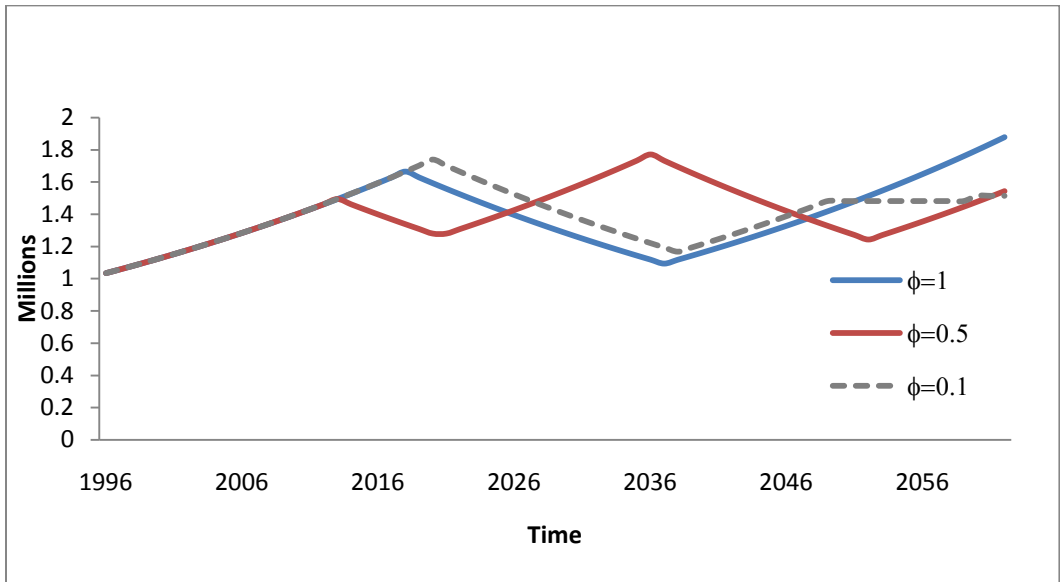


Figure 41. Population trajectories.

Notes. The population trajectory when the parameter vectors are: ( $\phi = 0.1, \gamma = 1.054841, \varphi = 71.65\%$ ), ( $\phi = 0.5, \gamma = 1.045444, \varphi = 71.65\%$ ), and ( $\phi = 1, \gamma = 1.012596, \varphi = 71.65\%$ ).

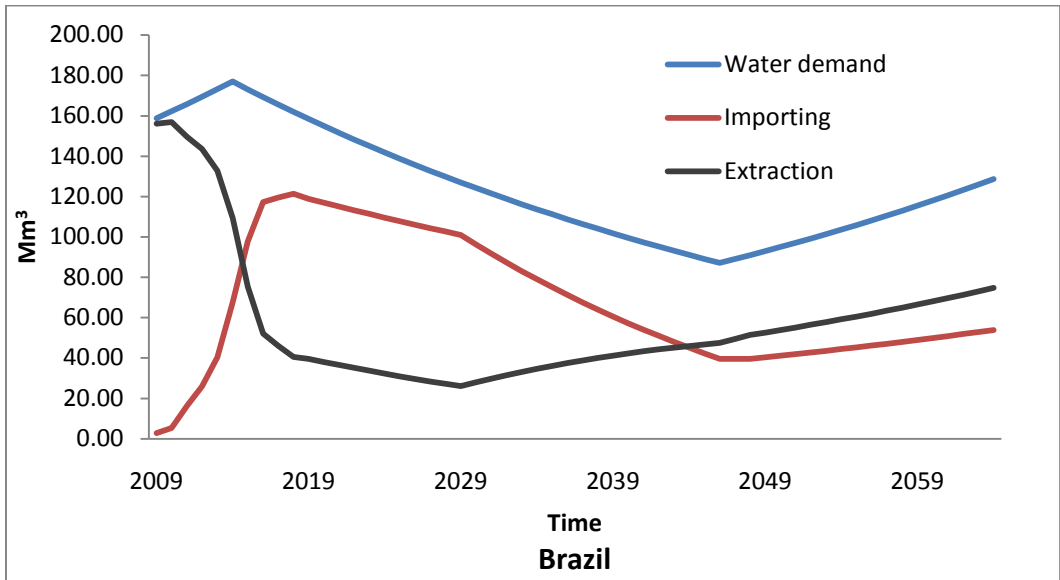


Figure 42. Water demand, importing, and extraction (Brazil).

Notes. This figure represents the optimal trajectories of the water demand, imported water, and ground water over the planning horizon when the parameter vector is ( $\phi=1.5, \lambda=1.3$ ) when wages are determined by Brazil.

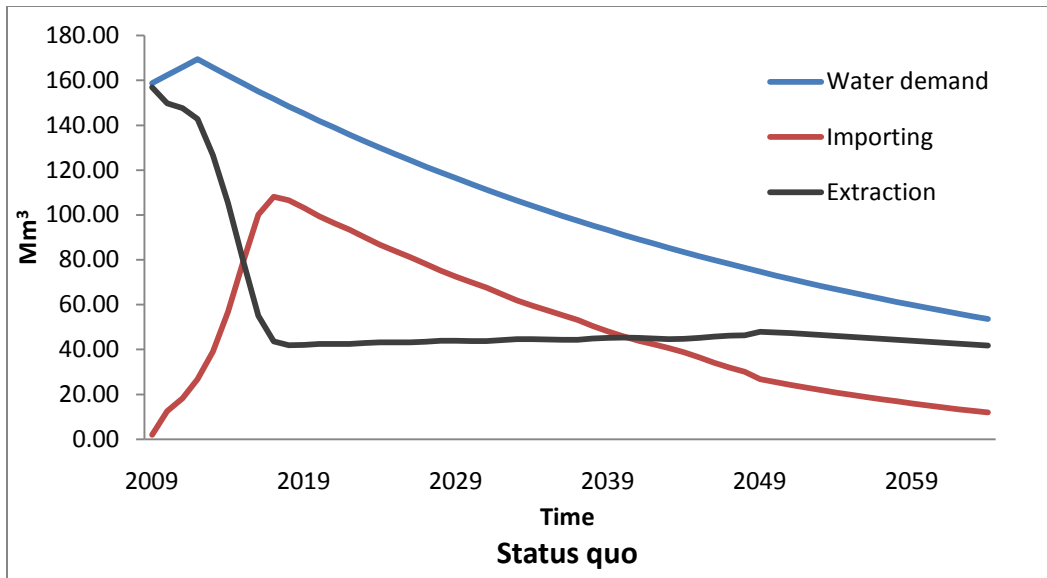


Figure 43. Water demand, importing, and extraction (status quo).

Notes. This figure represents the optimal trajectories of the water demand, imported water, and ground water over the planning horizon when the parameter vector is  $(\phi=1.5, \lambda=1.3)$  when wages are determined by the status quo.

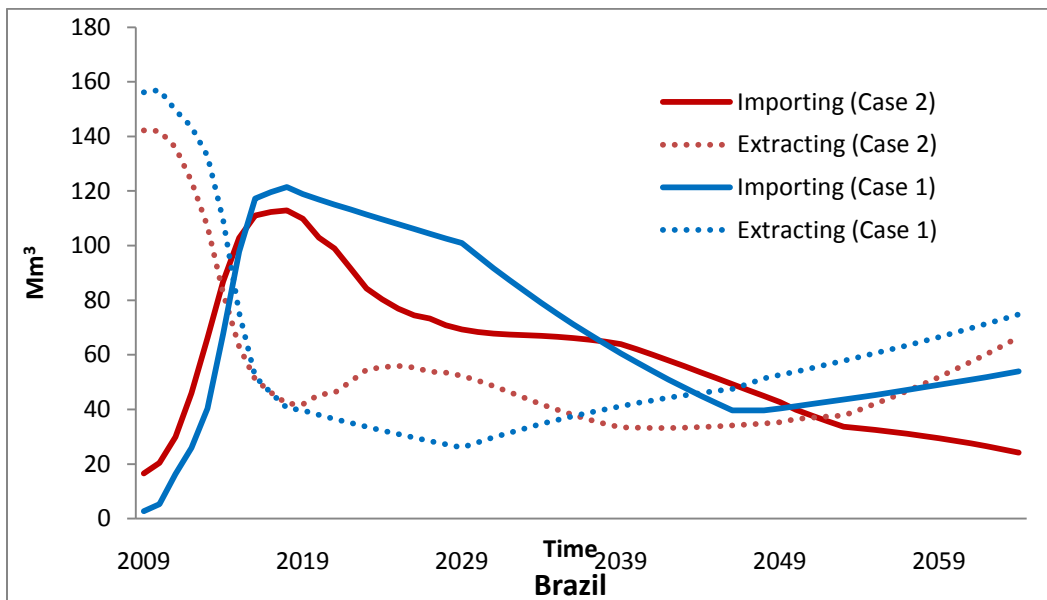


Figure 44. Water importing, and extraction Case 2 vs. Case 1 (Brazil).

Notes. This figure compares the importing and extraction trajectories of Case 2 with Case 1 when the wage is determined by Brazil.

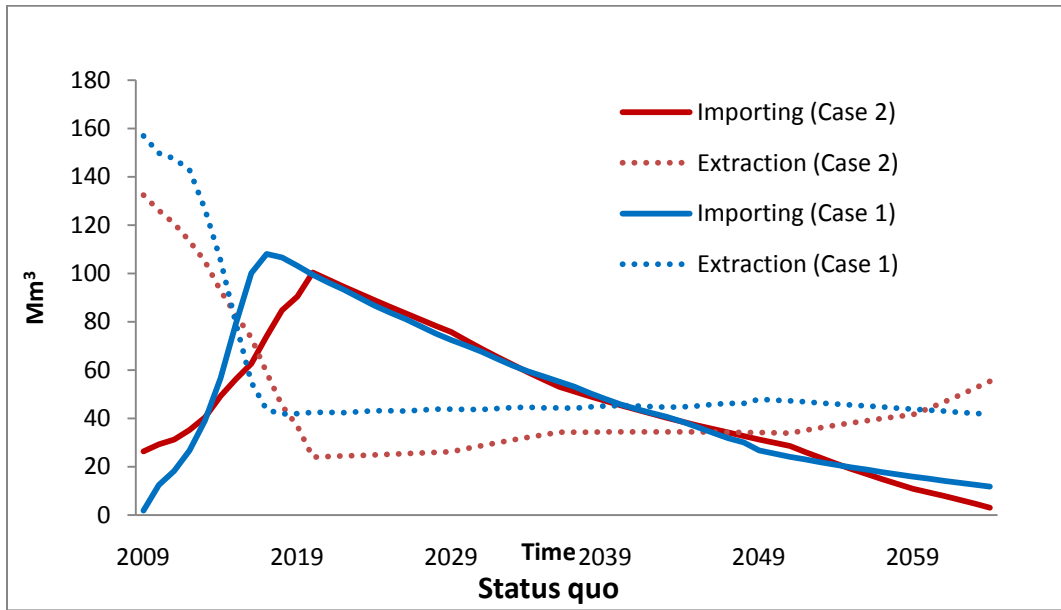


Figure 45. Water importing, and extraction case 2 vs. case 1 (Status quo).  
*Notes.* This figure compares the importing and extraction trajectories of Case 2 with Case 1 when the wage is determined by the status quo.

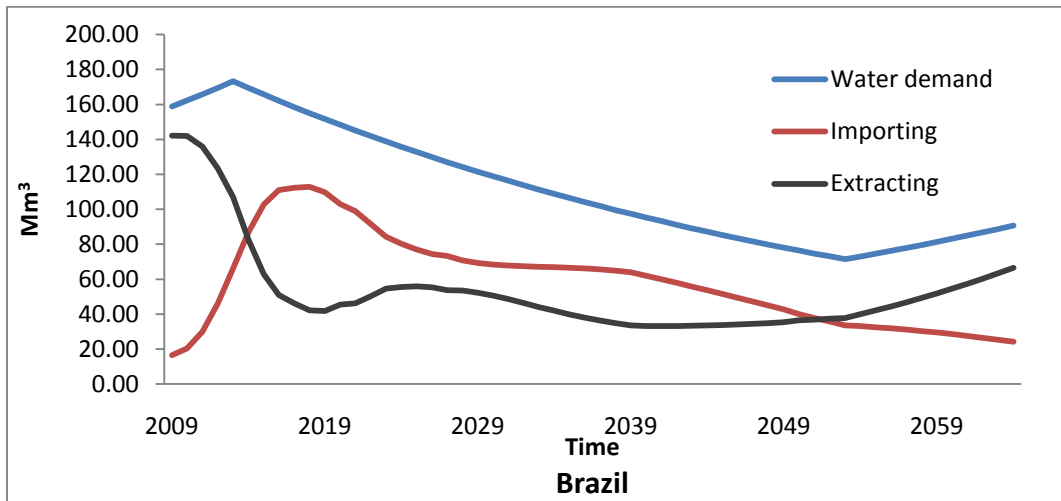


Figure 46. Water demand, importing, and extraction (Brazil).  
*Notes.* This figure represents the optimal trajectories of the water demand, imported water, and ground water over the planning horizon when the parameter vector is  $(\phi=3, \lambda=1.3)$  when wages are determined by Brazil.

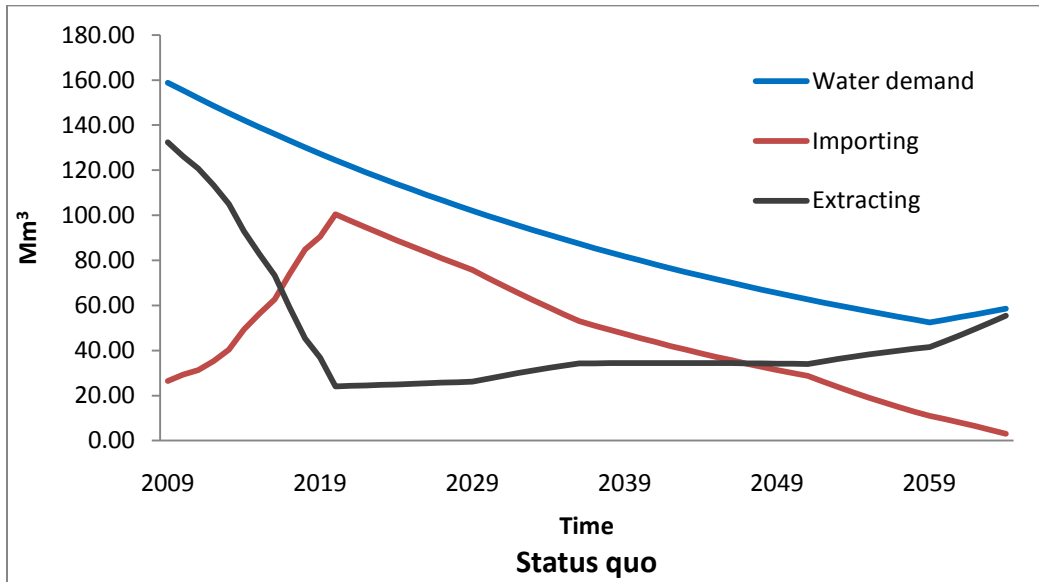


Figure 47. Water demand, importing, and extraction (Status quo).

