THREE ESSAYS ON FOOD-ENERGY-WATER NEXUS ANALYSIS AND AFGHANISTAN FOOD SECURITY AND POVERTY

A Dissertation

by

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ABSTRACT

Food Energy Water (FEW) Nexus is studied under water scarcity examine the economics of resource allocation and decision making among competing FEW users under the assumption that coordinated decision making would increase regional social welfare and improve the sustainability of environment and resources. Population growth and climate change are considered as they can stress a currently working water scarce Nexus system as it evolves into the future. The work is presented in three essays. The first two essays focus on a Nexus case study in South Central Texas where water scarcity is a key concern. Furthermore, the region is projected to exhibit a drier climate and doubled population, which will further exacerbate water scarcity. In order to mitigate this water scarcity problem, the Texas Water Development Board (TWDB) regional planning group has proposed a number of water projects. This work examines possible FEW Nexus actions in this region to see whether coordinated action can improve regional social welfare. To do this we employed an integrated model EDSIMRGW_NEX, which simulates regional agricultural and electricity production as well as water allocation between agriculture, cooling, fracking and M&I. We used that model to examine the impacts of population growth and climate change on agriculture, water project construction and water project operation decisions. We found that the drier future climate has negative effects on the agriculture sector, while population growth has little impact on agriculture. More water projects are constructed and operated with

population growth and climate change. We find climate change affects the selection and pace of water projects construction and operation.

Food security and poverty in Afghanistan is addressed in the third essay. In Afghanistan, food security is a severe problem, with about 36% of the households classified as food insecure. Poverty is also common in Afghanistan. According to the NRVA 2011 survey data, more than 80% of households fall under the global poverty line. In examining the situation we considered whether road blockages exacerbate poverty and food insecurity We find that road blockages have negative impacts on food security, nutrition balance, household income and coping strategies selection, but less impact on total calories intake. Road blockages also increased the proportion of households in poverty.

DEDICATION

To my dear family

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NOMENCLATURE

AFN	Afghan Afghani
ASR	Aquifer Storage and Recovery
ATT	the Average Treatment effects on the Treated
AUM	Animal Unit Month
CSO	the Afghanistan Central Statistics Organization
EAA	Edwards Aquifer Authority
EPIC	the Environmental Policy Integrated Climate Model
FAO	Food and Agriculture Organization of the United Nations
FEW	Nexus Food-Energy-Water Nexus
GAM	Groundwater Availability Model
GCM	Global Circulation Model
GHI	Global Hunger Index
HH	Household
IPCC	Intergovernmental Panel on Climate Change
M&I	Municipal and Industrial
NGO	Non-Governmental Organization
NRVA	the National Risk and Vulnerability Survey in Afghanistan
OCR	off-channel reservoirs
O&M	Operation and Maintenance
PSM	the propensity score matching (PSM) method

RCP	Representative Concentration Pathway
RDA	USDA Recommended Dietary Allowances
SWAT	Soil & Water Assessment Tool
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board
USGS	United States Geological Survey
USDA	United States Department of Agriculture
WRAP	Water Rights Analysis Package

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CHAPTER I

INTRODUCTION

Food Energy Water (FEW) Nexus studies under water scarcity address resource allocation among competing FEW users. Bazilian et al. (2011) argue that FEW coordinated decision making "would lead to a more optimal allocation of resources, improved economic efficiency, lower environmental impacts and better economic development conditions, in short, overall optimization of welfare".

In studying the FEW Nexus focus is placed on coordinated decision making at the intersection of the sectors that produce and use FEW products and associated resources (McCarl et al. 2017). For example, agriculture is often a vital sector in a FEW Nexus system. Typically, agriculture uses a significant amount of land, water, and energy to produce food and fiber for use by humans and livestock. In turn, when increasing crop production, agriculture needs more water, energy, and land. Such actions require additional energy production and that in turn uses more water for cooling or fracking. Also, energy generating wind and solar farms are typically placed on agricultural lands competing with agriculture. This demonstrates the interrelationships between agriculture/food and energy involving all three aspects of the FEW nexus with resource competition for land and water. Furthermore, altering agriculture can release land and water for possible welfare increasing uses in energy and municipal/industrial settings.

Sustainability is also a Nexus goal. For example, in a water scarce region, FEW Nexus decision making can attempt to find improved patterns of water allocation that would enhance the sustainability of future usage, especially when depletable aquifers are involved. The effects of water allocation on environmental quality, fisheries and endangered species are also involved. Finally, population growth and climate change are relevant factors as they can stress a currently working Nexus system as it evolves into the future.

This dissertation addresses broad FEW related issues largely in two settings. In the first two essays I will focus on a Nexus case study in South Central Texas where water scarcity is a key concern and in the third I will look at food and poverty issues in Afghanistan.

South Central Texas Nexus Studies

In terms of the South Central Texas study, the study region covers the cities of San Antonio and Corpus Christi TX as well as the area containing the Guadalupe, Blanco, San Antonio, Nueces and Frio Rivers and lands in between. Groundwater is also regionally important with pumping occurring from the Edwards, Edwards-Trinity, Gulf Coast and Carrizo-Wilcox Aquifers.

This region suffered a severe drought in 2011 and 2012 (U.S. Drought Monitor[1]), and is projected to likely get drier under climate change, which will not only reduce

[1] The U.S. Drought Monitor is jointly produced by the National Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Map courtesy of NDMC-UNL.

surface water supply (Gurdak, Hanson and Green 2009; IPCC 2014), but also groundwater recharge and increase municipal water consumption (Chen, Gillig and McCarl 2001). The area is also projected to exhibit doubled population by the end of this century. Such growth coupled with a drier future stresses the regional water situation. Therefore, it is meaningful to examine possible regional FEW Nexus actions to see whether coordinated action can improve regional social welfare. A number of the Nexus actions involve Texas Water Development Board (TWDB) regional planning group proposed water projects (TWDB 2015a; TWDB 2015b). Others involve agricultural management and manipulation of electrical energy cooling.

Climate change is also an important regional issue. Regional water and agriculture are vulnerable to climate change, with many possible vulnerabilities, such as alterations in crop yields, livestock performance, pest and pathogen incidents, irrigation water demands, irrigation water supplies, stream flows, aquifer recharge, urban and water demands among other items. (IPCC 2014; McCarl 2015; McCarl, Thayer and Jones 2016; Fan, Fei and McCarl 2017). To the best of our knowledge, TWDB did not consider the effect of climate change on the potential desirability of these water projects. But we believe it is an important factor that cannot be ignored.

Therefore, we want to examine the regional decisions under the Nexus analysis and climate changes. This dissertation will focus on two aspects of the Nexus analysis: agriculture and water projects construction decisions. We will examine the impacts of population growth and climate change on agriculture, water projects construction and operation decisions. In particular,

- The first essay will focus on Nexus analysis as it might affect agricultural decisions and the influence of climate change on the situation.
- The second essay will focus on Nexus analysis of water project construction and operation selection as affected by both climate change and population growth.

Afghanistan Study

Food security and poverty in Afghanistan is also addressed. Food security, as one of the most important human needs, is at risk in Afghanistan (Messer, Cohen and Marchione 2001). According to the World Food Summit (1996), a country is food secure, *"when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life".* Afghanistan is not totally food secure. Rosen, et al. (2015) indicate that 6.5 million people (20% of the total population) suffered food insecurity with a 45 million ton food gap in 2015. Over time the incidence of food insecurity has been reduced as the 1995 estimate was that 15.8 million people (out of 17.6 million) were food insecure compared to the more recent estimate of 6.5 million. Based on the survey data used in this research, in 2011 on a per capita basis about 36% of the households in Afghanistan consume less than 2550 Cal per day. (Note 2550 Cal is an estimate of the average calorie intake requirement for normal activities). Thus insuring availability of sufficient food is a primary challenge for the Afghanistan government.

Poverty is also common in Afghanistan. According to the 2011 National Risk and Vulnerability Survey in Afghanistan (NRVA 2011), average household income is around 149 thousand Afghan Afghani (AFN), which is equivalent to $1,918 US dollars (computed based on an April 2019 exchange rate). Furthermore since the average household size in Afghanistan is 7.5 people, this means per capita income is 256 US$, much lower than the World Bank estimates $1.25 US per day global poverty line (World Bank 2019). Additionally people in Afghanistan are affected by social and climate shocks. More than 70% of Afghanistan households employ temporary coping strategies in the face of such shocks, such as reducing non-food expenditures, increasing household income sources, selling properties, decreasing food quality and quantity, borrowing money or begging.

One potential factor contributing to this is road blockage. Over 36% of households reported obstructed road access to the outside of village at least once in the 2011-2012 survey. Roads may be blocked by heavy snows and avalanches in the winter or by conflict and armed fire at any time of year. Poor road access, especially outside of the capital, complicates further economic development, food security gains, and household income. This raises our interest to investigate the impact of road blockages on food security and income. Consequently, in the third essay, we investigate the impact of road blockages on food security, household income and the coping strategies using a propensity score approach.

CHAPTER II

AGRICULTURE AND THE FEW NEXUS UNDER WATER SCARCITY

Introduction

Studies on Food, Energy and Water (FEW) Nexus concerns focus on decision making at the intersection of the sectors that produce and use FEW products and associated resources (McCarl et al. 2017). Instead of only considering the effects of on a single sector, FEW Nexus studies consider resource allocation and the impact across multiple sectors and their interaction. For example, agriculture is often a vital FEW Nexus sector. In such a setting agriculture uses a significant amount of land, water, and energy to produce food and fiber for use by humans and livestock. Typically, when we increase crop production, agriculture needs more water, energy, and land. In turn, more energy production is needed and this often demands more water for cooling or fracking. Also, energy generating wind and solar farms are typically placed on agricultural lands, which demonstrates water and land competition between agriculture/food and energy involving all three aspects of the FEW Nexus. However, altering that nature of agriculture can release land and water with possible welfare increasing uses in energy and municipal/industrial settings. The purpose of FEW Nexus studies is to examine possible resource allocation schemes and possibly make gains through coordinated action. FEW Nexus analysis also aims to increase the sustainability of development actions. For example, in a water scarce region, FEW Nexus decision making would attempt to find improved patterns of water allocation that would improve the sustainability of future usage, especially when depletable aquifers are involved. The impact of water allocation on environmental quality, fisheries and endangered species are also Nexus concerns. Population growth and climate change are also relevant as they can stress a currently working Nexus system as it evolves into the future.

In this chapter, we examine Nexus decisions within a case study in South Central Texas where water scarcity is a key concern. The research region covers San Antonio and Corpus Christi TX as well as the Guadalupe, Blanco, San Antonio, Nueces and Frio Rivers along with the small river basin between the San Antonio and Nueces Rivers. Groundwater is also regionally important with pumping occurring from the Edwards, Edwards-Trinity, Gulf Coast and Carrizo-Wilcox Aquifers. This region suffered a severe drought in 2011 and 2012 (U.S. Drought Monitor), and is projected to be drier under climate change. Meanwhile, as projected by the Texas Demographic Center, the population in the research region is expected to grow quickly, especially in the San Antonio and Corpus Christi metropolitan areas. Such growth coupled with a drier future stresses the regional water situation. Therefore, it is meaningful to examine possible FEW Nexus actions in this region to see whether coordinated action can improve regional social welfare. This chapter focuses on Nexus analysis as it might affect agricultural decisions and the influence of climate change on the situation. FEW Nexus Background

Economic Aspects of the FEW Nexus

FEW Nexus studies under water scarcity represent involve important areas of work in natural resource economics involving the economics of resource allocation among competing FEW users. It has been argued that FEW coordinated decision making "would lead to a more optimal allocation of resources, improved economic efficiency, lower environmental impacts and better economic development conditions, in short, overall optimization of welfare" (Bazilian et al. 2011). This raises the economic issues and modeling changes for the FEW studies, as discussed in McCarl et al. (2017). Here we just list several important economic issues that arise and will be addressed in this study.