*Notes.* This figure represents the optimal trajectories of the water demand, imported water, and ground water over the planning horizon when the parameter vector is  $(\phi=3, \lambda=1.3)$  when wages are determined by the status quo.

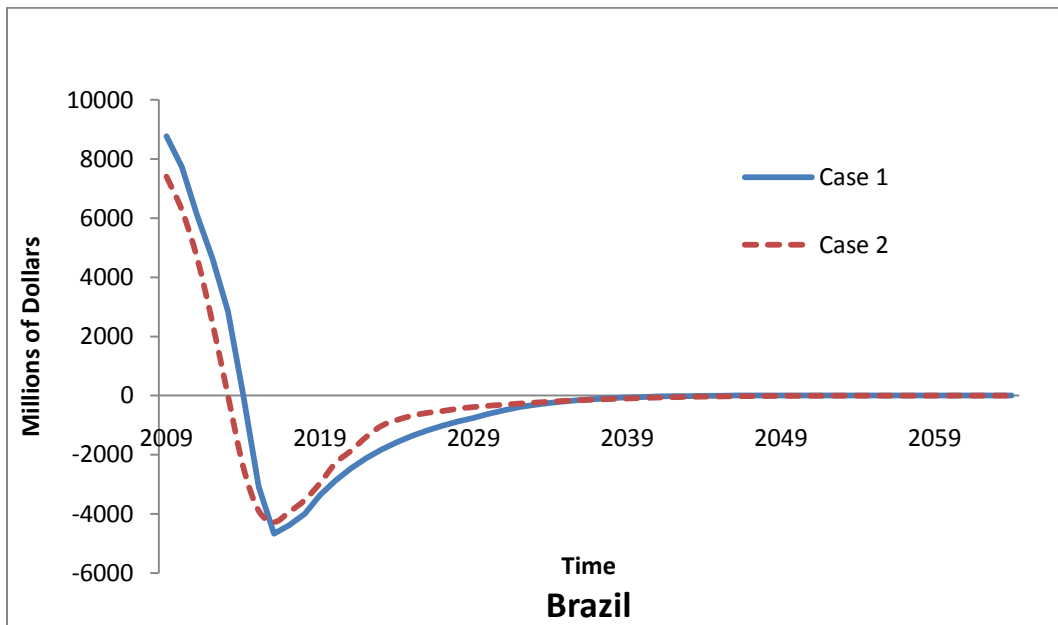


Figure 48. Welfare trajectories Case 1 and Case 2 (Brazil).

*Notes.* This figure represents the welfare trajectory for Cases 1 and 2 when wages are determined by the competition with Brazil.

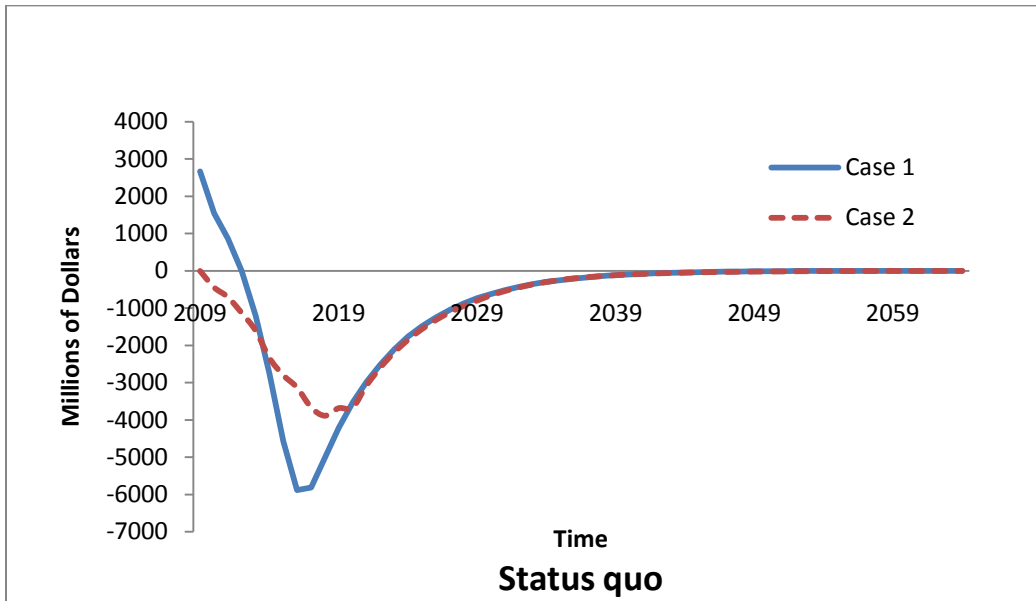


Figure 49. Welfare trajectories case 1 and case 2 (Status quo). *Notes.* This figure represents the welfare trajectory for Cases 1 and 2 when wages are determined by the status quo.

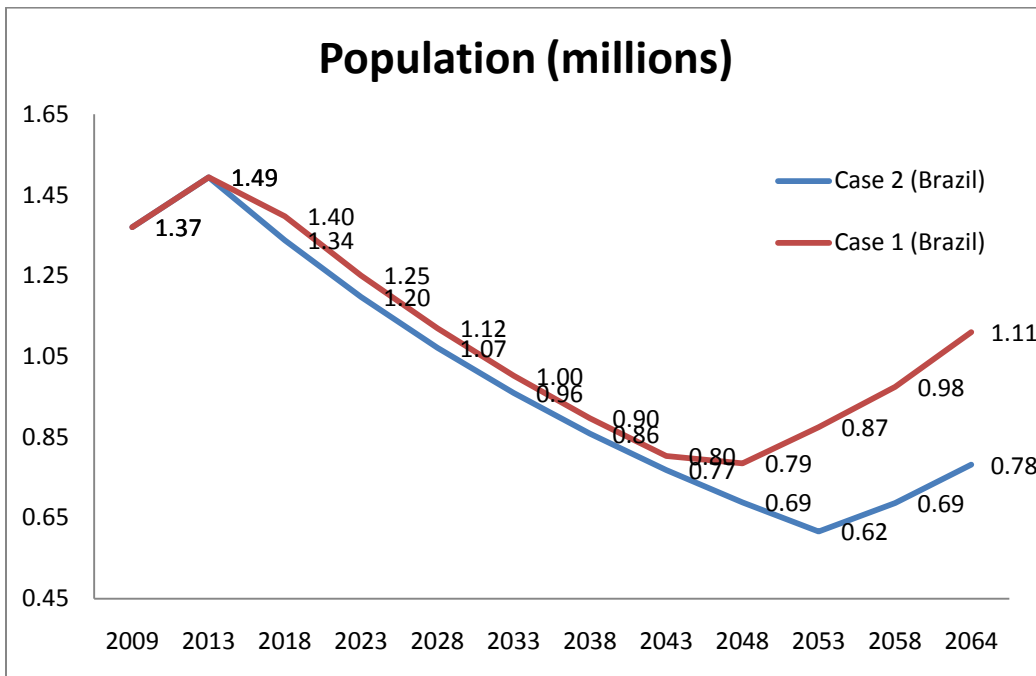


Figure 50. Population trajectories Case 2 and Case 1 (Brazil). *Notes.* This figure compares the population trajectories of Case 2 with Case 1 when the wage is determined by Brazil.

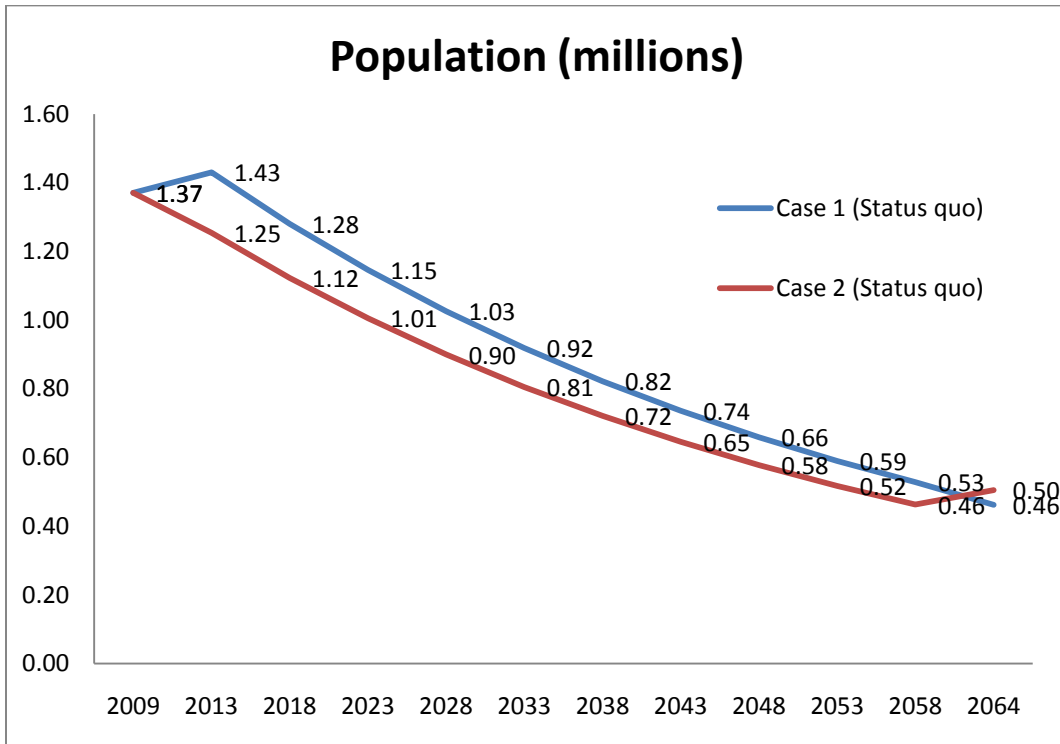


Figure 51. Population trajectories Case 2 and Case 1 (status quo).

Notes. This figure compares the population trajectories of Case 2 with Case 1 when the wage is determined by the status quo.

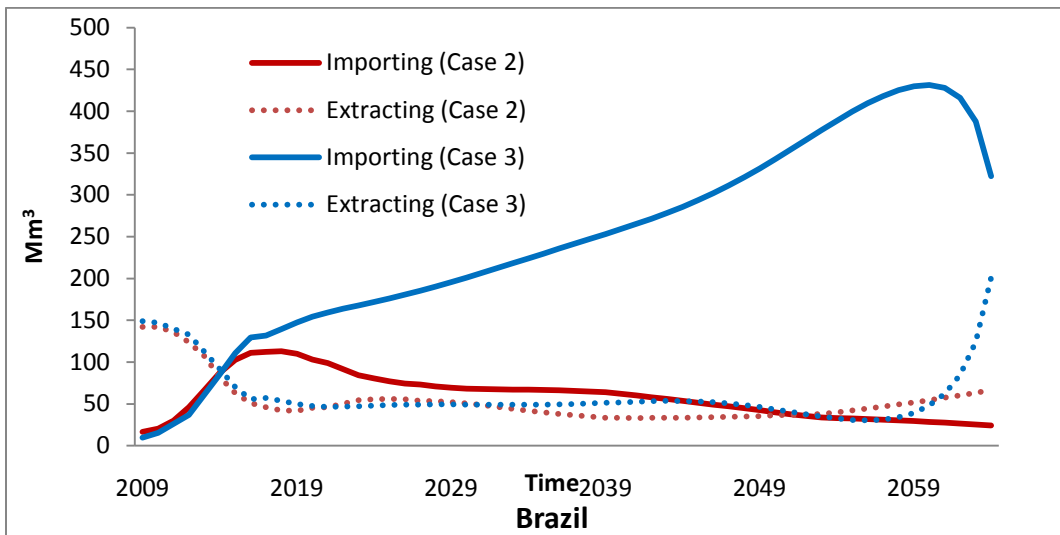


Figure 52. Water importing, and extraction Case 2 vs. Case 3 (Brazil).

Notes. This figure compares the importing and extraction trajectories of Case 2 with Case 3 when the wage is determined by Brazil.

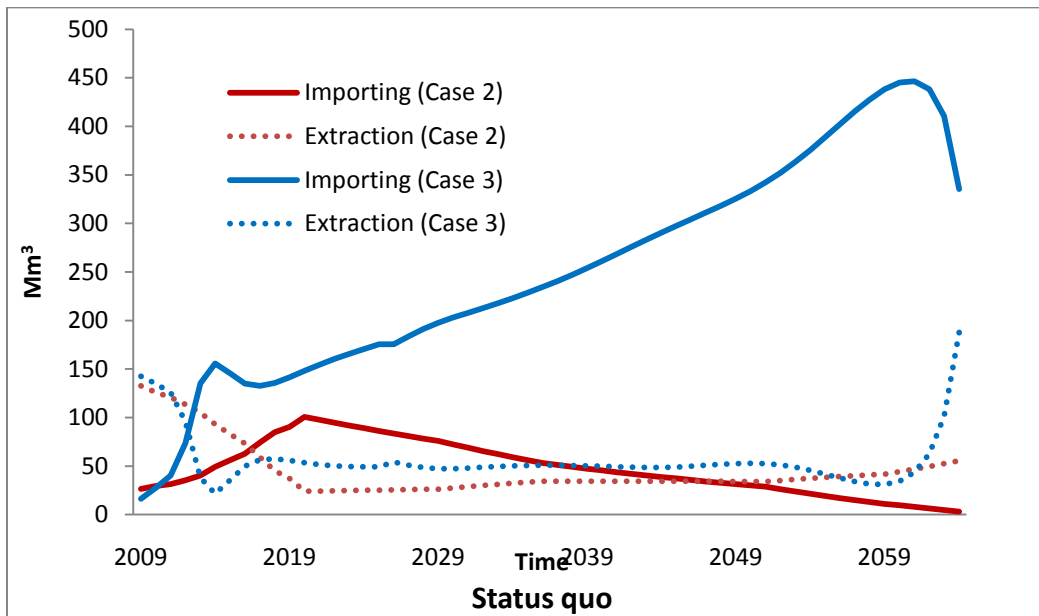


Figure 53. Water importing, and extraction case 2 vs. case 3 (Status quo).