Welfare

Increasing total regional welfare across the entire nexus is the goal of the coordinated Nexus decision-making. The Nexus line of analysis embodies the basic assumption that we can increase social benefits by coordinating decision-making regarding the resources used by the FEW sectors. Economics can be used to evaluate whether such decisions achieve welfare increases.

In this research, we set up price endogenous demand curves for municipal, industrial water usage and the electricity demand along with that perfectly elastic demand curve for agricultural production and inelastic demand curves for fossil fuel production. The perfectly elastic, fixed price for agricultural production is used because the case study region is too small in terms of the amount of agricultural production to affect agricultural commodity prices. We also use a linear programming based marginal cost curve to determine the supply curves for agricultural products and electricity as well as the demand for water from agriculture, municipal, industrial and the energy sector. We believe that there is a set of major possible nexus investments and asset operation decisions that can increase regional social welfare. These include building new water projects to increase regional water supply, changing electrical power plant cooling method to reduce water consumption, and utilization of deficit irrigation to reduce agricultural water use.

Incorporation of Demand and Supply Relations

Demand and supply curves represent the relationship between prices and quantities, and embody the own-price elasticity of products. In the FEW Nexus, the Nexus decisions or projects can lead to shifts in demand and supply curves by making more water, energy or food available at different prices. In turn this will change the prices of inputs and FEW commodities. This consequentially alters the welfare gains arising from the Nexus projects through impacts on revenues and costs. Therefore, it is important to consider the input and output prices changes due to Nexus decisions in order to correctly estimate the total welfare effects of Nexus alternatives. For example, in our research, a water project could increase the region water supply by moving water from out of the region via a pipeline but in doing this would consume substantial amounts of electricity. This will shift out the supply curve of water, which would immediately lead to a cheaper water price, but also shift out the demand curve of electricity and the water demand from electricity for cooling. This in turn would raise the price of electricity and possibly create need for construction of new electrical power plants. More generally this indicates the types of interactions that may occur between the sectors.

Value of Water in Different Sectors

Water has different values in different sectors. This is due to the different costs of water distribution across sectors plus the historical water allocation procedures (basically the surface rights follow the doctrine of prior appropriation, the Edwards aquifer groundwater rights are tradable and the other groundwater reservoirs are owned by the land owners above them subject to some controlled by groundwater districts). In our case, the value of water in agriculture sector is often lower than the marginal values in other sectors, e.g. municipal, industrial, mining sectors, power plant usage, etc. This is major because agricultural sector has the longest history of water usage in the region with prior use rights. There are or were obstacles to water trading and the rapid growth in some sectors mandates expensive water development projects.

Differential values for water across sectors indicates there would be value from coordinated FEW Nexus decisions potentially achieving a higher level of regional welfare. In further considering this it is useful to estimate the use value by sector (Colby 1989; Young and Loomis 2014). The market approaches include: comparable sales approach, capitalization approach, replacement approach, econometric approach and land value differential approach. The value of water belongs to the land property rights should also be counted (McCarl 1997). In this research, we use endogenous demand and supply analysis plus water trading possibilities to determine water values and the levels of potential trading. We also use the capitalization approach to estimate the value of water in other sectors.

Externalities and Public Good Concern

Projects identified in the Texas Water Development Board (TWDB) regional water management plans gives a number of adaptation strategies for coping with increasing demands, falling water supplies and the other effects of climate change and population growth. However, the water management plans, such as building off channel reservoirs, transfers of water from supplies within water surplus regions to the water deficit region, and utilization of aquifer storage and recovery (ASR), are all expensive, and are broader in scope than efforts that nominally could be undertaken by anyone individual. Therefore, the projects within the water management plans are generally public goods in an economic sense and are likely only reasonably implemented by public agencies (IPCC 2014; Fan et al. 2017). For more details, please see the discussion in Chapter III.

Other Economic Concerns

Other economic concerns that need to be considered within a Nexus analysis include: a) high transaction costs for dissemination, measurement and monitoring on many forms of water conservation, b) the consequences of Nexus actions for the distribution of welfare including identification of those who might lose and those who would gain; c) the needed level of incentives reallocation that will stimulate cooperation on behalf of those who might lose and also the manner in which this compensation can be funded, and d) the limitation of regulatory, taxation and subsidy means to help implement Nexus actions etc. For more discussion, please see McCarl and Yang (Forthcoming) and McCarl et al. (2017).

Climate Change and Agriculture

As projected by Intergovernmental Panel on Climate Change (IPCC 2013), it appears inevitable that the global average temperature will increase about by 1℃ in the next 25 years. The pattern of other climate variables such as the pattern of precipitation, soil moisture, the frequency of extreme events, will change as well, and the changes will vary across regions.

As stated by many studies, agriculture is very vulnerable to climate change (IPCC 2014; McCarl 2015; McCarl et al. 2016; Fan et al. 2017). Climate change impacts on agriculture by altering crop yield, livestock performance, pest and pathogen incidents, irrigation water demands, and irrigation water supplies, etc. In this study, we focus on the impacts of climate on crop yield, irrigation water consumption and the supply of water.

Crop yield can be altered by temperature, precipitation, heat waves, precipitation intensity etc. Temperature and precipitation have been found to reduce the yield of maize and wheat at a global scale (Lobell and Field 2007). Extreme heat was found to damage the yields of corn and soybeans (Schlenker and Roberts 2009). Increases in the number of hot days have been found to reduce the yield of soybeans, cotton, corn and sorghum in US while in increase in CO_2 concentrations have been found to positively contribute to the yields of soybeans, cotton and wheat (Attavanich and McCarl 2014). Attavacnich and McCarl (2014) also simulated the impact of climate change on yield by region. They found regionally uneven results where the yield of corn and sorghum would be reduced in our study region within the Southern Plains while in that region the yield of soybeans, cotton and wheat would increase.

Adaption strategies such as altering crop mixes (Park, McCarl and Wu 2016; Adams et al. 1999), moving the crops poleward or to higher elevations (Cho and McCarl 2017; Fei, McCarl and Thayer 2017), and changing the planting and harvesting timing (Sacks and Kucharik 2011) are major observed farmer adaptations.

The changing climate will also alter both water supply and demand. Regionally the climate is projected to become more arid and soil moisture to dramatically decrease. These drier conditions are projected to directly reduce surface water availability and are also likely to decrease the recharge to aquifers (Gurdak et al. 2009; IPCC 2014). The increased temperature we also operate on the demand side to raise crop respiration and evapotranspiration, in turn, increasing the water needs for any single acre of irrigated crops while also lowering the yield of dryland crops (Adams et al. 1999). Moreover, based on our analysis and the findings in Chen, Gillig, and McCarl (2001), the increased temperature is also projected to decrease recharge to the Edwards Aquifer (For more details, please see the model documentation). The increased temperature and dryer conditions are also found to be likely to increase the municipal and industrial water demand (Chen et al. 2001).

When the drought index increases and temperature, farmers may well transfer irrigated land to pasture as found in Mu, McCarl, and Wein (2013) and projected by Ding (2014). In a projection based on an econometric study land in the southern US was projected to be transferred from cropland to grazing land under climate change (Mu et al.

2018). Deficit irrigation can be used by farmers to cope with the reduction in rainfall as well (Geerts and Raes 2009). Irrigation suspensions in dry years (transfer irrigated land to dryland) would be another adaptation strategy adopted by farmers (Keplinger 1998; Keplinger and McCarl 2000).

Background on the Research Region

Water supply and demand

Our research region is located in South Central Texas in the area surrounding the cities of San Antonio and Corpus Christi. This area contains 4 river basins (Guadalupe/Blanco, San Antonio, Nueces/Frio and San Antonio-Nueces). The region also has access to several aquifers (Edwards Aquifer- San Antonio Segment, part of the Edwards-Trinity Aquifer, a segment of the Carrizo-Wilcox Aquifer, part of the Gulf Coast Aquifer and a few other minor aquifers) (Figure 1). The terrain in South Central Texas is higher in the north and west part of the region and then falls as we traverse South and East, which causes the river to flow from the northwest to the southeast. The terrain, water flow and location of key aquifers results in the upstream region predominantly using groundwater from the Edwards and Carrizo-Wilcox Aquifers. Downstream region near the principally rely on more on surface water. The largest regional demands are in the area around San Antonio and that region exhibits the most water scarcity.

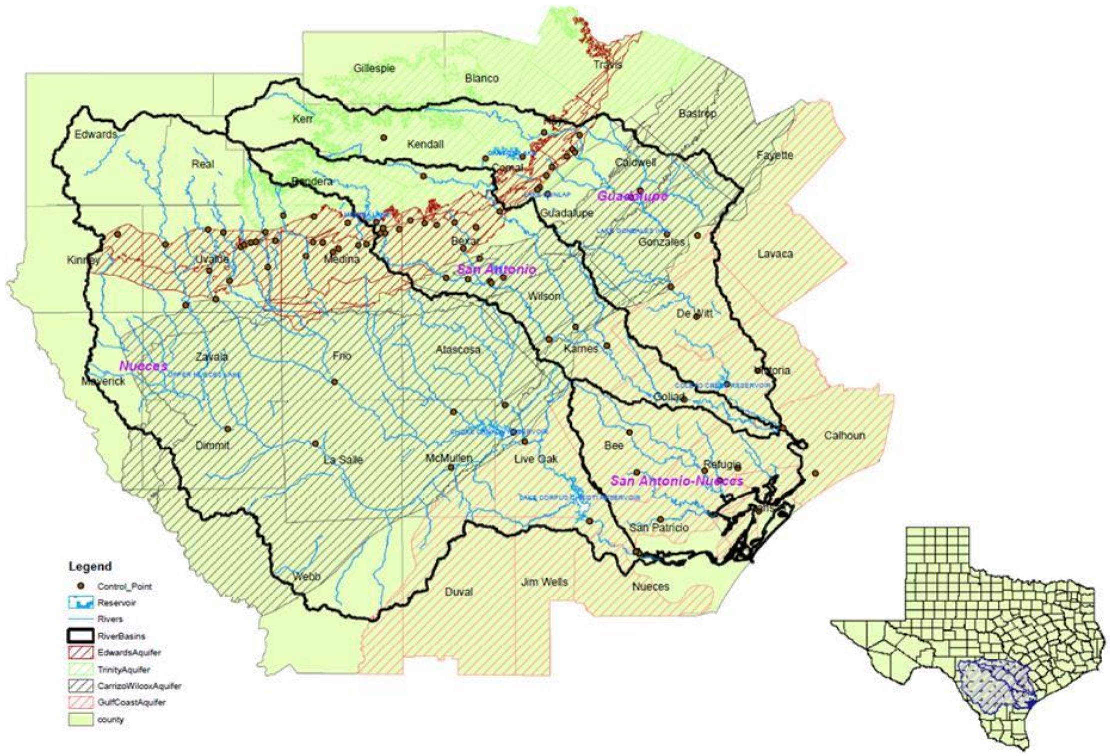

Figure 1: Research Region (South Texas), River Basins and Aquifer

The Edwards Aquifer (red shadow in Figure 1) is important water source for metro San Antonio and the surrounding rural region, plus spring flows from it are important sources of water inflows into the Guadalupe and San Antonio Rivers. However, due to its character as a karst aquifer, the water level in the Edwards Aquifer highly depends on regional precipitation and the aquifer rapidly discharges through springs and pumping. The yearly discharge amounts for Edwards Aquifer vary in the range of 500 thousand to over a million acre feet, but the recharge amount varies in a much larger scale over time (Figure 2). Secondly, the groundwater elevation is highly related to the recharge of that year, and it falls quickly in low recharge years.

Simultaneous concerns over increasing water demands, highly variable, stochastic levels of recharge, rapid discharges of excess water and the protection of endangered species led to the establishment of the Edwards Aquifer Authority (EAA) in 1993. That Authority was formed with the intent of assuring sufficient water supply, maintaining good water quality and protecting the environment and endangered species (Patoski 2018). There was also a judgment in a federal lawsuit that strengthened the role of the EAA requiring management of the springs to protect the endangered species habitat (The State of Texas 1993). In its management duties on discharging, the EAA allocated water use rights and promulgated trading of Edwards Aquifer water. Generally, the amount that could be pumped by the each water user is determined through water rights permits and annual use of those permits is determined by reference well elevations. For example the amount of pumping was reduced when the J17 Well elevation goes down during 2011-14, but the discharge was still substantially more than the recharge which results in falling ending elevations and low spring flow levels (Figure 2).