Notes. This figure compares the importing and extraction trajectories of Case 2 with Case 3 when the wage is determined by the status quo.

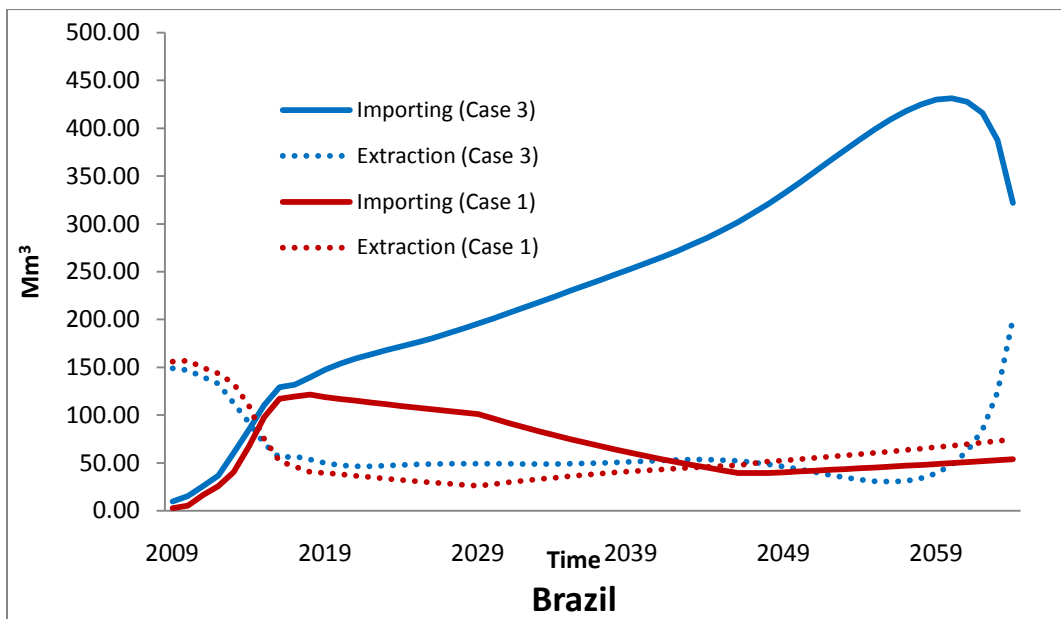


Figure 54. Water importing, and extraction Case 3 vs. Case 1 (Brazil). Notes. This figure compares the importing and extraction trajectories of Case 3 with Case 1 when the wage is determined by Brazil.



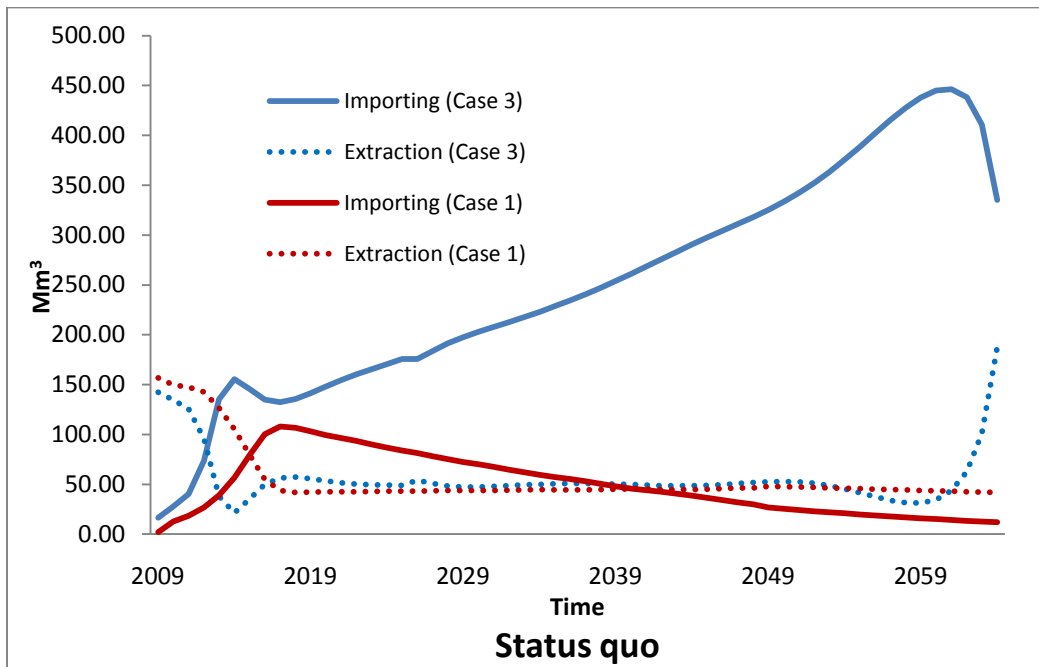


Figure 55. Water importing, and extraction Case 3 vs. Case 1 (status quo). *Notes.* This figure compares the importing and extraction trajectories of Case 3 with Case 1 when the wage is determined by the status quo.

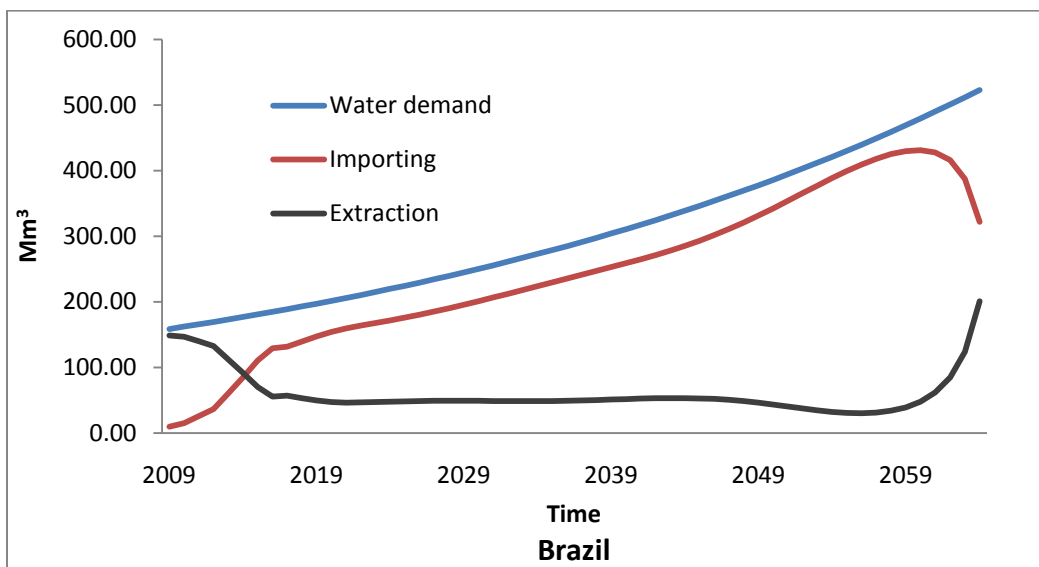


Figure 56. Water demand, importing, and extraction (Brazil). *Notes.* This figure represents the optimal trajectories of the water demand, imported water, and ground water over the planning horizon when the parameter vector is  $(\phi=1.5, \lambda=1.1)$  when wages are determined by Brazil.

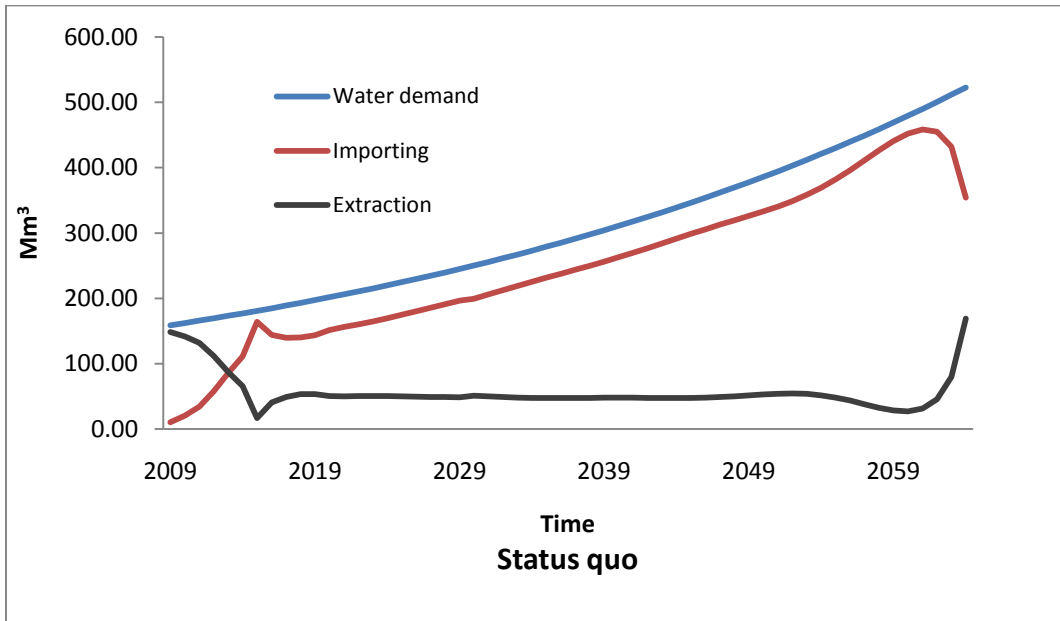


Figure 57. Water demand, importing, and extraction (Status quo). *Notes.* This figure represents the optimal trajectories of the water demand, imported water, and ground water over the planning horizon when the parameter vector is  $(\phi=1.5, \lambda=1.1)$  when wages are determined by the status quo.

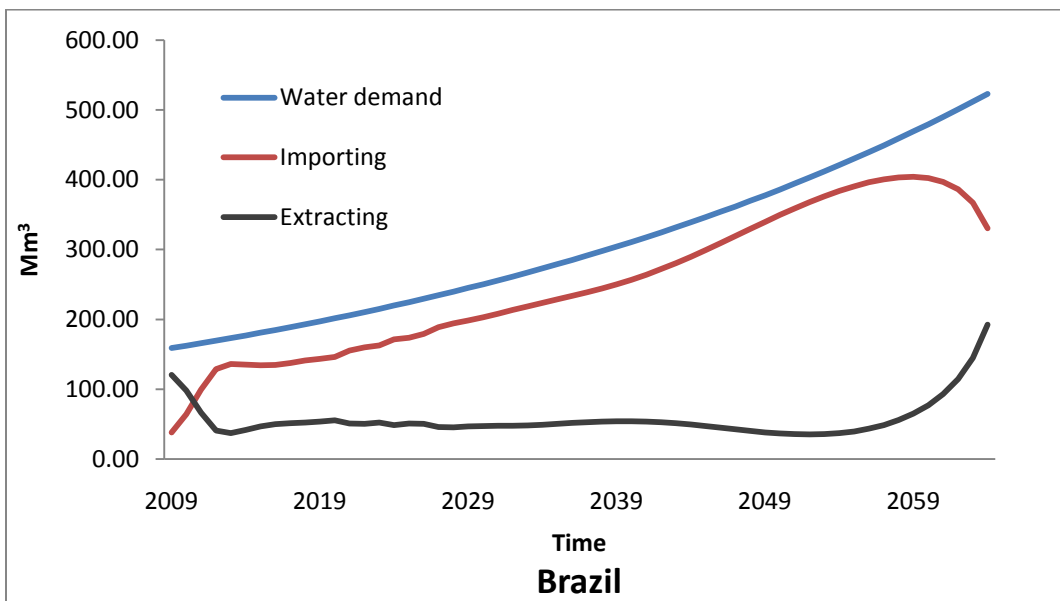


Figure 58. Water demand, importing, and extraction (Brazil). *Notes.* This figure represents the optimal trajectories of the water demand, imported water, and ground water over the planning horizon when the parameter vector is  $(\phi=3, \lambda=1.1)$  when wages are determined by Brazil.

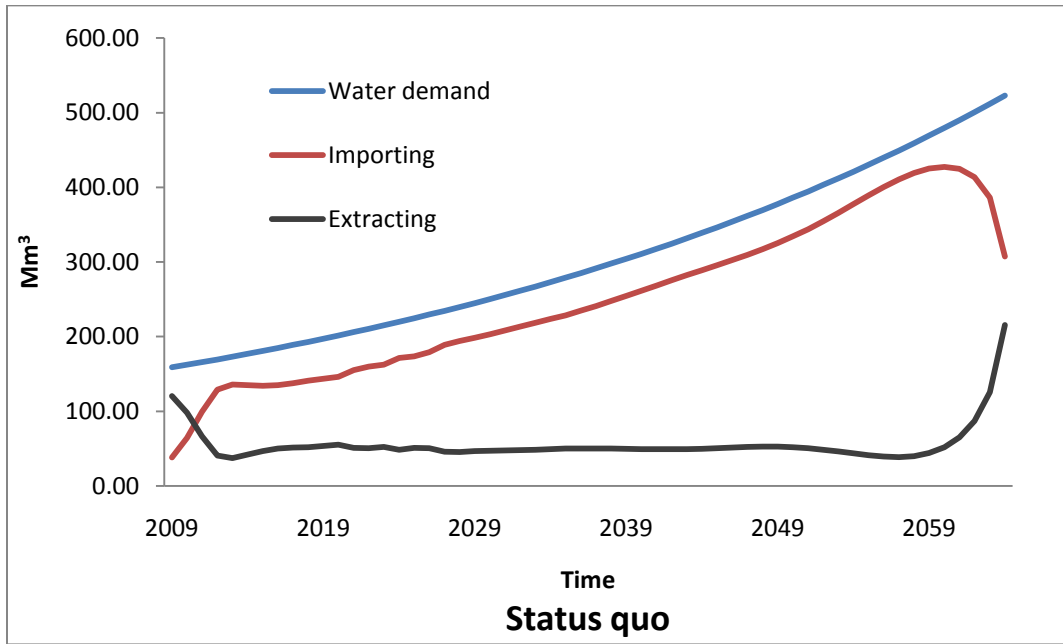


Figure 59. Water demand, importing, and extraction (Status quo). *Notes.* This figure represents the optimal trajectories of the water demand, imported water, and ground water over the planning horizon when the parameter vector is  $(\phi=3, \lambda=1.1)$  when wages are determined by the status quo.