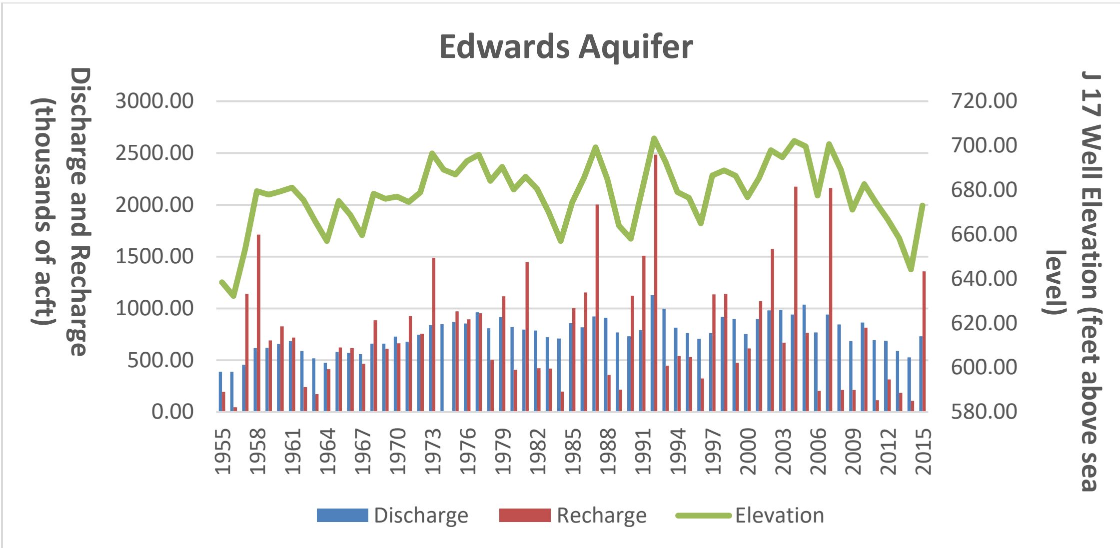

Figure 2: Edwards Aquifer Recharge and Discharge and the Elevation of J17 Well[2]

In term of surface water, the water rights are regulated by Texas Commission on Environmental Quality (TCEQ), which issues the surface water rights and limits the amount of pumping, in order to assure sufficient water for downstream permits holders and protect the fishery and environment in the estuaries.

Coupled with the regulations and the limited availability of water resource, the increasing water demand worsens the scarcity situation in our research region. Municipal, agriculture and power plants are the top three water demand sectors (Figure 3). About 80% of the regional water is withdrawn from aquifers, but power plants only withdraw from rivers.

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[2] J17 Well is one of the two indicator wells of Edwards Aquifer.

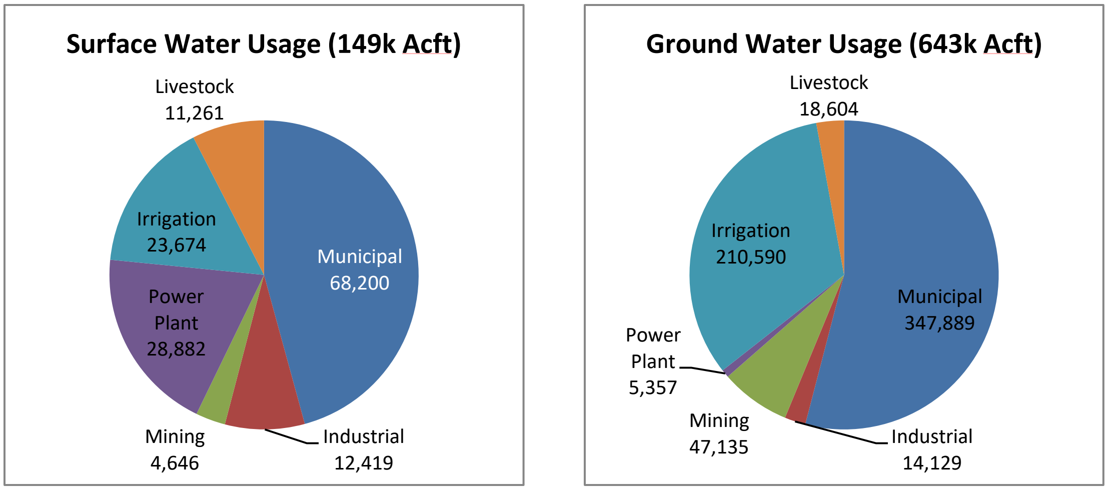

Figure 3: Surface and Ground Water Usage in the Region in 2015[3]

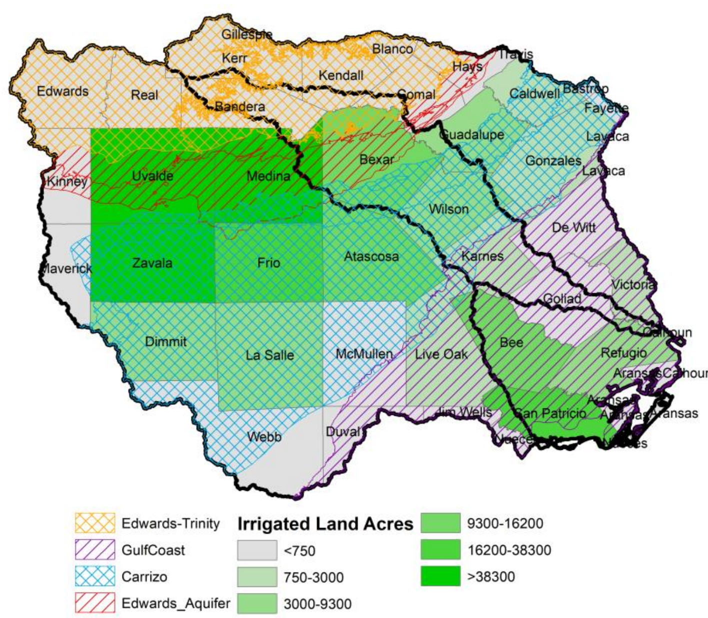

Figure 4: Irrigated Land by county in 2015[4]

[3] The data is calculated by the authors based on the data of TWDB water use survey.
[4] The map is plotted by the authors based on the data from USDA QuickStats (USDA 2018)

Agriculture Sector

Figure 4 presents the distribution of irrigated land in 2015. Most of the irrigated land pumps from the Edwards and Carrizo-Wilcox Aquifers with some near the coastline. The Winter Garden Region, spanning Dimmit, Frio, La Salle, part of Uvalde, Medina, Bexar and Atascosa counties, has a long history of year-round production of vegetables. Since the precipitation decreases from east coastline to west inland (Figure 5), the field crops and vegetables in the winter garden region are mostly irrigated. A significant amount of water withdrawn from the Edwards Aquifer and Carrizo Aquifer is for the irrigation purpose (Figure 6 and Figure 7). Agriculture is the largest water usage in the Carrizo Aquifer and the second largest usage in the Edwards Aquifer. With the growth of population and the expansion of urban areas over time, more water was used in municipal sector to meet the increase demand in both aquifers, and more water is expected to transfer from agriculture sector to municipal in the future. After the innovation of oil and gas fracking technology, a significant amount of water withdrawn from Carrizo Aquifer has been used for fracking the oil and gas in Eagle Ford since 2010. Therefore, less and less water has been left for agriculture irrigation and this makes the sustainability of regional agriculture vulnerable.

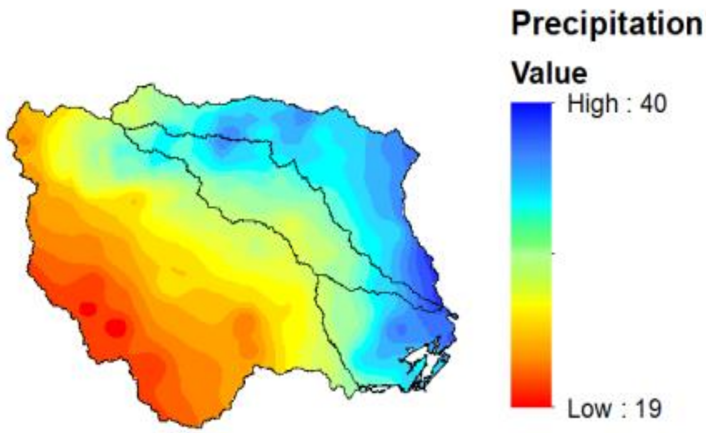

Figure 5: Average annual Precipitation from 1980 to 2010 (Unit: Inches)

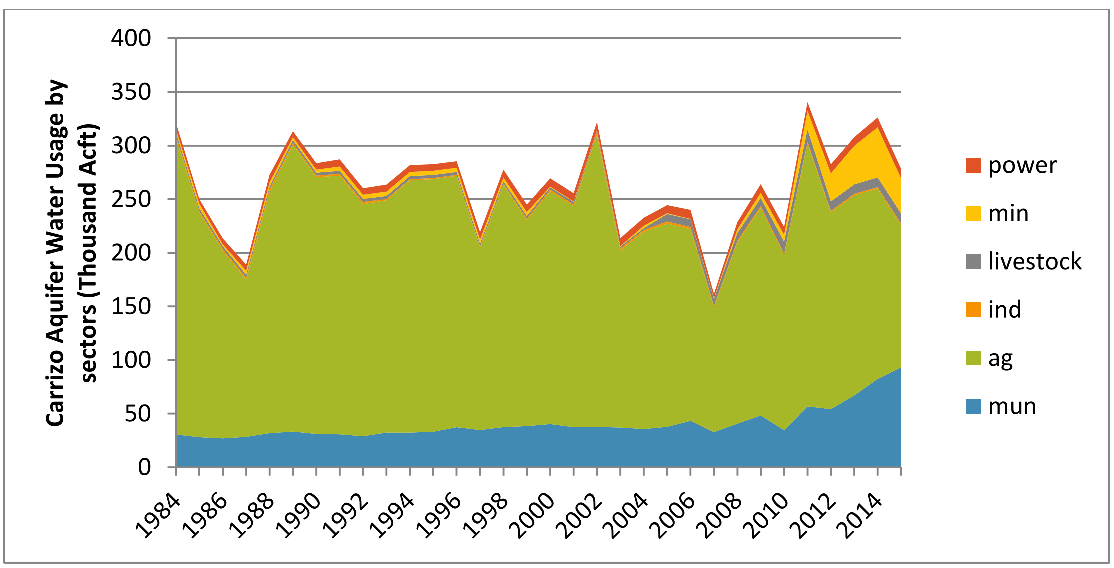

Figure 6: Carrizo Aquifer Water Usage by Sector (Thousand Acre feet)

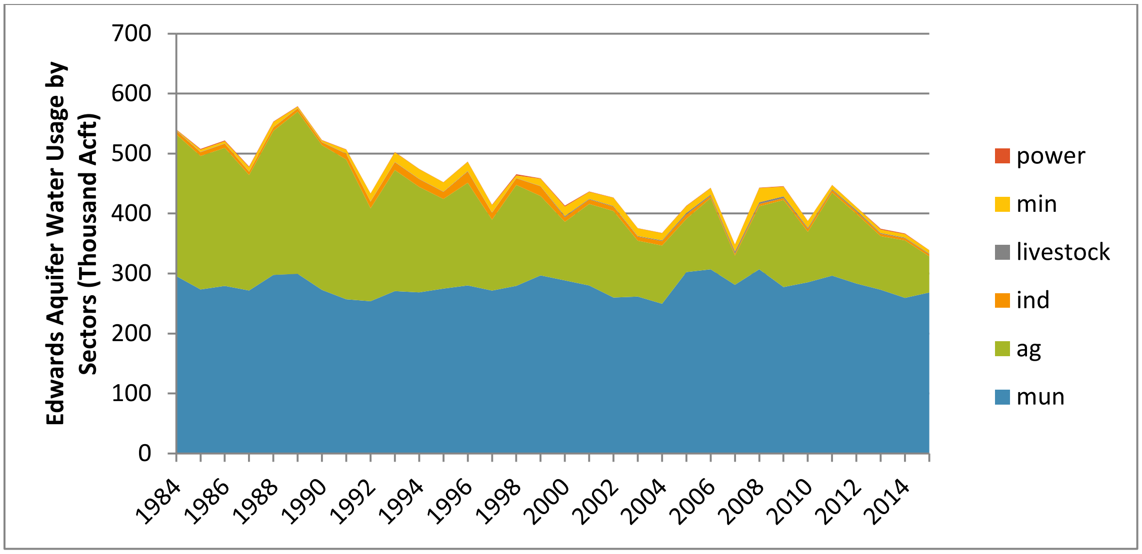

Figure 7: Edwards Aquifer Water Usage by Sector (Thousand Acre feet)

Climate Change in the Research Region

A number of General Circulation Models (GCMs) have been used by the IPCC to simulate the climate change to the end of this century (IPCC 2013). We chose to use a few of these to develop study area scenario. Namely based on the advice of the Texas state climatologist – Dr. John Nielson-Gammon, we considered to use: a) BCC-CSM1-1developed by Beijing Climate Center, China Meteorological Administration (Wu 2012; Xin et al. 2013), b) GFDL-ESM2M developed by NOAA Geophysical Fluid Dynamics Laboratory (Dunne et al. 2012; Dunne et al. 2013), c) IPSL-CM5A-LR developed by Institute Pierre Simon Laplace, France (Dufresne et al. 2013), d) MIROC5 developed by University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (Watanabe et al. 2010), e) MRI-CGCM3 developed by Meteorological Research Institute (Yukimoto et al. 2011; Yukimoto et al. 2012), f) NORESM1-M Norwegian Climate Centre (Iversen et al. 2013), which are most suitable to predict the climate change in South Texas. Among these GCMs, the IPSL-CM5A-LR predicts the driest scenarios, and MIROC5 simulates the wettest case. IPSL-CM5A-LR is also the hottest scenario. We then chose to use IPSL-CM5A-LR and MIROC5 to test the climate effects in this region as they spanned the situation.

We generated the grid historical climatic data from PRISM (PRISM Climate Group, Oregon State University 2004) during 1980 to 2016 and the downscaled projected climatic data generated by the 2 GCMs selected from 2020 to 2099 (Maurer et al. 2007; U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center 2013). The average changes of temperature and precipitation over the historical period (1980-2016) for the decades 2030s, 2050s, 2070s, and 2090s were then calculated and presented in Table 1. The overall precipitation in the research region will decrease even in the wettest scenarios and the average temperature increases in all cases. In doing this we used the 4 future Representative Concentration Pathway (RCP) developed in IPCC (2013).

Table 1: Climate Change in South Central Texas

Panel A: Precipitation Change Based on Average Precipitation during 1981-2016					
GCMS	**RCP**	**2030**	**2050**	**2070**	**2090**
IPSL-CM5A-LR (Driest)	RCP2.6	-4.24%	-0.26%	-6.06%	-2.92%
	RCP4.5	-13.27%	-14.83%	-11.31%	-11.77%
	RCP6.0	0.22%	-23.70%	3.62%	5.79%
	RCP8.5	12.86%	-4.53%	-17.82%	-24.02%
MIROC5 (Wettest)	RCP2.6	-9.33%	20.81%	17.51%	7.13%
	RCP4.5	1.11%	17.26%	5.65%	13.86%
	RCP6.0	8.50%	2.16%	15.47%	3.44%
	RCP8.5	13.32%	-1.07%	-10.53%	2.86%
Panel B: Temperature Change Based on Average Temperature during 1981-2016					
GCMS	**RCP**	**2030**	**2050**	**2070**	**2090**
IPSL-CM5A-LR	RCP2.6	7.54%	8.30%	7.19%	6.84%
	RCP4.5	10.01%	11.67%	12.55%	13.49%
	RCP6.0	6.16%	11.47%	11.88%	14.81%
	RCP8.5	7.18%	15.22%	21.81%	31.02%
MIROC5	RCP2.6	6.75%	6.44%	6.70%	7.25%
	RCP4.5	8.08%	10.41%	10.94%	12.72%
	RCP6.0	4.83%	8.74%	11.21%	13.24%
	RCP8.5	8.00%	13.31%	18.96%	23.89%

Population Change in the Research Region

The research region is a small and food deficit region, which relies on the food imports from other regions and is a price taker. Therefore, the population growth scenarios will not alter the price is assumed for food demand or have a direct impact on the market faced by the agricultural sector. But the population growth will increase the water demand of municipal and industrial interests, and consequently intensify the water competition between agriculture and other sectors. The Texas Demographic Center (2018) projects rapid population growth for South Central Texas from current to 2050 based on an assumption of half the migration rate observed during 2010-15 (Table 2). We then extended the population growth rate to 2090 by assuming the same growth rate from 2050s-2090s as in 2030-2050s. By 2090s, regional population is expected to double relative to the population level in 2015. This certainly contributes to the regional water scarcity issue.

Table 2: Population Growth Rate relative to the population in2015

	2030	2050	2070	2090
Metro San Antonio	16.2%	40.4%	67.1%	98.8%
Regional	16.4%	41.6%	70.9%	106.2%

Thus, we considered the population growth as a factor that impacts the agricultural sector in this chapter.

Data

Crop Yield and Water Usage Implication

To model crop yield and irrigation water change under climate change, we use data from EPIC simulation and from the Blaney-Criddle Method. In terms of cropping, we used the same crop irrigation strategies as Ding (Ding 2014), which are implemented different levels deficit irrigation and alternative irrigation ending dates across irrigation methods (furrow, sprinkler or dryland) and different state of natures. The yields and monthly water use for each crop under different irrigation strategies and state of nature are simulated by the Environmental Policy Integrated Climate (EPIC) Model (Texas A&M Agrilife Research 2018). For vegetables, simulations were conducted for alternative deficit irrigation levels and irrigation methods. Alternative irrigation ending dates were not used for vegetables since vegetables require continuous irrigation. The dryland yield of sorghum hay is calculated by adjusting the irrigated land yield of sorghum hay. The yield of sorghum hay is used as proxy for hay and pasture. We assume the base irrigation strategy is when soil moisture reaches 75 percent with sprinkler irrigation under normal state of nature. Then we calculate the percentage change of yield and water use by using alternative irrigation strategies compared with the base strategies.

Since the EPIC Model data setups we had available only covered 12 crops (corn, cotton, sorghum, oats, wheat, peanuts, rice, cabbage, cucumber, onion, spinach and cantaloupe) and were only simulated for the base scenario without climate change effects, we used the Blaney-Criddle Method to estimate the evapotranspiration rate and then simulate the yield and water usage in each month based on the yield response factor of the crops for the non-EPIC simulated crops in base scenario and all crop irrigation strategies in climate scenarios. We built crop irrigation strategies under different levels of deficit irrigation. The details of this method are described in *Irrigation Water Management: Irrigation Water Needs* (FAO 2018b). The yield response factor of the crops (Table 3) used in the model is from FAO (FAO 2018a). The higher the yield response factor is, the more sensitively the crops response to soil moisture. The temperature and precipitation data are applied by the average county level historical PRISM data (PRISM 2018) of responding county by state of nature.

Table 3: The yield response factor

Field Crops Names		Vegetables Names	
Cotton	0.85	Peanut	0.9
Soybeans	0.85	Sesame	0.9
Canola	0.9	Cabbage	0.95
Hay	0.9	Cantaloupe	1.1
Sorghum	0.9	Cucumber	1.1
Sorghum hay	0.9	Onion	1.1
Barley	1.05	Spinach	1.1
Honeydew	1.05	Watermelon	1.1
Oats	1.05		
Wheat	1.05		
Rice	1.2		
Corn	1.25		

Data Source: Crop yield response to water (FAO 2018a)

Municipal and Industrial Water Demand Implications

The municipal and industrial sector current water demand data for year 2015 at county level is observed from TWDB water usage survey. We assume the demand of M&I water usage per capita can be expressed as an endogenous demand curve with a constant elasticity in a reasonable range, and the total demand of M&I water would increase at the same rate of population growth rate. The elasticity of municipal sector is estimated by Griffin and Chang (1991) and the elasticity of industrial water demand is obtained from Renzetti (1988). Table 4 presents the overall percentage change of M&I water demand based the level of year 2015.

Table 4: Percentage Change of M&I Water Demand Based on the Level of 2015

Row Labels	2030	2050	2070	2090
Industrial Sector	7.72%	25.22%	47.10%	75.12%
Municipal Sector	12.18%	27.30%	45.02%	67.38%

Agriculture and Other Datasets

In order to set up the integrated model, we used data from multiple sources. For example, agriculture crop and livestock budgets were drawn from the Texas A&M AgriLife Extension (Texas A&M Agrilife Extension 2017); current level of crop and livestock production and land usage data were from USDA Quickstat (USDA 2018); hydrology part of the model was specified using data from WRAP (Wurbs 2003), SWAT (Arnold et al. 2013) and the Groundwater Availability Model GAM using data sets developed by USGS, TWDB and Texas A&M University. For more details about data generation, please see the data part of the model documentation.

Methodology

As stated above, climate change has a strong and direct impact on water supply and demand, and crop yields, which will directly impact the production level and management strategies within the agriculture sector. The rapid population growth will also increase the water demand and stress the water scarcity in this region, in turn having an indirect impact on agriculture. In this chapter, we would like to examine how climate change and population growth affect the agricultural sector, and how could farmers cope with the impacts. In order to examine the impacts, we expanded on earlier models and developed Edwards aquifer regional simulation model that included Rivers and Groundwater Components plus energy can considerations in a Nexus Model. We will call this model EDSIMRGW_NEX and will use it to simulate the regional climate implication. In the remainder of this section, we will introduce the scope of EDSIMRGW_NEX model, followed by the analysis design for this study.

Model Scope

EDSIMRGW_NEX and its previous versions (RIVERSIM/EDSIMR) are regional hydrological and economic simulation models developed and improved by Dillon (1992), Dillon et al. (1993), Lacewell and McCarl (1995), Williams (1996), Keplinger (1998), Keplinger et al. (1998), Keplinger and McCarl (2000), Chen, Cillig and McCarl (2001), Gillig, McCarl and Boadu (2001), Gillig et al. (2004), Boadu, McCarl and Gillig (2007), Cai (2009), Ding (2014) and this study.

Previous versions of the model used herein have been widely used to analyze regional water related issues, such as water use tradeoffs between agriculture and municipal use (Dillon et al. 1993; Chen et al. 2001; Ding 2014), and water project selection (Gillig et al. 2001; Cai 2009). EDSIMRGW_NEX simulates regional agricultural and electricity production as well as water allocation between agriculture, cooling, fracking and M&I. It also models water flows, groundwater usage, water project development, electricity usage, cooling retrofits and new power plant construction. The model covers 4 rivers and 4 aquifers, simulating the river flows using the naturalized net inflow simulated by the hydrological model Water Rights Analysis Package (WRAP) (Wurbs 2003) and Soil & Water Assessment Tool (SWAT) (Arnold et al. 2013). It constrains the water withdrawn by the surface water rights permits issued by Texas Commission on Environmental Quality (TCEQ). For the ground water part, the model simulates the pumping of all sectors, the pumping lift and ending elevation changes simultaneously by involving the simulation result of specified SEAWAT model of Edwards Aquifer and Groundwater Availability Model (GAM) of Carrizo Aquifer, Gulf

Coast Aquifer and Trinity-Edwards Aquifer. The environmental protection requirements of estuary and aquifer water elevation are also considered in EDSIMRGW_NEX.