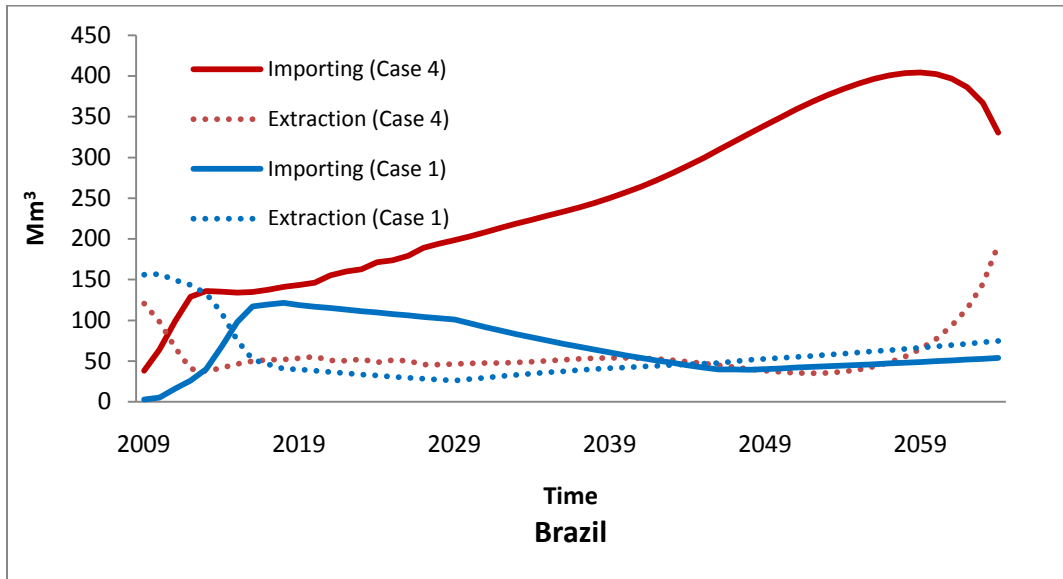


Figure 60a. Water importing, and extraction Case 4 vs. Case 1 (Brazil). *Notes.* This figure compares the importing and extraction trajectories of Case 4 with Case 1 when the wage is determined by Brazil.

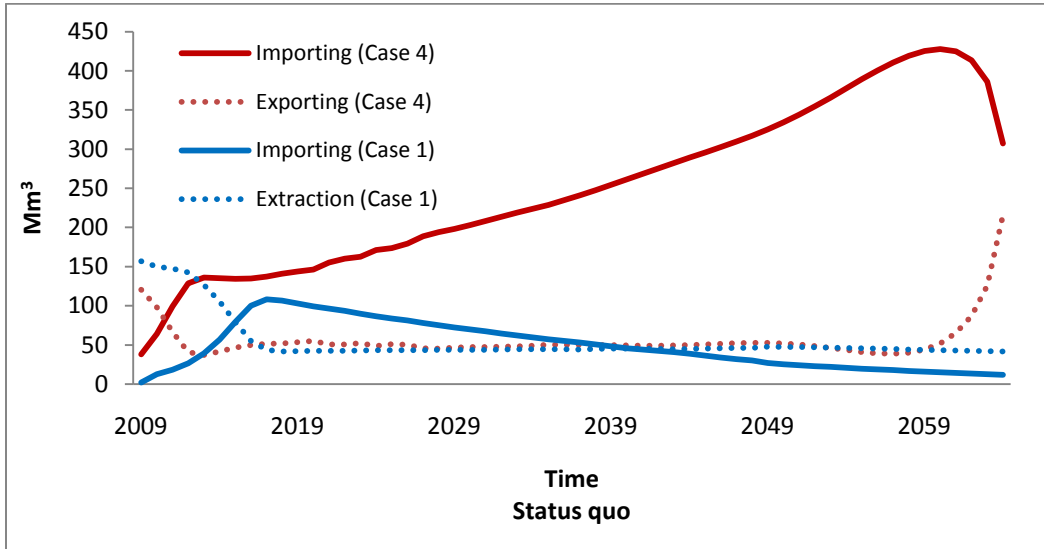


Figure 60b. Water importing, and extraction Case 4 vs. Case 1 (Status quo). *Notes.* This figure compares the importing and extraction trajectories of Case 4 with Case 1 when the wage is determined by the status quo.

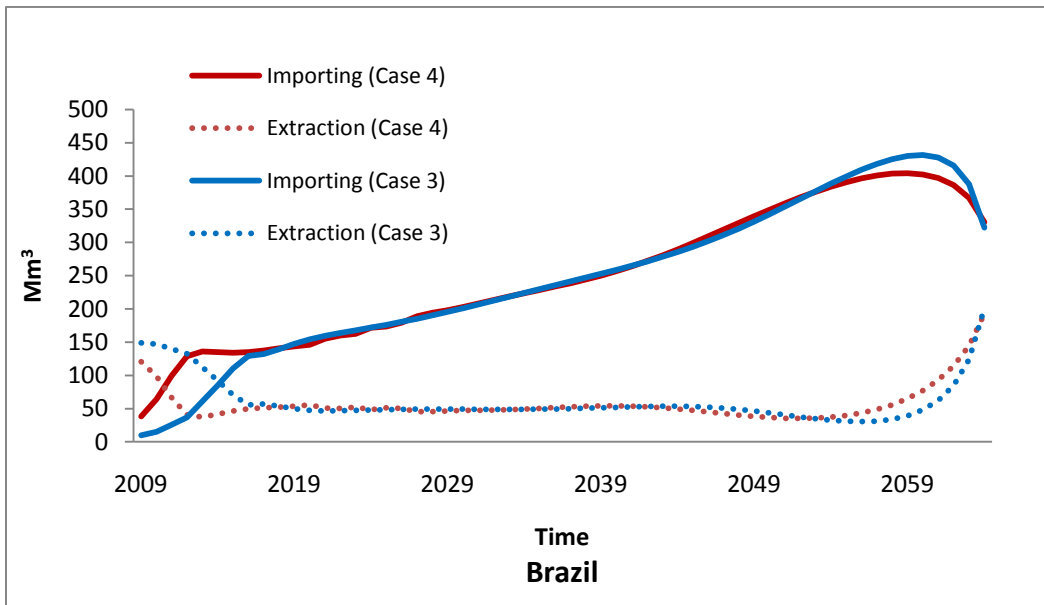


Figure 60c. Water importing, and extraction Case 4 vs. Case 3 (Brazil). *Notes.* This figure compares the importing and extraction trajectories of Case 4 with Case 3 when the wage is determined by Brazil.

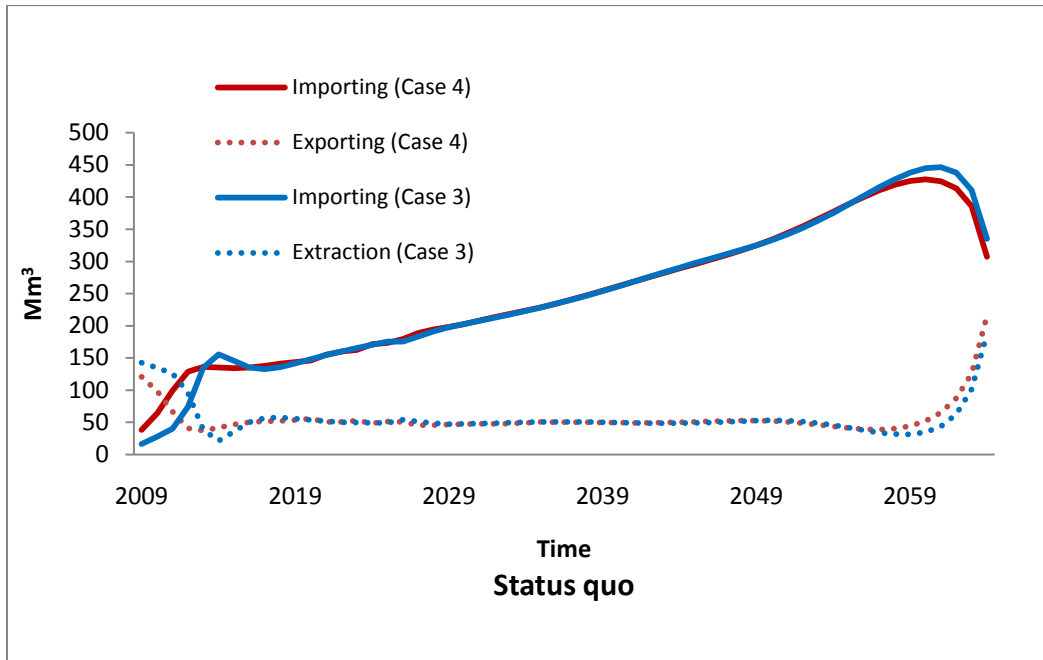


Figure 60d. Water importing, and extraction Case 4 vs. Case 3 (status quo). *Notes.* This figure compares the importing and extraction trajectories of Case 4 with Case 3 when the wage is determined by the status quo.

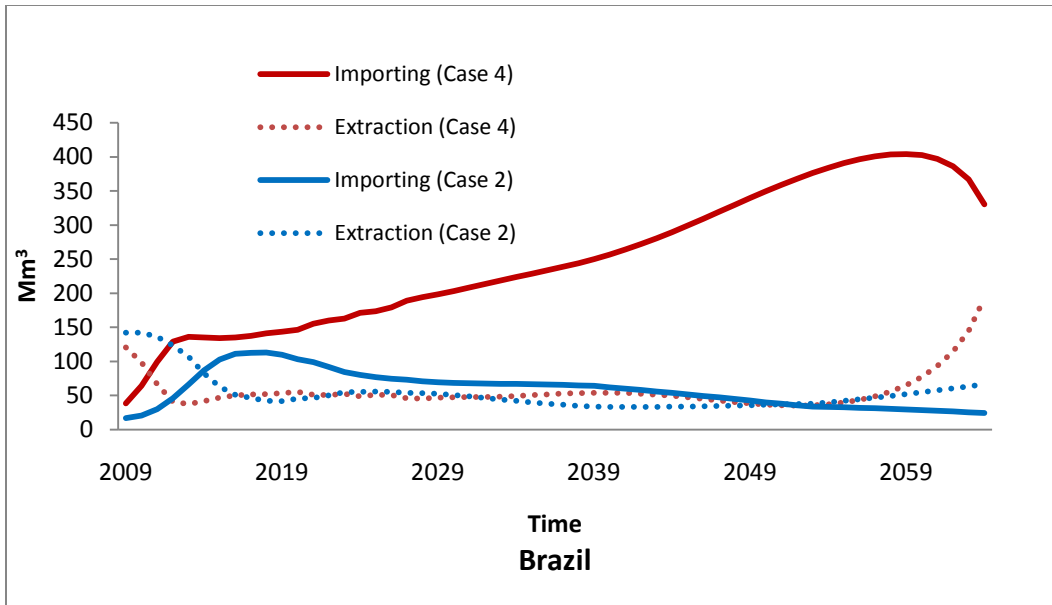


Figure 60e. Water importing, and extraction Case 4 vs. Case 2 (Brazil). *Notes.* This figure compares the importing and extraction trajectories of Case 4 with Case 2 when the wage is determined by Brazil.

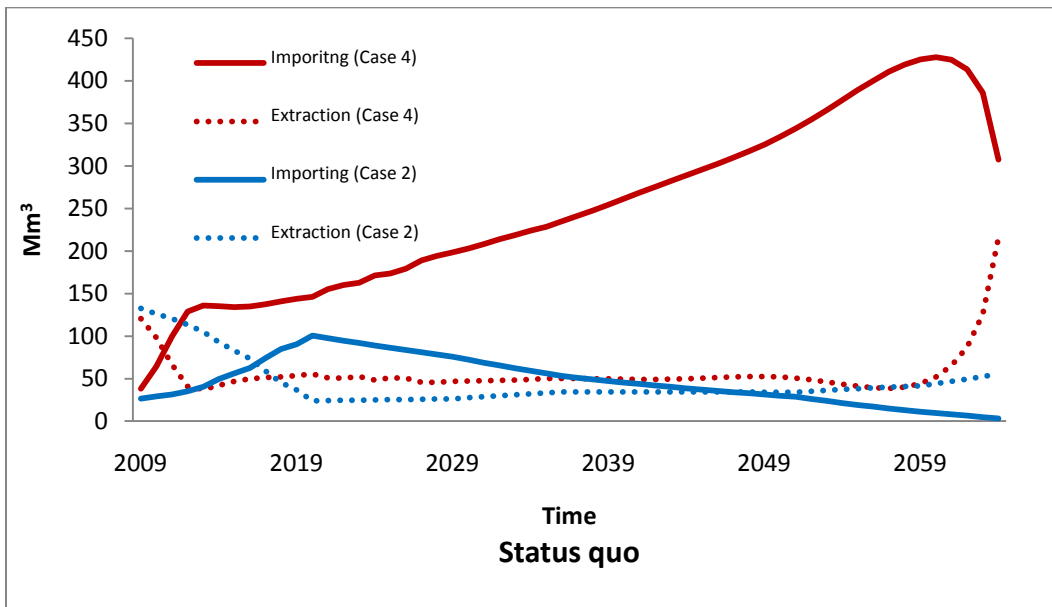


Figure 60f. Water importing, and extraction Case 4 vs. Case 2 (Status quo). *Notes.* This figure compares the importing and extraction trajectories of Case 4 with Case 2 when the wage is determined by the status quo.

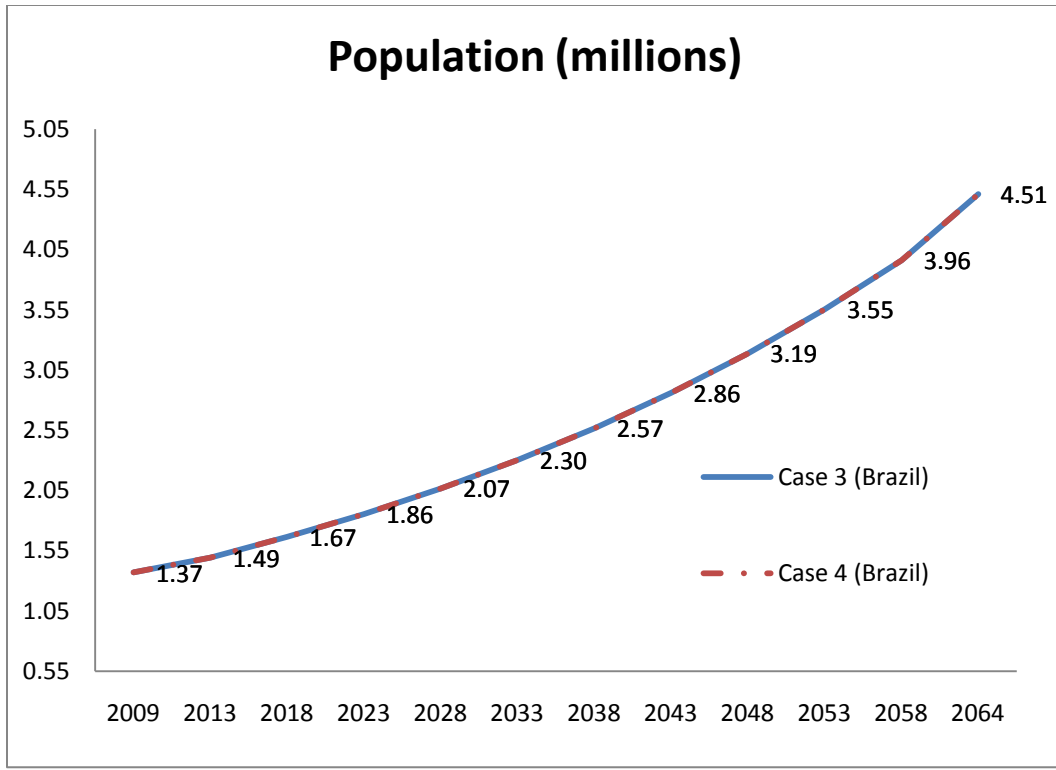


Figure 61. Population trajectories Case 3 and Case 4 (Brazil). *Notes.* This figure compares the population trajectories of Case 2 with Case 1 when the wage is determined by Brazil.

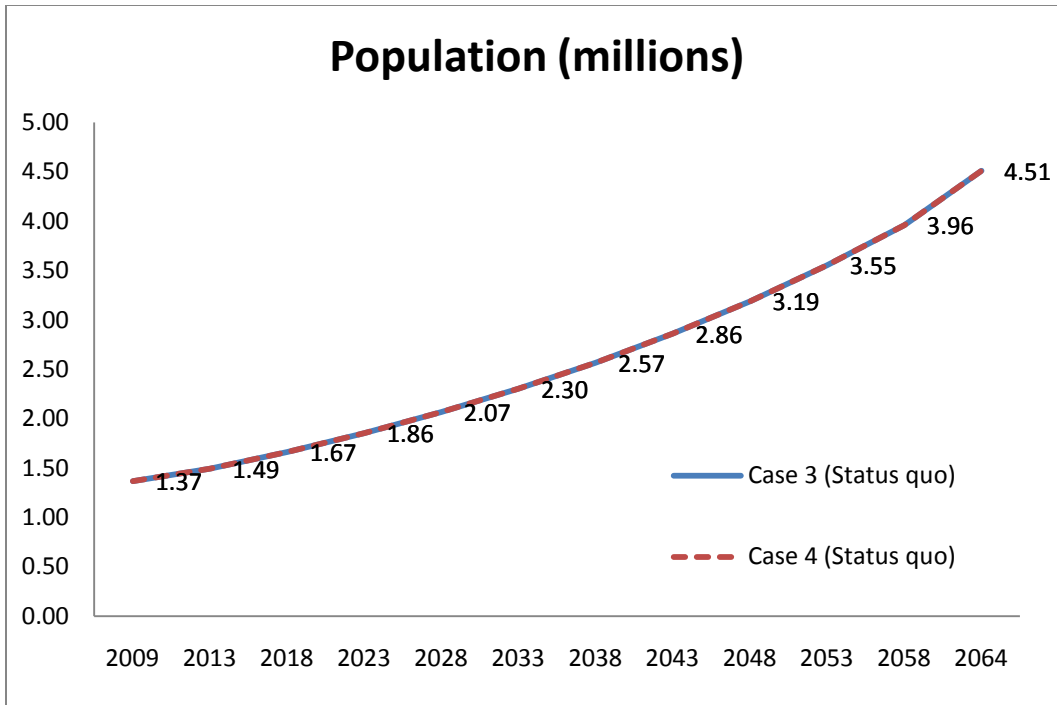


Figure 62. Population trajectories Case 3 and Case 4 (status quo). *Notes.* This figure compares the population trajectories of Case 2 with Case 1 when the wage is determined by the status quo.

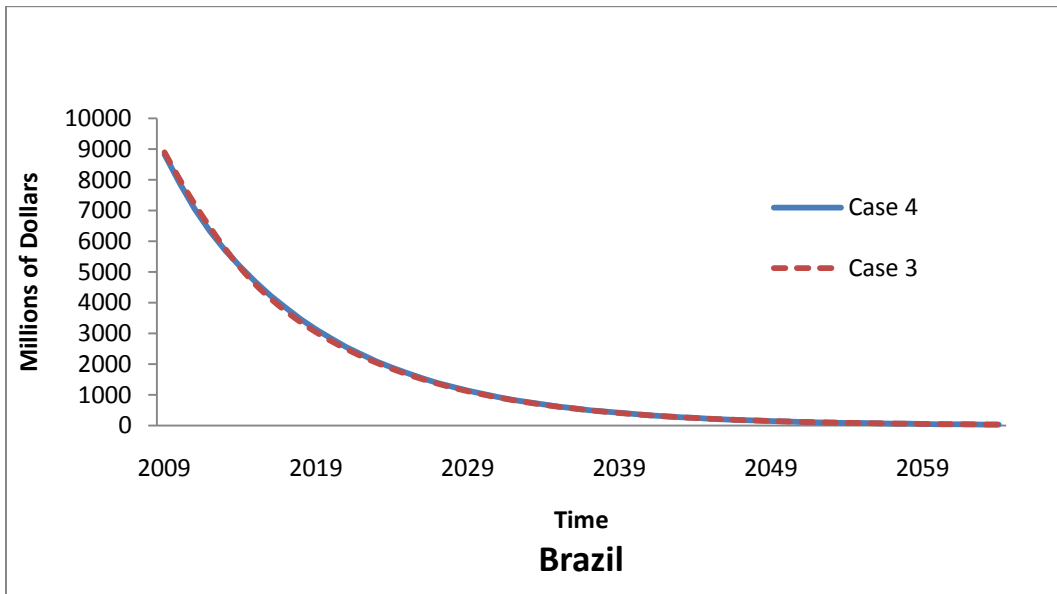


Figure 63. Welfare trajectories Case 3 and Case 4 (Brazil). *Notes.* This figure represents the welfare trajectory for Cases 4 and 3 when wages are determined by the competition with Brazil.



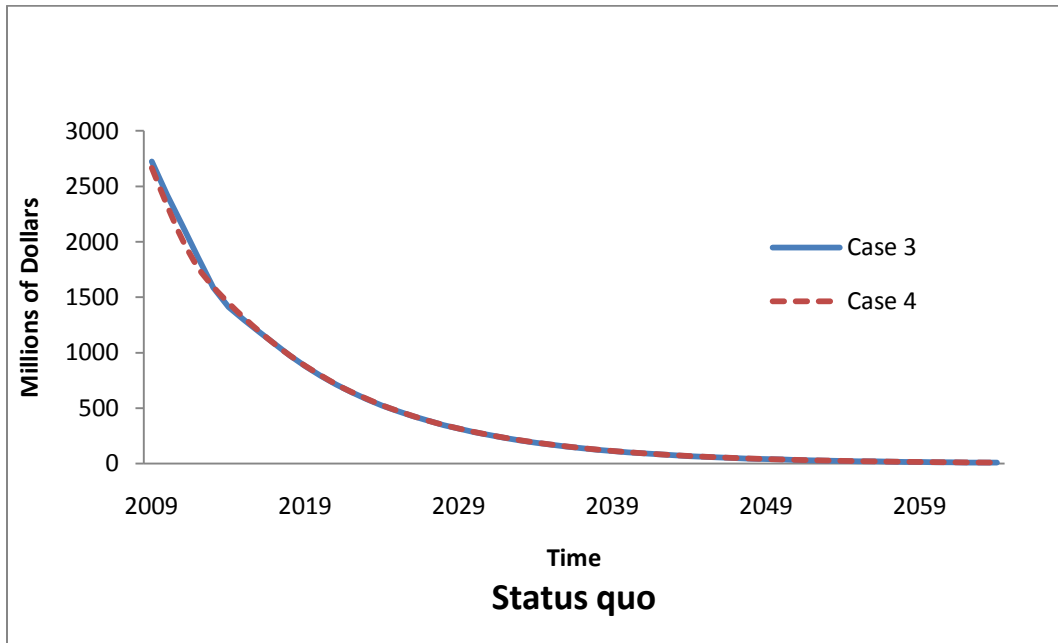


Figure 64. Welfare trajectories Case 3 and Case 4 (status quo).

*Notes.* This figure represents the welfare trajectory for Cases 3 and 4 when wages are determined by the status quo.

## CHAPTER 6

### CONCLUSION

Ciudad Juarez has limited water resources to meet its municipal water demand. It depends on ground water resources that at this point are being exhausted because the rate of use is higher than the rate of recharge. As a result, the cost of water extraction has increased not only because the water table is falling but also because the quality of ground water is deteriorating.

The economic growth of the city and many other cities at the border in the last four decades has been largely built on assembly factories (maquiladoras) that are mostly foreign owned and financed, and that are attracted to this region because of low wages and government incentives. The employment opportunities created by these factories have encouraged inward migration from other parts of Mexico—accounting for around one quarter of the urban labor force in the 1990s.

The first objective of this dissertation was to understand how water scarcity affects the development of Ciudad Juarez. In particular it explored the conditions in which Ciudad Juarez might be expected to achieve sustainable levels of water use, employment, investment and output. The objective was achieved by constructing an economic growth model in which output depends on two factors of production, labor and capital. Capital comes from foreign direct investment and labor comes from immigration from elsewhere in Mexico. Foreign capitalists are assumed to invest in Ciudad Juarez if nominal wage in the city is lower than in other locations with which Ciudad Juarez competes. In other words, the opportunity cost of investing in Ciudad Juarez is

determined by the nominal wage relative to the “international” nominal wage. Workers are assumed to migrate to Ciudad Juarez if disposable income, the nominal wage less the cost of water, is higher than average disposable income in Mexico. That is, migration to Ciudad Juarez will continue up to the point where the relative disposable income in Ciudad Juarez is equal to average disposable in the rest of Mexico. The limiting factor in this model is the cost of supplying water. As the population grows the cost of supplying water increases which in turn reduces disposable income and, therefore, in-migration to Ciudad Juarez.

It is shown that water scarcity has an important influence on the long run trajectory of both investment and employment. The more that population growth in Ciudad Juarez drives up the cost of water, the less attractive the city will be to in-migrants. That in turn affects the wages paid in the maquiladoras and hence the comparative advantage of Ciudad Juarez. Eventually the local economy is shown to converge on equilibrium levels of employment, investment, output and income. At this point the economic growth will end. The levels of capital and employment in the long run will depend on how information on water scarcity and supplying water costs is conveyed to the economic agents as well as on the initial conditions—i.e., ground water table, technology, wages, and operational costs. For instance, if the water tariff covers the total cost of supplying water each period the economy will converge to a steady state where the levels of employment and capital are positive. At this point the economy will be using the water resources in a sustainable way. On the other hand, if water tariffs are subsidized, the economy will achieve lower or zero levels of employment and capital in the long run. In this case, the economy will be not

sustainable. In other words, all else being equal the level of development in the long run depends on the water management strategies implemented by the city.

The second objective of this dissertation was to characterize efficient and sustainable water management strategies in Ciudad Juarez under particular demographic, economic and environmental conditions (a) when the only source of water is an aquifer, or (b) when there is conjunctive use ground and imported water. In the context of the growth model developed in the first part of the dissertation this required the identification of efficient water management strategies that lead both to sustainable (positive) levels of population and capital, and to the use of water at rates no greater than the recharge rate (natural and artificial) in the long run.

Two water resource situations were studied. In the first Ciudad Juarez relies exclusively on ground water to meet the water demand of the city—this reflects the current situation of Ciudad Juarez. It was assumed that the water utility can recharge reclaimed water to reduce the cost of ground water extraction. Hence, the problem for the utility was obtaining the optimal recharge trajectory to minimize the cost of supplying water and to reach a “sustainability target”—i.e. the ground water level set up by the water authorities to reduce the risk of climatic variability.

It was shown that the aquifer may be managed efficiently and sustainably by letting the utility minimize the cost of supplying water, by recharging ground water, and by setting water tariffs equal to the marginal cost of providing water. As a result of implementing efficient water management it was found to be possible to extend the life of groundwater resources by artificially recharging the aquifer in a cost-effective fashion. Furthermore, it was found that the disposable income of the residents of

Ciudad Juarez could be maximized, and in the long run the economy will be using ground water at sustainable rates—i.e. by equating abstraction and recharge rates.

The optimal recharge trajectory was found to depend on relative costs, the planning horizon, reclaiming and recharge capabilities, and the sustainability objectives of the municipal authorities. For instance, the utility is found to reclaim and recharge more water if the relative cost of extraction is higher. As the planning horizon or the recharging capability increases, the utility is able to smooth out the recharge trajectory. In particular, if the recharge capability increases, the utility will reduce the amount of water recharged in initial periods. However, as the sustainability target decreases, the amount of water recharged decreases only in later periods.

Population and economic growth (or decline) and the steady state levels of capital and employment both depend on the disposable income of the residents of Ciudad Juarez and hence the cost of water extraction, reclamation and recharge, on average disposable income in Mexico, and on the international nominal wage. For instance, if the cost of water extraction, reclamation and recharge decreases, or the international nominal wage increases, economic and population growth can persist for a longer period, and the steady state levels of capital and employment will be higher. The stability of the long run dynamics of the system are, however, sensitive to the parameter values selected. In particular, as the planning horizon increases, recharging behavior tends to be erratic when relative initial extraction cost is high. This causes migratory flows to fluctuate drastically around the steady state.

The other situation modeled assumes that Ciudad Juarez is able to import water, as well as to abstract, reclaim and recharge water to meet demand. This model is

motivated by the fact that Ciudad Juarez is considering importing water from elsewhere to maintain its economic growth and to offset the overdraft of the Bolson del Hueco aquifer. The problem for the utility is to deciding the optimal amount of water to abstract and to import to cover water demand at each period of time. As in the previous model, the utility is assumed to face a sustainability target. Two cases were analyzed: one with and without water recharge. It was shown that the aquifer is managed efficiently and sustainably by letting the utility minimize the cost of supplying water by recharging water and setting the water tariff equal to the marginal cost of providing water. As a result of implementing efficient water management it is possible to extend the life of ground water resources by artificially recharging the aquifer. In this case, however, the amount of water recharged will also depend on the relative cost of water imports, and may exceed the rate of groundwater abstraction. In the long run the economy will balance abstraction and reclamation and recharge rates.