EDSIMRGW_NEX is a mathematical programming model with a two-stage stochastic decision making procedure (Dantzig 2010). Generally, the model implements 9 states of nature responding to the degrees of water availability and aquifers' recharge, which is considered as the uncertainty part in the model. Investment, crop and livestock mix decisions are made in advance of time when the water availability is unknown (stage 1), while operational decisions like irrigation, water withdrawal and power generation are set given knowledge of water state of nature. For example, farmers have to decide the acres of each crop and whether to plant crops in the furrow field or lands with sprinkler installed before they know the precipitation information and aquifer lifts for the next year. While they decide how much water should be applied to crops per acre in the second stage and the crop yield is then calculated by the decision in two stages. The farmer can also decide to install new sprinkler equipment in the furrow land in the first stage before planting to convert furrow land to sprinkler irrigation land. Land can also be moved to dryland or pasture.

For agriculture, we constrain the crop mix to be a convex combination of the historical crop mix, in order to constrain the other resources we don't model in EDSIMRGW_NEX in a reasonable range, such as labor, capital investment and other inputs to agriculture.

EDSIMRGW_NEX is a typical year equilibrium model with within year disaggregation on a monthly scale. The initial status of items such as reservoirs is set to the probability weighted average of the ending status. We allow drawdown of the aquifer water table.

Due to the complexity and time consumption of solving a long term dynamic model, we use EDSIMRGW_NEX as a recursive model when estimating the effects of climate change and population growth on the Nexus. We set the initial status of available land, aquifer water table, water projects and power plants as same as the ending status of those items in the last decade of same climate scenario to present the dynamic process. For more details of model structure, please see the model documentation.

Analysis Design

To test the effect of climate change and population on agricultural sector, we set up multiple scenarios. First, we ran the model under Base 2015 conditions, which does not include any climate change and population growth effects (called the base 2015 scenario). The results of that scenario permit us to examine model validity by comparing the model results with observed data. We should note that the model depicts full Nexus cooperation and as such may deviate from real world situations.

Second, we ran the base scenarios with only population growth effect and base climate assumptions. We call these scenarios the Base 2030, Base 2050, Base 2070 and Base 2090 scenarios where the year in the title denotes the population assumption. The population growth rate from 2015 to 2050 is based on the projected population growth rate on the half the historical immigration rate projection that was constructed by the Texas Demographic Center (2018). The net population growth rate for 2070s and 2090s are assumed to be the same rate as it is from 2030s to 2050s. Comparing the result of these four scenarios with the Base 2015 result, the impact of population growth on the water projects selection will be identified.

Third, we ran climate scenarios with both climate change effects and population growth effects. A number of General Circulation Models (GCMs) have been used by the IPCC to simulate the climate change till the end of this century (IPCC 2013). Based on the advice of the Texas State Climatologist – Dr. John Nielson-Gammon and the consideration of extreme cases, we then chose to use IPSL-CM5A-LR (Dufresne et al. 2013) and MIROC5 (Watanabe et al. 2010) to test the climate effects in this region. IPSL-CM5A-LR predicts the driest and hottest scenarios among the suggested GCMs, and MIROC5 predicts the wettest case. In doing this, we employed all of the four Representative Concentration Pathway (RCPs) developed in IPCC (2013). The aggregated average of climate change variables for the study region are presented in Table 1 using the downscaled projected climate data by the GCMs from 2020 to 2090 (Maurer et al. 2007; U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center 2013). The average temperature increases in all eight different climate scenarios with different paces, and the overall precipitation decreases in most cases.

Considering all cases for climate change (GCMs crossed with RCPs), and population growth alternatives we set up 32 alternative climate change scenarios. Comparing results of climate scenarios with base scenarios, the climate change effect on the agricultural sector will be identified.

Note as we set the model as medium-term equilibrium model that we will run repeatedly for different time periods without linkages between the time periods.

However, a number of the actions in the model are irreversible. This includes land transfer out of irrigation or cropping, water project construction, new power plants construction and power system cooling retrofit decision. To handle this, the initial status of the irreversible items in later decades their values in prior decades were set equal to. For example, the water projects constructed under the Base 2015 scenario were set equal to one being forced to be included in the 2030s scenarios the future population and all 2030 climate scenarios. The Base 2050 scenario the projects built in the 2015 case and in the 2030 case.

To clearly state the impact of climate change and population growth on agricultural sector, we compare the result with those arising under the base 2015 scenarios, and in cases with those with only a population growth effect.

Results

Welfare

In the base solution the largest welfare components come from consumers' welfare from using electricity, and the consumers' welfare arising from the consumption of municipal and industrial water and (Figure 8). Note this is certainly expected as the integral underneath the demand curves is typically quite large. We also observe a significant welfare increase in these welfare accounts as the population grows in the base scenarios and climate scenarios with the time changes. On the other hand the welfare accruing to agriculture and other sectors are relatively small and did not increase with population growth. But the welfare changes across GCMs and RCPs are not clear in Figure 8.

Welfare also increases across the stochastic states particularly for the agricultural sector. Figure 9 shows a plot of agricultural welfare versus yearly precipitation changes compared with the 2015 base scenario, where the positive correlation between the two items is readily apparent, though they are under different population growth rate. The wetter the climate is, the higher the agricultural sector gains. The result is consistent with the previous study (Ding 2014), that agricultural sector becomes more vulnerable under the drier conditions with climate change.

Municipal, industrial and other sectors will be discussed in Chapter III.

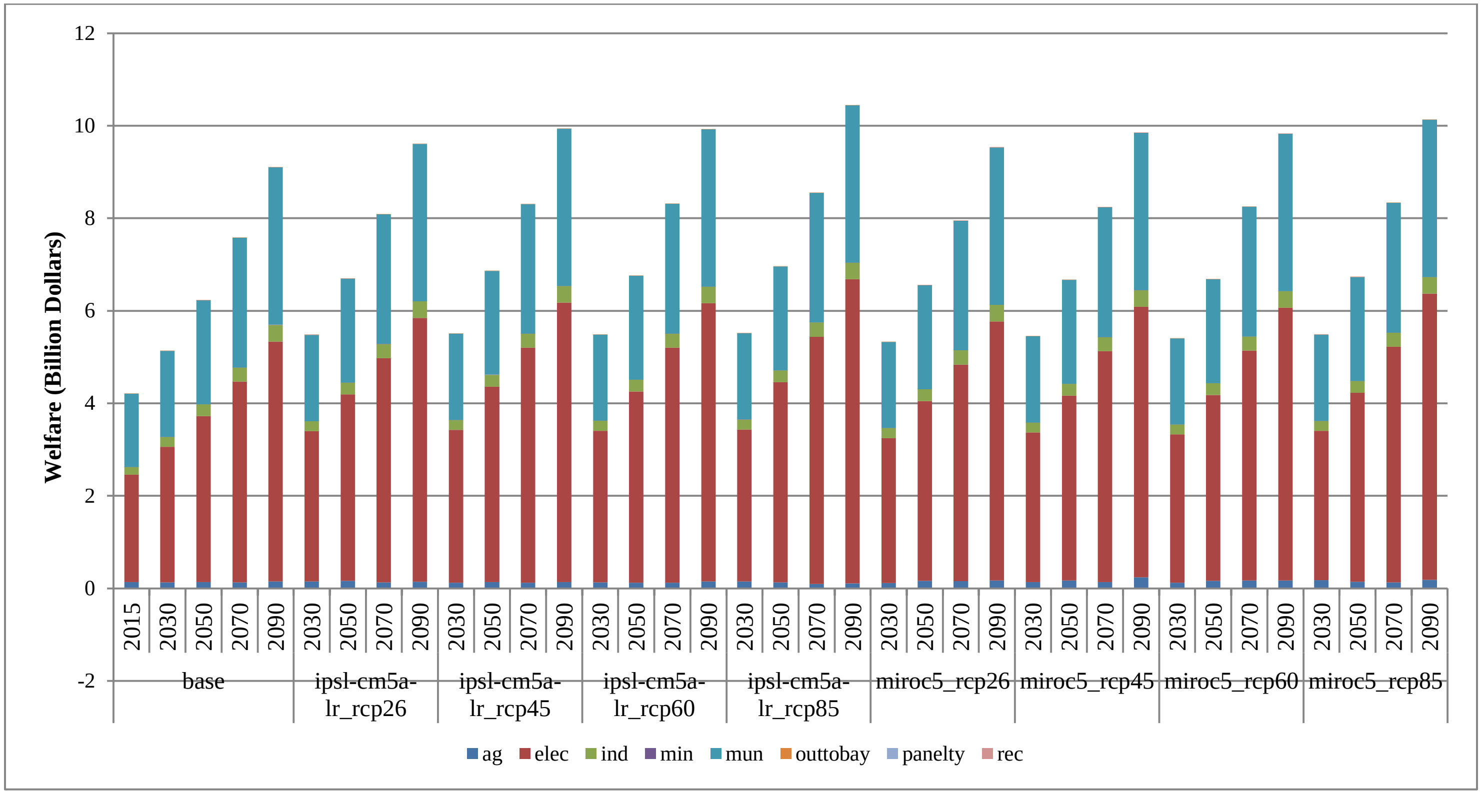

Figure 8: Net Welfare by Nexus Sectors under Climate and Population Scenarios

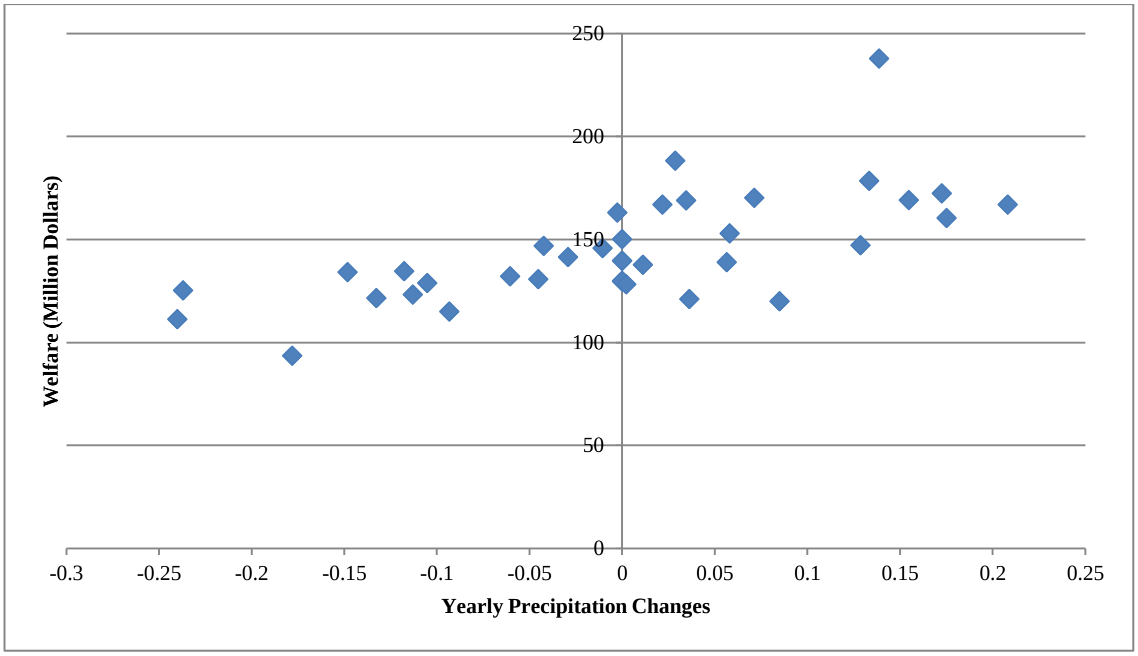

Figure 9: Welfare Gain from Agricultural Sector vs. Yearly precipitation Changes

Water Sources and Water Allocation

Figure 10 and Figure 11 present the water allocation results of surface and ground water. Municipal sector and industrial sector are the top two surface water users, which used to be municipal sector and power plants. This is because the model includes retrofit options for power plant cooling and also provides more water sources for municipal and industrial through water projects. The results indicate municipal and industrial sectors will use as much of the Edwards aquifer and permitted surface water as possible under their water rights to meet the increased demand due to projected population growth, as these sources are cheaper than water provided by projects. For more details, please see the discussion in Chapter III. On the power plant cooling side retrofits occur from once-through or recirculating cooling to dry cooling saving water, in turn letting more water flows into the bay to achieve environment value. This is one aspect of the Nexus cooperation. Details on the retrofitting options for cooling are contained in Yang (2019). Agricultural sector only take the surface water under its surface water rights and little ground water. The surface water taken by agricultural sector is similar as the amount observed in the real world, and less water is diverted in the wetter MIROC5 scenarios as will be discussed in the Water Usage section below.

Municipal sector is the dominant groundwater user. The amount pumped by the municipal sector under the Base 2015 scenario is close to the amount we observed in the real world, and municipal achieved its increased demand due to population growth from ground water sources. Agricultural water pumping from ground water is less than 5 thousand acre feet (Figure 12), while which used to be the second largest user of ground water with about 210 thousand acre feet water consumption. This is due to the huge land transfer from sprinkler land to dryland in the Base 2015 scenario that reduces the water demand of agricultural irrigation for all scenarios as the setting of recursive model.

This result indicates that beneficial Nexus decision alternatives are available. Since agricultural sector is a relatively low valued user trading water to the municipal and industrial sectors is increases efficiency and social welfare. However, this only happens when there is no transfer limits (groundwater case). When there are regulation and transfer limits, such as the Edwards aquifer water rights and the 1 acre foot transfer regulation, agricultural can still use its water. The unrestricted market assumption causes the surface water to be the major water source for agriculture sector (Figure 12), while ground water used to provide more than 8 times water to agricultural sector than the surface water.

In the base scenario, there is a small decreasing trend in total water usage in agricultural sector, especially in the ground water with population growth (Figure 12). But compared with the impact of climate change on agriculture water usage, the impact of population growth on water usage in agricultural sector is not sizable. More water is needed in the drier cases by agricultural sector (see the discussion in Water Usage).

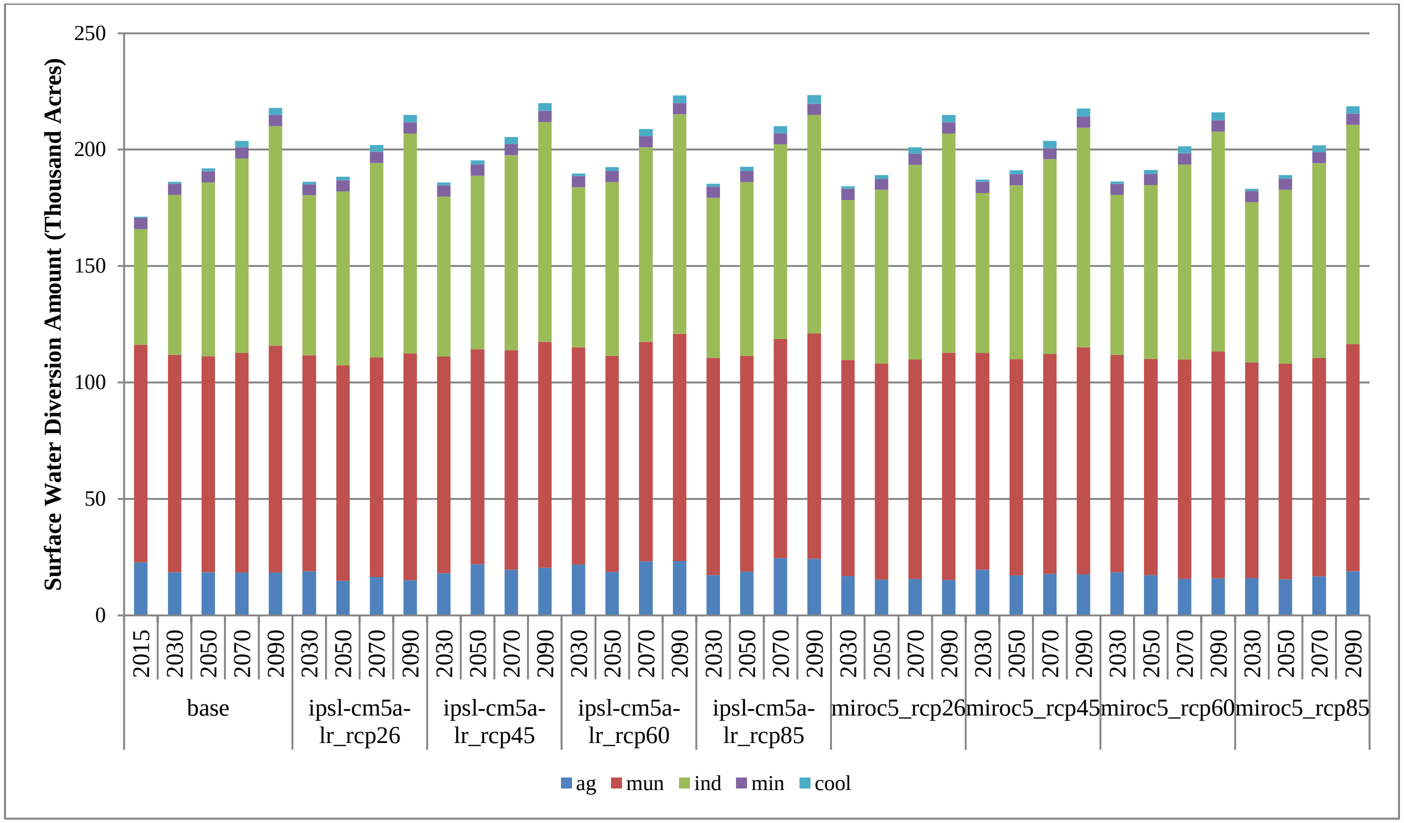

Figure 10: Surface Water Diversion and Allocation (Thousand Acre feet)

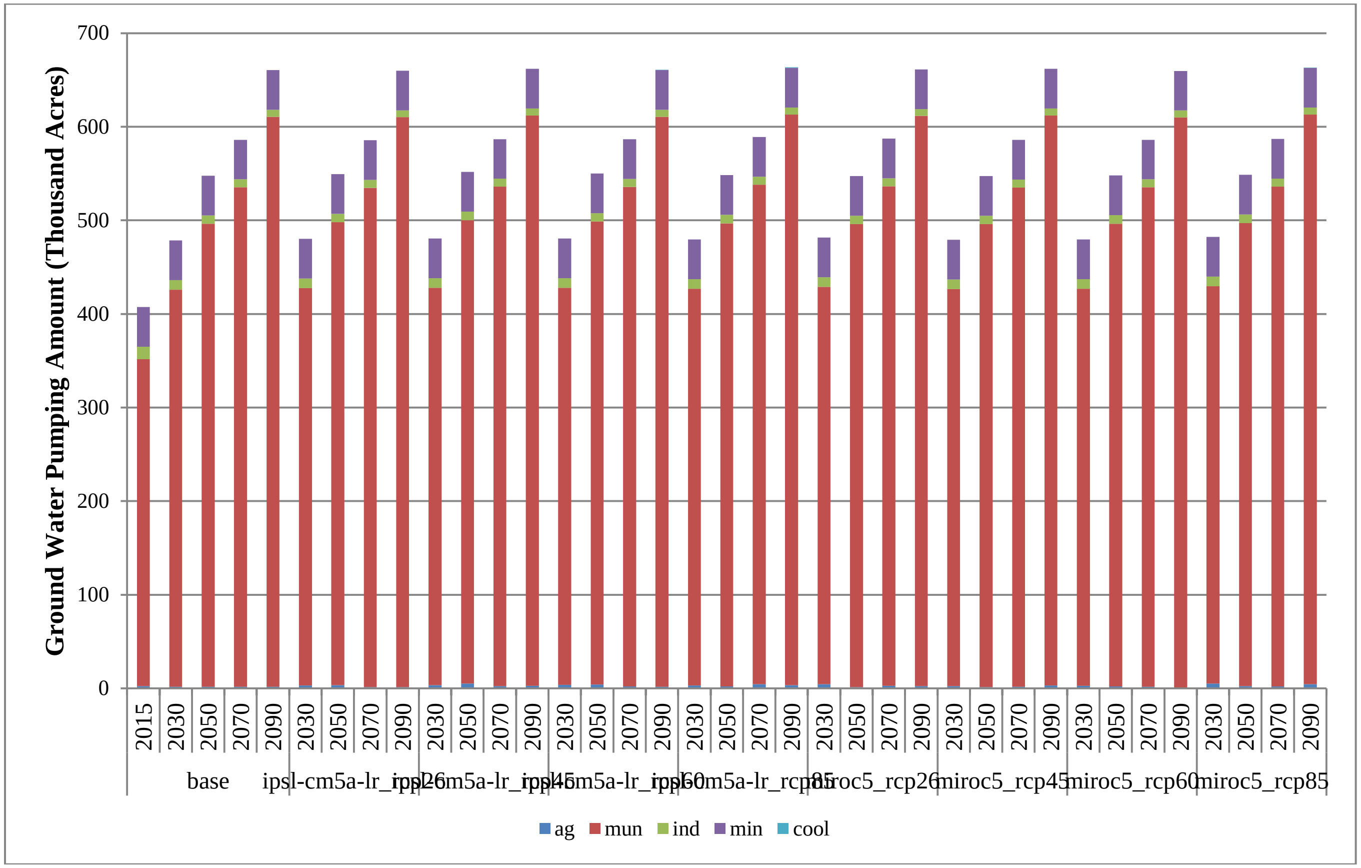

Figure 11: Groundwater Pumping Amount and Allocation (Thousand Acre feet)