It was shown that relative extraction cost, technology, recharge capability, and the sustainability target jointly determine the trajectories of water extracted, imported, reclaimed and recharged. For instance, as the relative extraction cost increases, water imports rise and water abstraction decreases. However, if the relative cost of water imports is low, economic and population growth can persist for longer periods, and the steady states levels of capital and employment will be higher than when Ciudad Juarez relies only on ground water. As in the previous case, it was also found that the calibrated model produced more variability in long run levels of employment, output and investment than expected. This is because of the non-convexities caused by the constant population rate of growth.

The main policy implications of this dissertation follow from the model results directly. In a desert (water constrained) environment, water management influences very much more than the price and reliability of supply. It influences the sustainable level of employment, output, investment and income. Although the efficiency of water management is not a necessary condition for the sustainability of these things, it turns out that efficient strategies may also be sustainable strategies. This requires taking into account the scarcity rents and externalities derived from the use of ground water as well as the cost of water infrastructure. However, water management must be associated with positive levels of economic activity to be sustainable. Not implementing these will imply externality for future generations of water users and lower levels of economic activity. These policy considerations coincide with the water management recommendations of OECD, UNESCO and World Bank (see Chapter 1).

However, implementing these policy recommendations is not an easy task in Mexico because, as stated in Chapter 3, the local, state, and the federal government do not have the monetary resources to renew and build water infrastructure, or to enforce the regulations with respect to the water resources. There may also be political gains to implementing inefficient water management policies, such as electricity subsidies. Indeed, the strategic interaction between stakeholders tends to affect the efficiency of water management strategies.

To close we identify four areas for further research:

1. Understanding implementation. The next step towards advancing the sustainable development agenda in this region will require research on options for the implementation of water management strategies that

provide more resources for infrastructural investment, that reduce the political gains from water use. It is one thing to identify the conditions that need to be met for water use strategies to induce sustainable levels of economic activity. It is another to implement those strategies, or at least to secure the conditions that would support their implementation.

2. Climate change. A second line of inquiry would be to explore the consequences of expected changes in environmental conditions. Most regional projections for climate change in the region suggest that mean temperatures are likely to increase, that mean precipitation is likely to fall, and that the variance in rainfall is likely to increase. Developing water strategies that are sustainable in these conditions does not involve a qualitative change in the approach, but would change the costs and benefits of alternative management options.
3. Agriculture. The agricultural sector is in fact the largest user of water in the Ciudad Juarez area, as it is in many other parts of the desert South West. In this dissertation the sector has not been addressed since it has been insulated from other water users. Agriculture has rights to water from the Rio Grande. It would be important to develop a general strategy for managing all water supplies together, and that would require an understanding of the marginal social benefit of water committed to food production in the area.
4. Equity. To simplify the problem this dissertation has not addressed heterogeneity in the labor force. It makes the assumption that all people consume the same quantity of water inelastically. But in fact patterns of use



are highly sensitive to income, and not all users are equally able to pay. An important extension of this research would be to understand the heterogeneity of the resident population, and to develop more effective models of water demand.

## REFERENCES

Agrawal, A., and Goyal, S. (2001). Group size and collective action - Third-parts monitoring in common-pool resources. *Comparative Political Studies* 34(1): 63-93.

Albiac, J., Sánchez-Soriano, J. and Dinar, A. (2008). Game theory: a useful approach for policy evaluation in natural resources and the environment. In Dinar, A., Albiac, J., Sánchez-Soriano, J. (pp.1-12). *Game theory and policymaking in Natural Resources and the Environment*. New York: Routledge. 400.

Allen, R. C. and M. Gisser (1984). Competition versus optimal-control in groundwater pumping. *Water Resources Research* 20(7): 752-756.

Arias, H. M. (2000). International Groundwaters: The Upper San Pedro River Basin Case. *Natural Resources Journal* 40(2): 199.

Asad, M., and Dinar, A., (2006). The Role of Water Policy in Mexico: Sustainability, Equity, and Economic Growth Considerations. *En breve*. Number 95. World Bank. Retrieved from <http://www.worldbank.org/lac>.

Asad, M. and Garduno, H. (2006). Water Resource Management in Mexico: the role of the Water Rights Adjustment Program (WRAP) in water sustainability and rural development. *Sustainable Development Working Paper. No 24*. World Bank. Retrieved from <http://www.worldbank.org/>.

Ashworth, J.B., and Hopkins, J., (1995). *Aquifers of Texas*. Texas Water Development Board Report 345. Austin, Texas.

Ashworth, J.B., (1990). *Evaluation of Ground-Water Resources in El Paso County, Texas*. Texas Water Development Board. Report 324. Austin, Texas.

Banco de Mexico (2010), Estadísticas Financieras. Retrieved from: <http://www.banxico.org.mx>

Baland J.M., and Platteau J.P. (2003). Economics of Common Property Management Regimes. In Mäler, K.-G. and J. R. Vincent. *Handbook of environmental economics*. Volume I (pp. 127-190). Amsterdam ; Boston, North-Holland/Elsevier.

Baliga S. and Maskin, E. (2003). Mechanism Design for the Environment. In Mäler, K.-G. and J. R. Vincent (2005). *Handbook of environmental economics*. Volume I (pp. 305-324). Amsterdam ; Boston, North-Holland/Elsevier.

Barret, S. (2005). The theory of International Environmental Agreements. In Mäler, K.-G. and J. R. Vincent (2005). *Handbook of environmental economics*. Volume III (pp. 1457-1512). Amsterdam ; Boston, North-Holland/Elsevier.

Barrett, S. (1999). International Cooperation and the International Commons. *Duke Environmental Law and Policy Forum* X (1): 131-147.

Barrett, S. (1994). Conflict and cooperation in managing international water resources. *Policy research working paper*, The World Bank, Policy Research Dept., Public Economics Division.

Barret, S. (1994b). Self-Enforcing International Environmental Agreements, *Oxford Economics Papers*, 48, 878-94.

BECC (2009). Border Environment Cooperation Commission. Retrieved from: <http://www.cocef.org>.

Becker, N. and Easter, K. W. (1999). Conflict and cooperation in managing international water resources such as the great lakes. *Land Economics* 75(2): 233-245.

Bennett, L., Howe, C., and Shope, J. (2000). Water Allocation Mechanism: Efficiency Aspects. *American Journal of Agr. Econ.* 82(4): 1006-1015.

Bennett, L., Ragland, S., and Yolles, P. (1998). Facilitating International Agreements Through an Interconnected Game Approach: The Case of River Basins. In Just, R. E. and Netanyahu S. (1998). *Conflict and cooperation on trans-boundary water resources* (pp. 27-41). Boston, Kluwer Academic.

Bernheim, B. D., Peleg, B., and Whinston, M. (1987). Coalition-Proof Nash Equilibria I. Concepts, *Journal of Economic Theory*, vol. 42: 1-12.

Bernheim, B. D. and Whinston, M. (1987). Coalition-Proof Nash Equilibria II. Applications. *Journal of Economic Theory*, vol. 42: 13-29.

Biswas, A., (1999). Introduction: Water crisis: Current Perceptions and Future Realities. In. Salman, S. M. A. and World Bank. *Groundwater : legal and policy perspectives : proceedings of a World Bank seminar (2-20)*. Washington, D.C., World Bank.

Bloetscher, F., Muniz, A., and Witt, G. (2005). *Groundwater Recharge: Modeling, Risks, and Regulations*. USA: McGraw Hill. 338.

Brill, T. S. and Burness, H. S. (1994). Planning versus competitive rates of groundwater pumping. *Water Resource Research* 30(6): 1873–1880.

Bromley, D. W. (1989). Institutional change and economic efficiency. *Journal of Economic Issues* 23(3): 735–759.

Brown, B. Jr. (1974). An optimal program for managing common property resources with congestion externalities. *Journal of Political Economy* 82: 163–173.

Brown, G. and Deacon, R. (1972). Economic optimization of a single cell aquifer. *Water Resources Research* 8: 552–564.

Brown, C. (2005) Transboundary water resource issues on the US-Mexico border. [Electronic version] *VertigO - la revue électronique en sciences de l'environnement*, Hors-série 2 | september 2005. Retrieved from <http://www.vertig0.fr.org>

Brown, C. (2003). New directions in binational water resource management in the US-Mexico borderlands. *The Social Science Journal* 40(4), 555-572.

BSL (Bureau of Labor Statistics) (2009), Databases, Tables and Calculators (International). Retrieved from: <http://www.bls.gov/data/international>.

Burness, H. S. and Brill, T. C. (1992). The role for policy in common pool groundwater use. *Resource and Energy Economics* 23, 19–40.

Burness, H. S. and Martin, W. E. (1988). Management of a tributary aquifer. *Water Resources Research* 24, 1339–1344.

Burt, O. R., (1964). Optimal Resource Use over Time with an Application to ground water, *Management Science*, 11, 80-93.

Burt, O.R., (1966). Economic control of groundwater reserves, *Journal Farm Economics*. 48, 632-647.

Burt, O. R., (1967). Temporal allocation of groundwater, *Water Resource Research* 3(1), 45-56

Carillo, J. and Schatan, C. (2005). Introducción. In Carillo, J. and Schatan, C. (eds). *El medio ambiente y la maquila en México: un problema ineludible*. (pp. 13-21). México, D.F.: CEPAL.

Carter, N. and Ortolano, L. (2002). Impact of Two NAFTA Institutions on Border Water Infrastructure. In Fernandez, L., and R. Carson, (eds). *Both sides of the border transboundary environmental management issues facing Mexico and the United States* (pp. 29-53). Dordrecht ; Boston, Kluwer Academic Publishers. 501.

Caswell, M. and Zilberman, D. (1985). The choice of irrigation technologies in California. *American Journal of Agricultural Economics* 67: 224–234.

Cervera, L. E. (2007). Indicadores de uso sustentable del agua en Ciudad Juárez, Chihuahua. *Estudios Fronterizos. Nueva época* 8: 16.

Chavez, O. E. (2000). Mining of Internationally Shared Aquifers: The El Paso-Juarez Case. *Natural Resources Journal* 40(2): 237.

Clement, N. C. (2002). The U.S.-Mexican border environment : U.S.-Mexican border communities in the NAFTA era. Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Comrie, A. (2003). Climate Doesn't Stop at the Border: U.S.-Mexico Climatic Regions and Causes of Variability. In Diaz, H. F. and Morehouse, B. J. (2003). *Climate and water: transboundary challenges in the Americas*. Netherlands: Kluwer Academic Publishers. 401.

Cummings, R. G. and McFarland, J.W. (1973). Groundwater management and salinity control. *American Journal of Agricultural Economics*. 56, 830–836.

Dasgupta, P. (1982). *The control of resources*. Cambridge, Mass., Harvard University Press.

Dasgupta, P., and Heal, G. M. (1974). The Optimal Depletion of Exhaustible Resources. *Review of Economic Studies* 41. Symposium, 3-28.

Dasgupta, P. and Heal, G. M. (1979). *Economic theory and exhaustible resources*. Cambridge University Press.

Dasgupta, P. and K.-G. Mäler (1994). *Poverty, institutions, and the environmental-resource base*. Washington, D.C., World Bank.

Dasgupta D., Mäler K.G., and Vercelli A. (1997). Introduction: The Economics of Transnational Commons. In Dasgupta, P., K.-G. Mäler, and Vercelli, A. (1997). *The economics of transnational commons*. (pp.1-17). Oxford New York, Clarendon Press ; Oxford University Press.

De la Garza Toledo, E. (2007). The Crisis of the Maquiladora Model in Mexico. *Work and Occupations* 34(4): 399.

Díaz-Bautista, A., Avilés, J. A., and Rosas, M.A. (2003). Desarrollo Económico de la Frontera Norte de México. *El Colegio de la Frontera Norte* (mimeo).

Dinar, S. (2006). Assessing side-payment and cost-sharing patterns in international water agreements: The geographic and economic connection. *Political Geography* 25(4): 412-437.

Dinar, A. (2000). *The political Economy of Water Pricing Reforms*. World Bank. Oxford University Press.

Dinar, A. and Xepapadeas, A. (1998). Regulating water quantity and quality in irrigated agriculture. *Journal of Environmental Management* 54(4): 273–290.

Dixon, L.S. (1991) Common Property Aspects of Ground Water Use and Drainage Generation. In Dinar A. and Zilberman, D. (eds.), *The Economics and Management of Water and Drainage in Agriculture* (pp. 200-245). Norwell, MA: Kluwer Academic Publishers.

Dombrowsky, I. (2007). *Conflict, cooperation and institutions in international water management : an economic analysis*. Cheltenham, UK ; Northampton, MA, E. Elgar.

Dussel, E.P (2009). La manufactura Mexicana: ¿opciones de recuperación?. *Economía Informa*. Núm. 357. Marzo-abril: 41-52.

EPWU (El Paso Water Utilities) Hydrogeology Report 04-01 March. Retrieved from: <http://www.epwu.org/information>.

EPWU (El Paso Water Utilities) (2002). *Present and Future Sources of Water Supply*. Retrieved from: <http://www.epwu.org/sources.html>.

EPWU (El Paso Water Utilities) 2010. Public Information. Retrieved from: <http://www.epwu.org/information>.

Erickson, C. (2003). The economies of El Paso and Ciudad Juárez. In Sandalla, E. (Eds). *The U.S.-Mexican environment: Dynamics of human-environment interactions*. (pp 273-296). Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Carrasco, H. (2009, August 16). Por arrancar, suministro del agua concesionada a Carlos Slim. *EL DIARIO*.

Fahy, M.P., and Sheng, Z., (2000). Management Strategies for the Hueco Bolson. *El Paso Water Utilities*, Strategic Development Division. Retrieved from <http://www.epwu.org>.

Fernandez, L. (2008). Wastewater pollution abatement across an international border. *Environment and Development Economics* 14: 67-88.

Fernandez, L. (2006). Transboundary water amangement along the U.S.-Mexico border. In Goetz, R.-U. and D. Berga (eds). *Frontiers in water resource economics* (pp. 153-177). New York, Springer Science.

Fernandez, L. (2005). Coastal watershed management across an international border in the Tijuana River watershed. *Water Resources Research* 41(5). 20-55.