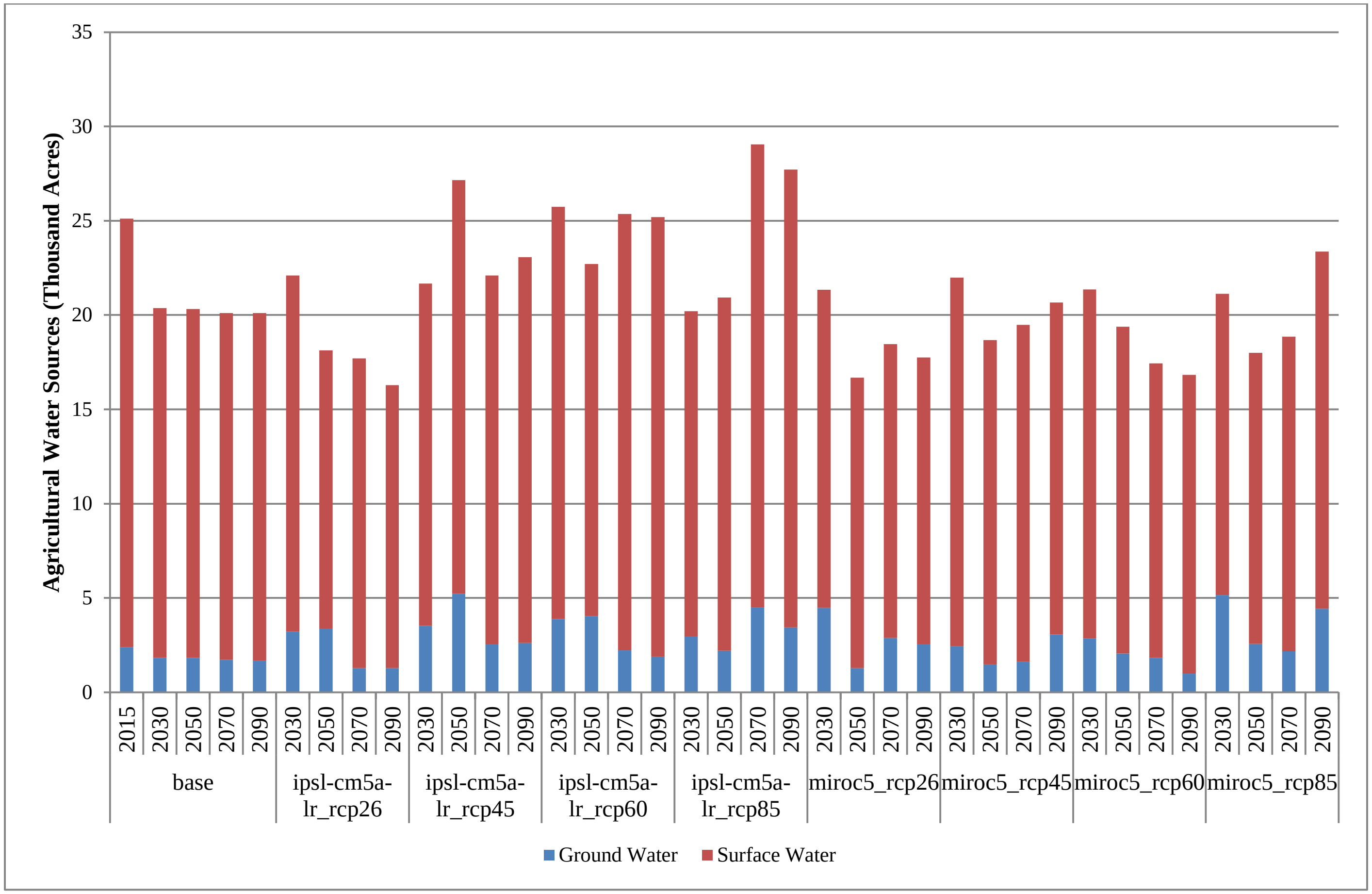

Figure 12: Agricultural Water Sources

Land Transfer

As found by others, climate change coupled with water shortages stimulates the transfer of irrigated land to dryland then finally to pasture (Mu et al. 2013; Mu et al. 2018). However, we find more complex pattern since we also allow for land to transfer from furrow irrigation into sprinkler irrigation. As we run the recursive model and restricted the inverse land transfer, it doesn't make much sense to plot the land transfer amount vs the precipitation or any climate variables. In the Base 2015 scenario, a huge amount of furrow and sprinkler irrigated lands transfer to dryland and most of the remainder furrow lands transfer to sprinkler irrigated land (Table 5) As we discussed in the subsection above, the land transfer could reduce the water usage by agricultural sector and improve the total social welfare of the nexus.

After the major land transfer in the Base 2015 scenario, more furrow lands are transferred to sprinkler irrigation method to save water in Base 2030 scenario and more sprinkler irrigated land transferred to dryland in all base scenarios to save water usage. This implies the indirect impact of population growth on agricultural sector. As more population in this region, the water demand by municipal and industrial sectors increases, agricultural sector is pushed to save water and transfer water to higher valued uses within other sectors to achieve the higher total regional social welfare. This is again a form of Nexus related decision cooperation.

Among the climate scenarios, different land transfer strategies are selected to cope with the impacts of climate change and population growth. More furrow lands are transferred to sprinkler irrigation method to save water in the drier IPSL-CM5A-LR scenarios, and more sprinkler irrigated lands are converted to dryland in the wetter MIROC5 scenarios. No croplands are transferred to pasture. This is because the research region has a climate that permits most of the field crops to be planted under dryland conditions. The different result with previous research like that in Mu et al. (2018) may because that the previous researches are all built in a larger geographical scale not in a specific region and they didn't consider the effects of water competition.

The land used by the wind and solar farms are also considered in the model (Table 6). As population growth and the hotter climate occurred, more electricity is demanded in the region, wind and solar farms are built to produce electricity without the extra water consumption. The agricultural land is taken as more social welfare could be gain from the energy sector. This is another evidence of trade-off among sectors in the FEW Nexus.

Table 5: Land Transfer under Climate Change Scenarios (Acres)

Original Land Type	Transferred Land Type	Climate Scenarios and RCPs	2015	2030	2050	2070	2090
Dryland	Pasture	BASE	40.8	0.0	0.0	0.0	0.0
Furrow	Dryland	BASE	174277.4	0.0	0.0	0.0	0.0
Furrow	Sprinkler	BASE	7340.0	14.6	0.0	0.0	0.0
		MIROC5-RCP2.6	0.0	343.8	64.0	0.0	0.0
		MIROC5-RCP4.5	0.0	296.6	0.0	621.5	0.0
		MIROC5-RCP6.0	0.0	196.3	0.0	1.1	251.3
		MIROC5-RCP8.5	0.0	193.6	3.0	249.8	2.0
		IPSL-CM5A-LR-RCP2.6	0.0	4.8	191.2	0.0	150.0
		IPSL-CM5A-LR-RCP4.5	0.0	259.8	128.2	3.6	0.0
		IPSL-CM5A-LR-RCP6.0	0.0	343.4	5.3	1.1	994.4
		IPSL-CM5A-LR-RCP8.5	0.0	1190.7	150.0	101.0	0.0
Sprinkler	Dryland	BASE	155208.1	678.3	37.6	265.9	4.3
		MIROC5-RCP2.6	0.0	64.6	6354.6	290.3	67.4
		MIROC5-RCP4.5	0.0	755.7	927.2	9.4	6534.6
		MIROC5-RCP6.0	0.0	77.7	663.8	5978.3	3.1
		MIROC5-RCP8.5	0.0	2360.2	5196.9	0.0	3.1
		IPSL-CM5A-LR-RCP2.6	0.0	786.0	5953.0	0.0	20.2
		IPSL-CM5A-LR-RCP4.5	0.0	48.5	75.2	0.0	5.8
		IPSL-CM5A-LR-RCP6.0	0.0	48.3	3.7	95.4	760.2
		IPSL-CM5A-LR-RCP8.5	0.0	879.8	4.2	126.1	45.0

Table 6: Agricultural Lands Transfer to Wind and Solar Farm (Acres)

			2030	2050	2070	2090
Solar Farm	Pasture	BASE	15018.52	24442.17	32407.5	32407.5
Wind Farm	Pasture	BASE				6023.391
		MIROC5_RCP2.6	3705.438	4672.338	9268.116	10533.7
		MIROC5_RCP4.5	4164.831	5632.242	6816.282	7774.635
		MIROC5_RCP6.0	4178.592	5634.222	6816.282	7772.655
		MIROC5_RCP8.5	4178.592	9001.779	10658.41	11777.31
		IPSL-CM5A-LR_RCP2.6	4198.392	5165.292	6359.496	7323.096
		IPSL-CM5A-LR_RCP4.5	4786.716	5951.715	7135.755	7802.949
		IPSL-CM5A-LR_RCP6.0	4498.461	5951.715	7135.755	7878.717
		IPSL-CM5A-LR_RCP8.5	4984.815	6129.915	7606.698	8782.521

Agricultural Production Indices

To develop a summary measure of what happens within the agricultural sector we computed index numbers for total production and by production component. These are calculated by state of nature then probabilistically weighted to an average and compared with a similar measure developed within the Base 2015 scenario, which has neither climate effect nor projected population growth effect. The indices show agricultural production is highly affected by climate but not population growth. In particular the agricultural production indices are very stable indices in the base non-climate scenarios. But the index numbers are substantially smaller in the drier IPSL-CM5A-LR scenarios and larger in the wetter scenario - MIROC5 (Figure 13). We also decompose the indices into three major components: field crops, vegetables and livestock to better examine the climate change effects (Figure 14).

The field crop indices are the most affected by the climate scenarios increasing in the wetter scenarios, but decreasing in the drier scenarios. This is because most of the field crops are not irrigated and, the increased precipitation is a major determinant of yield. While in the drier cases, more dry-tolerant crops are selected to overcome the effects of decreased precipitation and to offset the reduction of agricultural production (for details, please see the discussion in crop mix). The land transfer from irrigated land to dryland in the wetter cases also contributes to the increase of field crop indices.

Vegetable results are opposite, where production level decrease more in the drier scenarios, but increase less in the wetter scenarios. Compared with field crops, the vegetables are much more sensitive to the soil moisture level (See the yield response factor in Table 3). And about one third of the vegetables are planted in the irrigated land with furrow or sprinkler system, in turn relying more on the water availability in the region. However, agriculture is still lower valued across the FEW Nexus sectors so water trades. This results in less water available under drier conditions and consequently less vegetable production.

Livestock production indices are relatively stable across climate scenarios. This is because the livestock yields are not varied with climate change. The only effect of climate change on livestock comes from the yield changes of hay and the AUM (Animal Unit Month) carrying capacity changes on pasture land, which in turn decreases feed supply and increases cost. Pasture land is also used for wind and solar farms under some climate scenarios (Table 6), which also contributes to the variance of livestock production index.