Fernandez, L. (2004). Revealed preferences of an international trade and environment institution. *Land Economics* 80(2). 224-238.

Fernandez, L. (2002). Trade's dynamic solutions to transboundary pollution. *Journal of Environmental Economics and Management* 43(3). 386-411.

Finus, M. (2001). *Game theory and international environmental cooperation*. Cheltenham, UK ; Northampton, MA, Edward Elgar.

Foster, C. and Hamlyn, E. (2003). Modeling Water Availability and Use in the Paso del Norte Region. In Sandalla, E. (Eds). *The U.S.-Mexican environment: Dynamics of human-environment interactions*. (pp 273-296). Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Forster, Craig., B. (2003), Overview of the Border +20 System Model Prototype: The Paso del Norte Region. In Sandalla, E. (Eds). *The U.S.-Mexican environment: Dynamics of human-environment interactions*. (pp 273-296). Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Frisvold, G. and Schimmelpfennig, D. (1998). Trans-Boundary Water Agreements. In Just, R. E. and Netanyahu S. (1998). *Conflict and cooperation on trans-boundary water resources* (pp. 27-41). Boston, Kluwer Academic.

Frisvold, G. B. and Caswell, M. F. (2000). "Transboundary water management Game-theoretic lessons for projects on the US–Mexico border." *Agricultural Economics* 24(1): 101-111.

Frisvold, G. B. and Caswell, M. F. (2002). Financing Bilateral Water Projects on the U.S.-Mexico Border: Past, Present and Future. In Fernandez, L., and R. Carson, (eds). *Both sides of the border transboundary environmental management issues facing Mexico and the United States* (pp. 131-161). Dordrecht ; Boston, Kluwer Academic Publishers. 501.

Fuentes, C. M. (2000). "Urban Function and Its Effect on Urban Structure: The Case of Ciudad Juarez, Chihuahua". *Journal of Borderlands Studies* 15(2).15-23.



Ganster, P., Sweedler, A., and Clement, N. (2003a). Development, Growth, and the Future of the Border Environment. In *The U.S.-Mexican Border Environment*.

Ganster, P., Pijawake, D., Rasmussen, P., and Van Schoik, (2003b). Overview-Findings of Border Institute I, The U.S.-Mexican border environment: a road map to a sustainable 2020. In Ganster, P. (ed). *The U.S.-Mexican border environment : A road map to a sustainable 2020*.(pp 1-32). Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Ganster, P. (2003c) . Economy and Environment: Overview and Recommendations. In Ganster, P. (ed). *The U.S.-Mexican border environment : Economy and environment for a sustainable border region*. Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Ganster, P. and D. E. Lorey (2005). *Borders and border politics in a globalizing world*. Lanham, MD, SR Books.

Ganster, P. and D. E. Lorey (2008). *The U.S.-Mexican border into the twenty-first century*. Lanham, Rowman and Littlefield.

Gisser, M., and Mercado, A., (1973) Economic aspects of ground water resources and replacement flows in semiarid agricultural areas, *American Journal of Agricultural Economics*, 55, 461-466.

Gisser M., and D. Sanchez (1979). "Some additional economic aspects of ground water resources and replacement flows in semi-arid agricultural areas", *International Journal of Control*. Vol. 31, No 2, 331-341.

Gisser, M., and Sánchez, D. A. (1980), Competition Versus Optimal Control in Groundwater Pumping, *Water Resour. Res.*, 16(4), 638–642

Gisser, M. (1983). Groundwater-Focusing on the Real Issue. *Journal of Political Economy* 91(6): 1001-1027.

Hall, R. E. (2004). Transboundary Groundwater Management: Opportunities under International Law for Groundwater Management in the United States-Mexico Border Region. *Arizona Journal of International and Comparative Law* 21: 873.

Hecht, A., Whelan, P. and Sowell, S. (2003). Sustainable Development on the U.S-Mexican Border: Past Lessons, Present Efforts, Future Possibilities. In Ganster, P. (eds). *The U.S.-Mexican border environment : Economy and environment for a sustainable border region*. Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Holland, S., (2006) "privatization of water resource development", *Environmental and Resource Economics* 34, 291-315.

Hume, B. B. (2000). Water in the U.S.-Mexico Border Area. *Natural Resources Journal* 40(2). 189-197.

Hutchison, P. G., (2004). "Hueco Bolson Groundwater Conditions and Management in the El Paso Area".

Heywood, C.E., and Yager, R.M., (2003). Simulated Ground-water Flow in the Hueco Bolson, an Alluvial-basin Aquifer System Near El Paso, Texas. *US Geological Survey Water-Resources Investigation Report 02-4108*, Albuquerque, NM.

Hibbs, B.J., Ashworth J.B., Boghici, R.N., Hayes, M.E., Creel, B.J., Hanson, A.T., Samani, B.A., and Kennedy, J.F., (1997). Trans-boundary Aquifers of the El Paso/Ciudad Juarez/Las Cruces Region, *Report prepared by the Texas Water Development Board and New Mexico Water Resources Research Institute for the U.S. Environmental Protection Agency, Region VI*.

IBWC (International Boundary and Water Commission) (2010). Treaties and Data. Retrieved from: <http://www.ibwc.state.gov>

IMF (International Monetary Fund) (2010). Data and Statistics. Retrieved from: <http://www.imf.org/data>.

INEGI (INSTITUTO NACIONAL DE ESTADISTICA Y GEOGRAFIA) (2010). Estadística. Retrieved from: <http://www.inegi.org.mx>.

Ingram, H. (2000). Transboundary Groundwater on the U.S.-Mexico Border: Is the Glass Half Full, Half Empty, or Even on the Table?. *Natural Resources Journal* 40(2): 185-188.

Ingram, H. (1999). Lessons Learned and Recommendations for Coping with Future Scarcity. *Natural Resources Journal*. 39(2): 179-192.

Ingram, H., and White, D. (1993). International Boundary Water Commission: an institutional mismatch for resolving transboundary water problems. *Natural Resource Journal* 33.

Just, R., Frisvold, G., Harrison, V., Oppenheimer, J., and Zilberman, D. (1998). Using Bargaining Theory and Economic Analysis as an Aid to Trans-Boundary Cooperation. In Just, R. E. and Netanyahu S. (1998). *Conflict and cooperation on trans-boundary water resources* (pp. 411-427). Boston, Kluwer Academic.

Just, R., and Netanyahu, S. (2000). The importance of structure in linking games. *Agricultural Economics* 24(1): 87-100.

Just, R., and Netanyahu, S. (1998). International Water Resource Conflicts: Experience and Potential. In Just, R. E. and Netanyahu S. (1998). *Conflict and cooperation on trans-boundary water resources* (pp. 1-27). Boston, Kluwer Academic.

JMAS (Junta Municipal de Aguas y Saneamiento), (2001). *Plan Maestro para el Mejoramiento de los Servicios de Agua Potable, Alcantarillado y Saneamiento*. Ciudad Juarez. Retrieved from <http://www.jmas.org.mx>.

JMAS (Junta Municipal de Aguas y Saneamiento), (2005). Ciudad Juarez. Retrieved from <http://www.jmas.org.mx>.

Kelso, M.M. (1961). The stock resource value of water. *Journal of Farm Economics* 43(5). 1112–1129.

Kemper, K., (1999). CH 7. Groundwater Management in Mexico: Legal and Institutional Issues. In. Salman, S. M. A. and World Bank. *Groundwater : legal and policy perspectives : proceedings of a World Bank seminar*.(pp 163-191). Washington, D.C., World Bank.

Kemper, K., Foster, S., Garduno, H., Nanni, M., and Tuinhof, A., (2003) Economic Instruments for Groundwater Management: using incentives to improve sustainability. *World Bank. Briefing Note 7*. Washington D.C.

Khanna, M. (2001). Non-mandatory approaches to environmental protection. *Journal of Economic Surveys* 15(3). 291–324.

Kim C., Moore, M., Hanchar, J., and Nieswiadomy M., (1989) “A dynamic model of adaptation to resource depletion: theory and a application to groundwater mining”, *Journal of Environmental Economics and Management*, 17, 66-82.

Knapp K., and Olson, L., (1995) The economics of conjunctive groundwater management with stochastic surface supplies, *Journal of Environmental Economic and Management* 28, 340-356.

Knapp, K. C. and Olson, L. J. (1996). Dynamic resource management: intertemporal substitution and risk aversion. *American Journal of Agricultural Economics* 78. 1004–1014.

Kneese, A. V. and Resources for the Future. (1962). *Water pollution : economic aspects and research needs*. Washington, D.C., Resources for the Future.

Kneese, A. V. (1975). Theoretical Analysis of Minute 242. *Natural Resources Journal* 15. 135.

Koundouri, P. and Xepapadeas, A. (2003). A new methodology to measuring groundwater scarcity: theory and application. In P. Koundouri, P. Pashardes, T. Swanson and A. Xepapadeas (eds.), *Economics of Water Management in Developing Countries: Problems, Principles and Policies*.(120-170) Cheltenham, UK: Edward Elgar.

Koundouri, P. (2004). Potential for groundwater management: Gisser-Sanchez effect reconsidered. *Water Resources Research* 40(6).

Krishna, R., and Salaman, M. A. (1999). International Groundwater Law and the World Bank Policy for Projects on Transboundary Groundwater. In. Salman, S. M. A. and World Bank. *Groundwater : legal and policy perspectives : proceedings of a World Bank seminar*(pp 163-191). Washington, D.C., World Bank.

LeMarquand, D. G. (1977). *International rivers : the politics of cooperation*. Vancouver, B.C., Westwater Research Centre, University of British Columbia.

Levesque, S. and Ingram, H. (2002). Lessons in Transboundary Resource Management from Ambos Nogales. In Fernandez, L., and R. Carson, (eds). *Both sides of the border transboundary environmental management issues facing Mexico and the United States* (pp. 161-183). Dordrecht ; Boston, Kluwer Academic Publishers. 501.

Magaña, V. and Conde, C., (2003). Climate Variability and Climate Change, and Their Impacts on the Freshwater Resources in the Border Region: A Case Study for Sonora, Mexico. In Diaz, H. F. and Morehouse, B. J. (2003). *Climate and water: transboundary challenges in the Americas*. Netherlands: Kluwer Academic Publishers. 401.

Maler, K. G. and De Zeeuw, A. (1998). The acid rain differential game. *Environmental and Resource Economics* 12(2). 167-184.

Maler, K. G. (1990). International environmental problems. *Oxford Review of Economic Policy* 6(1). 80-108.

Martin, P. (2002). Immigration, Agriculture, and the Border. In Fernandez, L., and R. Carson, (eds). *Both sides of the border transboundary environmental management issues facing Mexico and the United States* (pp. 29-53). Dordrecht ; Boston, Kluwer Academic Publishers. 501.

Mendoza, J. (2006). Ingresos, integración económica y empleo en las ciudades fronterizas. *Economía Mexicana. Nueva Época*, vol.XV, núm. 1, primer semestre de 2006, p 31-66.

Meyer, W.R. (1976), Digital model for simulated effects of ground-water pumping in the Hueco Bolson, El Paso area, Texas, New Mexico, and Mexico: U.S. *Geological Survey Water-Resources Investigations* 58-75, 31 p.

Missfeld, F. (1999). Game-theoretic Modelling of Transboundary pollution, *Journal of economic surveys*, vol. 13 N 3.

Morehouse, B. J., Carter, R. H., and Sprouse T., (2000). The Implications of Sustained Drought for Transboundary Water Management in Nogales, Arizona, and Nogales, Sonora. *Natural Resources Journal* **40**(4): 783.

Müller, D.A., and Price, R.D., (1979), Ground-water availability in Texas, estimates and projections through 2030. *Texas Department of Water Resources Report* 238.

Mumme, S. and Aguilar, I. (2003). Managing Border Water to the Year 2020: The Challenge of Sustainable Development. In Michel, Suzanne. (eds). *The U.S.-Mexican border environment : Binational Water Management Planning*. Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Mumme, S. P. (2000). Minute 242 and Beyond: Challenges and Opportunities for Managing Transboundary Groundwater on the Mexico-U.S. Border. *Natural Resources Journal* 40(2): 341.

Mumme, S. P. (1999). Managing Acute Water Scarcity on the U.S.- Mexico Border: Institutional Issues Raised by the. *Natural Resources Journal* 39(1): 149.

Negri, D. H. (1989). The Common Property Aquifer as a Differential Game. *Water Resources Research* 25(1). 9-15.

Netanyahu, S. (1998). Bilateral Water Policy Coordination Under Uncertainty. In Just, R. E. and Netanyahu S. (1998). *Conflict and cooperation on trans-boundary water resources* (pp. 363-381). Boston, Kluwer Academic.

Netanyahu, S., Just, R., and Horowitz, J. (1998). Bargaining over shared aquifers: the Case of Israel and the Palestinians. In Just, R. E. and Netanyahu S. (1998). *Conflict and cooperation on trans-boundary water resources* (pp. 41-61). Boston, Kluwer Academic.

Nitze, W. (2003). Meeting the Water Needs of the Border Region: A Growing Challenge for the United States and Mexico. In Michel, Suzanne. (eds). *The U.S.-Mexican border environment : Binational Water Management Planning*. Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

NRC 1997. Valuing Groundwater: Economic Concepts and Approaches. National Academy Press, Washington, D.C.

OECD (Organization for Economic Co-operation and Development) (1998), Water Consumption and Sustainable Water Resource Management, OECD Proceedings, Paris. Retrieved from <http://www.oecd.org/publications>.

(2003), Social Issues in the Provision and Pricing of Water Resources. OECD, Paris. Retrieved from <http://www.oecd.org> [www.oecd.org](http://www.oecd.org).

(2006a), *Improving Water Management: Recent OECD Experience*. OECD, Paris. Retrieved from [http://www.oecd.org  
www.oecd.org/publications/policybriefs](http://www.oecd.org/www.oecd.org/publications/policybriefs).

(2006b), *Water Management: Policy Brief for the Mexican Project by Environment Directorate*. Retrieved from <http://www.oecd.org>.

(2009). *Managing Water For All: An OECD Perspective on Pricing and Financing*. OECD, Paris. Retrieved from <http://www.oecd.org>.

Ostrom, E. (1990). *Governing the commons : the evolution of institutions for collective action*. Cambridge [England] ; New York, Cambridge University Press.

Panamerican Health Organization (1999), Leading Causes of Mortality on the United States-Mexico Border. *Epidemiological Bulletin*, Vol 20, N2. June 1999.

Peach, J. and Williams, J. (2000). Population and Economic Dynamics on the U.S.-Mexican Border: Past, Present, and Future. In Ganster, P. (eds). *The U.S.-Mexican border environment : A road map to a sustainable 2020*. (pp. 37-74). Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Peach., James., (2003), Modeling the Demographic Characteristics of the Paso del Norte Region. In Sandalla, E. (Eds). *The U.S.-Mexican environment: Dynamics of human-environment interactions*. (pp 273-296). Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Pena, S., Fuentes., Cesar, and Forster., and Craig., (2005) Land Use Changes in the Paso del Norte Region: A Brief History. In Sandalla, E. (Eds). *The U.S.-Mexican environment: Dynamics of human-environment interactions*. (pp 273-296). Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.



PNWTF (2001) (Paso del Norte Water Task Force). Water Planning in the Paso del Norte: Toward Regional Cooperation El Paso. Retrieved from [http://www.sharedwater.org/en/Projects/Reports/water\\_taskforce\\_report\\_rev1.Pdf](http://www.sharedwater.org/en/Projects/Reports/water_taskforce_report_rev1.Pdf).

Provencher, B., and Burt, O., (1993) "The externalities associated with the common property exploitation of groundwater", *Journal of Environmental Economics and Management* 24, 139-158.

Provencher, B., (1993a) "A Private Property Rights Regime to Replenish a Groundwater Aquifer", *Land Economics*, Vol. 69, NO. 4. Pp 325-340.

Provencher, W. (1993b). Approximating the Solution to Stochastic Dynamic Games-An Application to Groundwater. *American Journal of Agricultural Economics* 75(5): 1315-1315.

Provencher, B., and Burt, O., (1994) A private rights regime for the commons: The case for groundwater. *American Journal of Agricultural Economics*, Vol. 75, No. 4, pp 875-888.

Rausser, G. (2000). Collective Choice in Water Resource Systems. In Dinar, A. (2000). *The political economy of water pricing reforms*. (pp.49-79). Oxford ; Washington, D.C., World Bank.

Reichard, E., and Bredehoeft, J., (1984) "An engineering economic analysis of a program for artificial groundwater recharge", *Water Resource Bulletin* 20(5), 929-939.

Rogers, P. (1997). International River Basin: Pervasive Unidirectional Externalities In Dasgupta, P., K.-G. Mäler, and Vercelli, A. (1997). *The economics of transnational commons*. (pp.35-77). Oxford New York, Clarendon Press ; Oxford University Press.

Rubio, S., and Casino, B., (2001) "Competitive versus efficient extraction of a common property resource: The groundwater case", *Journal of Economics Dynamics and Control* 25, 1117-1137.

Sandler, T. (2001). On the financing global and international public goods. In Mody, A. (ed) *International Public Goods: Incentives, Measurements and Financing*, Dordrecht, NL: Kluwer. 221-247.

Sandler, T. (1998). Global and regional public goods: A prognosis for collective action. *Fiscal Studies* 19(3): 221-247.

Sánchez, R. A. (2002). Binational Cooperation and the Environment at the U.S.-Mexico Border: A Mexican Perspective. In Fernandez, L., and R. Carson, (eds). *Both sides of the border transboundary environmental management issues facing Mexico and the United States* (pp. 29-53). Dordrecht ; Boston, Kluwer Academic Publishers. 501

Sánchez, R. A. (1995). Water quality problems in Nogales, Sonora. *Environmental health perspectives* 103(Supplement 1): 93-7.

Schlager, E. and E. Ostrom (1992). Property Rights Regimes and Natural Resources- a Conceptual Analysis. *Land Economics* 68(3): 249-262.

Schmidt, C., and Scott J., 2000, Bordering on environmental Disaster. *Environmental Health Perspectives*, 108(7).

Schiffer, M. 1998. *The economics of Groundwater Management in Arid Countries*. GDS Book Series II. Frank Cass, London.

Seabright, P. (1993). Managing Local Commons- Theoretical Issues in Incentive Design. *Journal of Economic Perspectives* 7(4): 113-134.

Shapley, L. S., and Shubik, M. (1969 a). On Market Games. *Journal of Economic Theory* 1, 9-25.

Shapley, L. S., and Shubik, M. (1969b). On the Core of an Economic System with Externalities. *American Economic Review* **59**, 678-684.

Sheng, Z., and Devere, J., (2005). Understanding and managing the stresses Mexico-USA transboundary Hueco bolson aquifer in the El Paso del Norte region as a complex system. *Hydrology Journal* 13.813-825.

Sheng, Zhuping (2005). An aquifer storage and recovery system with reclaimed wastewater to preserve native groundwater resources in El Paso, Texas. *Journal of Environmental Management*. 75. 367-377.

Sheng, Z., Fahy, M.P., and Devere, J., (2001a). Management Strategies for the Hueco Bolson in the El Paso, Texas, USA and Ciudad Juarez, Mexico Region, in Bridging the Gap, *Proceedings of the World Water and Environmental Resources Congress*, Orland, FL, CD-ROM, ASCE.

Sheng, Z., Mace, R.E., and Fahy, M.P., (2001b). The Hueco Hueco Bolson: An Aquifer at the Crossroads. P.66-76. In: Mace, E.R., Mullican III, F. W., and Angle E.S., (2001). *Aquifers of West Texas*. Texas Water Development Board. Report 356. Austin, Texas.

Siebert, H. (2005). *Economics of the environment : theory and policy*. Berlin ; New York, Springer.

Stauffer, J. (1998). *The water crisis*, London (UK): Earthscan Publications.

Starret, D. (2003). Property Rights, Public Goods and the Environment. In In Mäler, K.-G. and J. R. Vincent (2005). *Handbook of environmental economics*. Volume I (pp. 98-123). Amsterdam ; Boston, North-Holland/Elsevier.

Spalding, M. (2003). Addressing Border Environmental Problems Now and in the Future: Border XXI and Related Efforts. In Ganster, P. (eds). *The U.S.-Mexican border environment : A road map to a sustainable 2020*. Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Sprouse T. (2005). The santa cruz, san pedro and Colorado rivers. *The university of Arizona, working paper, Water resources research center, College of Agriculture and Life sciences.*

Sprouse, T. and Vaughan, L. (2003). Water Resource Management in Response to El Niño-Southern Oscillation (ENSO) Droughts and Floods: The Case of Ambos Nogales. In Diaz, H. F. and Morehouse, B. J. (2003). *Climate and water: transboundary challenges in the Americas.* Netherlands: Kluwer Academic Publishers. 401.

Stromberg, P. (2005). La industria maquiladora Mexicana y el medio ambiente; una revision de los problemas. In Carillo, J. and Schatan, C. (eds). *El medio ambiente y la maquila en México: un problema ineludible.* (pp. 13-21). México, D.F. CEPAL.

Szekely, A. (1993). How to accommodate an uncertain future into institutional responsiveness and planning : the case of Mexico and the United States. *Natural Resources Journal.* 33. p. 397-403.

Szekely, A. (1991). Establishing a region for ecological cooperation in North America. Albuquerque, NM, International Transboundary Resources Center.

Szekely, A. (1986). Transboundary resources : a view from Mexico. *Natural Resources Journal.* 26. p. 669-694.

Tsur, Y. (1990). The stabilization role of groundwater when surface water supplies are uncertain: the implications for groundwater development. *Water Resources Research.* 26. 811-818.

Tsur, Y. (1991). Managing drainage problems in a conjunctive ground and surface water system. In A. Dinar and D. Zilberman (eds.), *The Economics and Management of Water and Drainage in Agriculture.* (pp. 75-100) Dordrecht, The Netherlands: Kluwer.

Tsur, Y., and Graham-Tomasi, T. (1991). The buffer value of groundwater with stochastic surface water supplies. *Journal of Environmental Economics and Management* 21: 201–224.

Tsur, Y. and Zemel, A. (1995). Uncertainty and irreversibility in groundwater resource management. *Journal of Environmental Economics and Management* 29: 149–161.

Turner, C., Hamlyn, E., and Hernández, O. I. (2003). The challenge of balancing water supply and demand in the Paso del Norte. In Michel, S. (eds). *The U.S.-Mexican border environment : Binational Water Management Planning*.(pp. 185-246) Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Unesco (United Nations). (2006). *Water : a shared responsibility*. Retrieved from <http://www.loc.gov/catdir/toc/fy0710/2006299804.html>.

Van der Ploeg, F., (1987) Inefficiency of credible strategies in oligopolistic resource markets with uncertainty, *Journal Economics Dynamics and Control*, 11, 123-145.

Van Schoik, D., Lelea, E., and Cunningham, J. (2003). Theory and Practice of Conservation Biology in the Security Bisected U.S.-Mexican Border Region. In Van Schoik, D., *et al.* (eds). *The U.S.-Mexican border environment : Transboundary Ecosystems Management*. Southwest Center for Environmental Research and Policy (SCERP). San Diego, CA, San Diego State University Press.

Wade, R. (1987). The Management of Common Property Resources: Finding a Cooperative Solution. *The World Bank Research Observer* 2(2): 219-234.

World Bank (2004). *Water resources sector strategies: strategic directions for World Bank engagement*. Washington, D.C., World Bank. Retrieved from <http://www.worldbank.org>

(2006) *Comparative Analysis of Water Sector-Related Policies: Exploration of Impacts of Water Productivity*. Washington, D.C., World Bank. Retrieved from <http://www.worldbank.org>.

World Bank (2009). *Water Supply and Sanitation*. Retrieved from site: <http://web.worldbank.org/> .

Worthington, W., Burt, O., and Brustkern, R., (1985) "Optimal management of a confined groundwater system", *Journal of Environmental Economics and Management* 12, 229-245.

Xepapadeas, A., and Koundouri, P. (2004). Introduction to special section on groundwater economics and policy. *Water Resources Research* 40(6).

Xepapadeas, A. (1997). *Advanced principles in environmental policy*. Cheltenham, UK ; Northampton, MA, E. Elgar.

APPENDIX A  
STABILITY OF STEADY STATE

The Jacobian of  $\dot{L}(t)$  and  $\dot{K}(t)$  at  $(L^{SS}, K^{SS})$  is,

$$\begin{bmatrix} \frac{L^{SS}}{S^{MX}} \left( -\frac{\alpha S(K^{SS}, L^{SS})^{CJ}}{L^{SS}} - \left( \frac{\partial P(W^{SS}, R^{SS})}{\partial R} gE \right) \right) & \alpha \frac{S^{CJ}}{S^{MX}} \frac{L}{K} \\ \alpha \frac{K}{L} & -\alpha \end{bmatrix} \quad (1)$$

The eigenvalues,  $r_{1,2}$ , are given by the following second degree equation,

$$r^2 - r(a_{11} + a_{22}) + (a_{11}a_{22} - a_{21}a_{12}), \quad (2)$$

$$r_1 = \frac{(a_{11} + a_{22}) + \left[ (a_{11} + a_{22})^2 - 4(a_{11}a_{22} - a_{12}a_{21}) \right]^{1/2}}{2},$$

$$r_2 = \frac{(a_{11} + a_{22}) - \left[ (a_{11} + a_{22})^2 - 4(a_{11}a_{22} - a_{12}a_{21}) \right]^{1/2}}{2},$$

Where,

$$a_{11} = \frac{L^{SS}}{S^{MX}} \left( -\alpha \frac{S(K^{SS}, L^{SS})^{CJ}}{L^{SS}} - \left( \frac{\partial P(W^{SS}, R^{SS})}{\partial R} gE \right) \right) < 0, \quad (3)$$

$$a_{12} = \alpha \frac{L}{K} > 0, \quad (4)$$

$$a_{21} = \alpha \frac{K}{L} > 0, \quad (5)$$

$$a_{22} = -\alpha < 0. \quad (6)$$

For stability it is required that eigenvalues are negative. Then, we have show that,



$$(a_{11} + a_{22}) > \left[ (a_{11} + a_{22})^2 - 4(a_{11}a_{22} - a_{12}a_{21}) \right]^{1/2} \quad (7)$$

Where,

$$(a_{11} + a_{22}) < 0. \quad (8)$$

This inequality is equal to,

$$\begin{aligned} (a_{11})^2 + 2a_{11}a_{22} + (a_{22})^2 &> (a_{11})^2 - 2a_{11}a_{22} + (a_{22})^2 + 4a_{21}a_{21}, \\ \Leftrightarrow a_{11}a_{22} &> a_{21}a_{12}, \end{aligned} \quad (9)$$

Since,

$$a_{11}a_{12} = \frac{\alpha}{S^{MX}} \left( \alpha S(K^{SS}, L^{SS})^{CJ} + L^{SS} \left( \frac{\partial P(W^{SS}, R^{SS})}{\partial R} gE \right) \right) > 0 \quad (10)$$

$$a_{21}a_{12} = \alpha^2 \frac{S^{CJ}}{S^{MX}} \quad (11)$$

Then,

$$\begin{aligned} a_{11}a_{22} - a_{21}a_{12} &= \\ a_{11}a_{12} &= \left( L^{SS} \left( \frac{\partial P(W^{SS}, R^{SS})}{\partial R} gE \right) \right) > 0 \end{aligned} \quad (12)$$

Then, the steady state is stable.

APPENDIX B  
STEADY STATE LEVELS

The steady state population value is given by solving the safe yield and zero migration conditions; that is (using conditions (3.2.3) and (3.2.15)),

$$(S^{US} - S^{MEX})L^{SS} = L^{SS} E P(W^T, R^T)^{WR}, \quad (1)$$

$$R^T + \bar{R} - EL^{SS} = 0, \quad (2)$$

Where  $R^T \in [0, \varphi EL^*]$  and  $W^T$  is the lowest groundwater stock.

That is, there exists a  $R^T$  equal to  $\varphi EL^{SS}$  such that conditions (i) and (ii) are satisfied.

Where  $g$  is a proportion of water treated and recycled, it is equal or less than  $\varphi$ , which is assumed to be 100%.

Then, condition (ii) becomes,

$$\varphi EL^{SS} + \bar{R} - EL^{SS} = 0, \quad (3)$$

Assuming that the price of water is equal to marginal cost of each cost (i.e. the marginal extraction cost and marginal recharge cost), condition (i) is given by<sup>43</sup>,

$$S^{US} - S^{MEX} = P_E f(W^T) E + \frac{\gamma P_R (gEL^{SS})^\gamma}{L^{SS}} \quad (4)$$

Solving equations (iii) and (iv) we can find the steady state population level.

---

<sup>43</sup> The water tariff is equal to:

$$P(t)^{WR} = P_E f(W_t) E + \gamma P_R (R_t)^{\gamma-1} \left( \frac{R_t}{L(1+n)^t} \right)$$