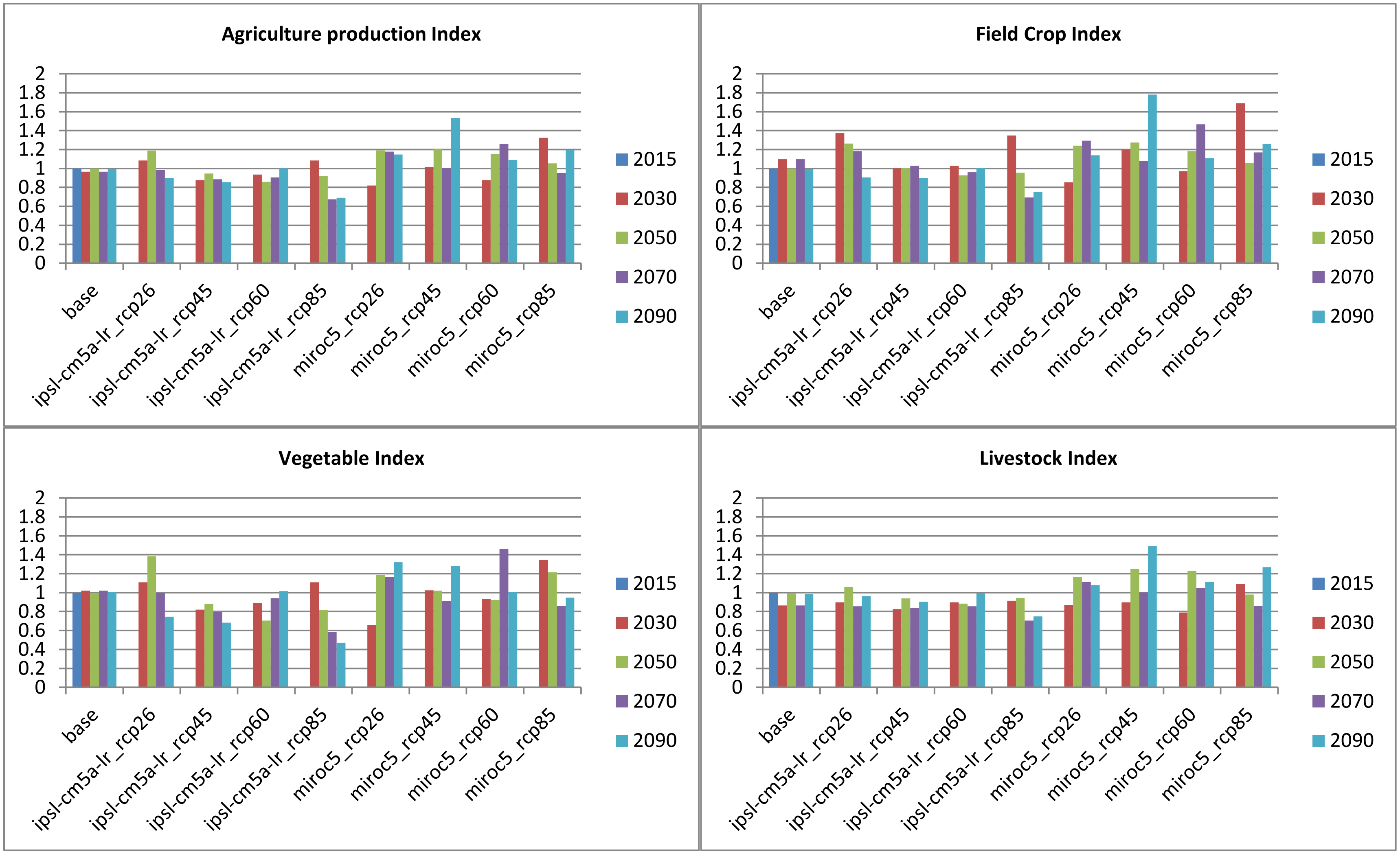

Figure 13: Agriculture Production Indices

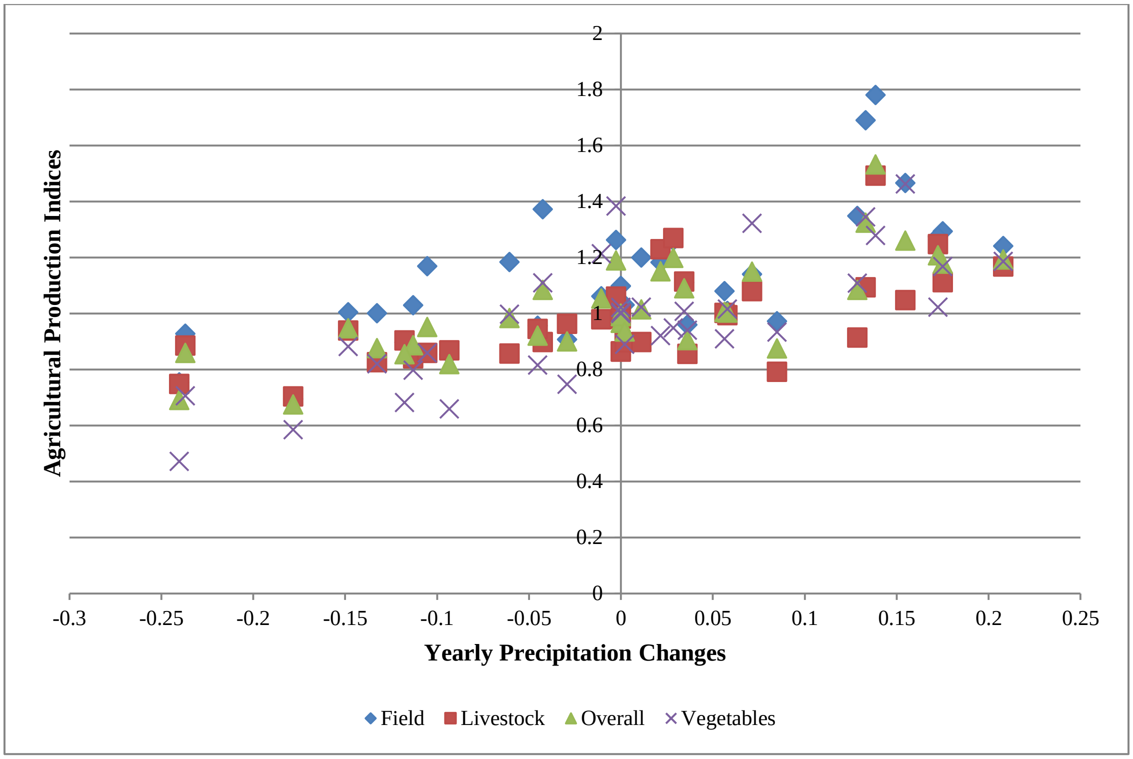

Figure 14: Agricultural Production Indices vs Yearly Precipitation Changes Crop Mix

As the impact of population growth on agricultural sector is small, we only report the crop mixes change across climate scenarios here. Precipitation has a large effect on dryland crop mixes due to its effects on crop yield and the drought tolerance of the crops. Figure 15 exhibits the acres of the top 5 dryland field crops vs the changes in yearly precipitation across climate scenarios. The acres of dryland corn vary the most as corn is quite sensitive to moisture stress. In the driest scenarios, the acres of corn is less than 100 thousand acres, while in the wettest scenarios, it is around 300 thousand acres. On the other hand cotton, as the most drought tolerant crops, is planted more in the drier conditions, but less in the wetter scenarios. Sorghum, wheat and oats are more neutral to soil moisture, in turn exhibiting smaller changes among climate scenarios. Moreover, the acres of each crop are affected by the acres of total available dryland, which is not exhibited in this figure.

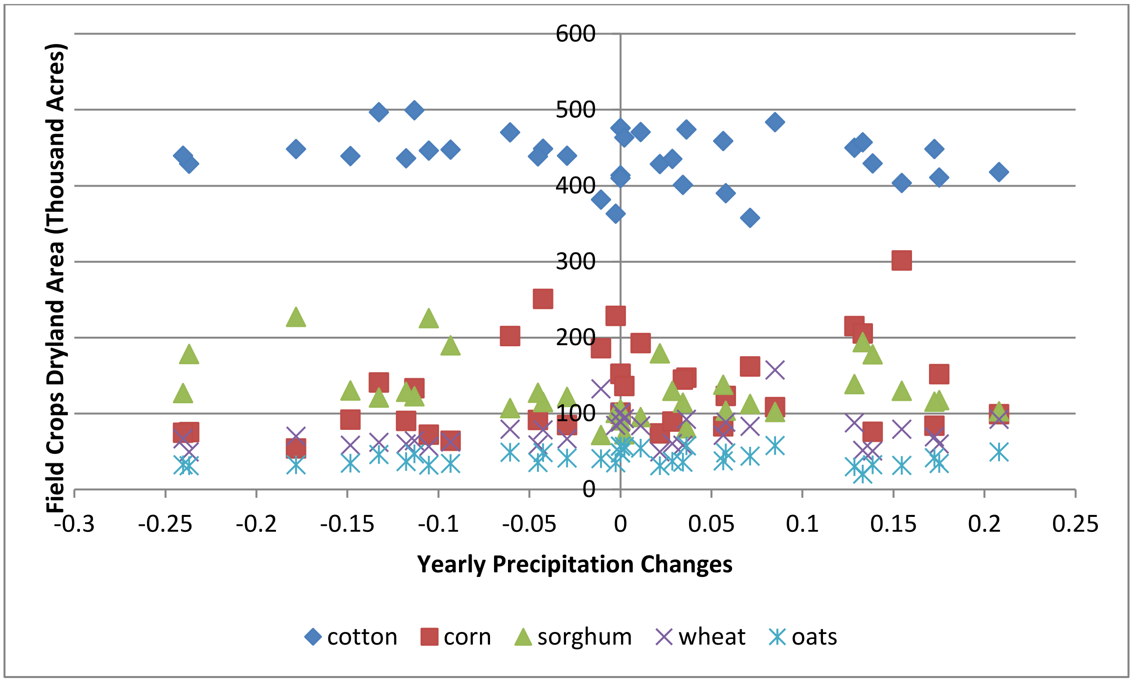

Figure 15: Top 5 field crops dryland acreage (Thousand Acres) vs yearly precipitation changes

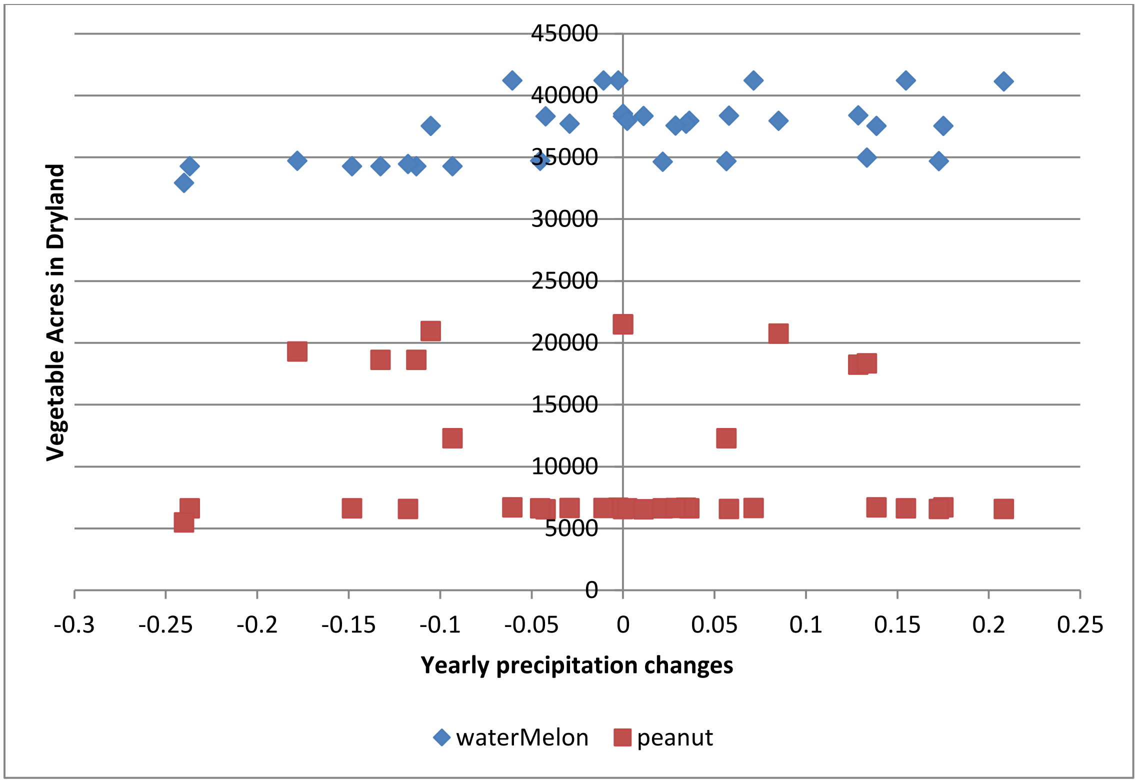

Figure 16: Vegetable acreage in dryland (Acres) vs yearly precipitation changes

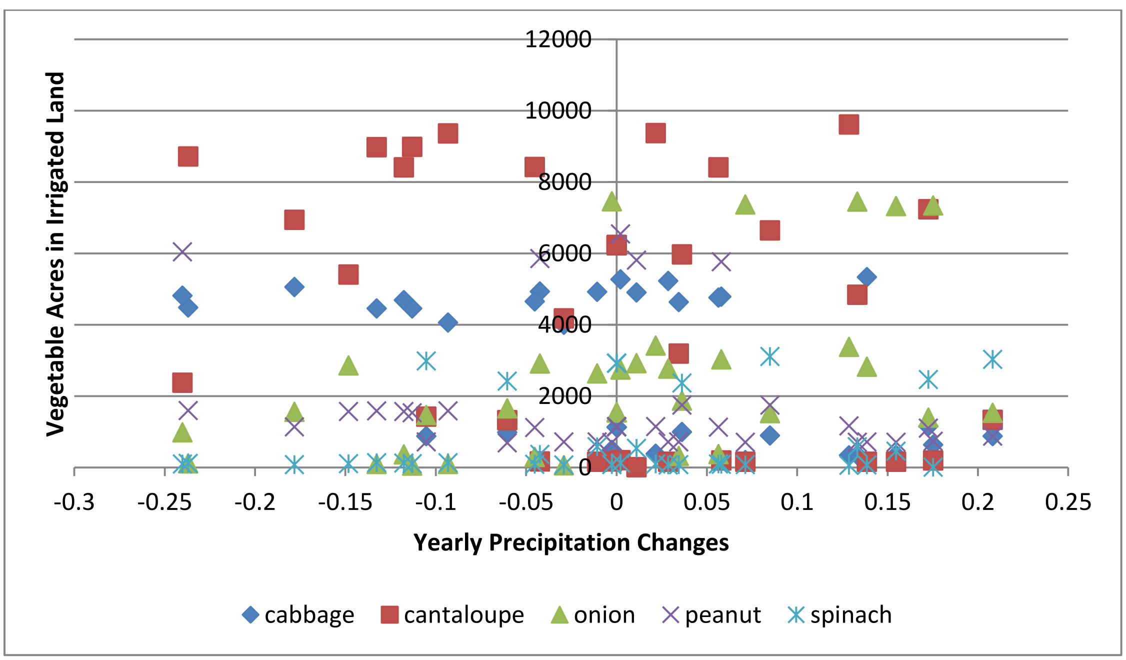

Figure 17: Top 5 vegetable acreage in irrigated land (Acres) vs yearly precipitation changes

Watermelon and peanuts are the only two vegetables planted that are planted under dryland conditions. Watermelon which is more water sensitive is planted more heavily in the wetter climate while peanut planting expands in the drier cases. The acreages are also affected by the dryland availability for vegetables.

The planted areas of the top 5 irrigated vegetables are not substantially impacted by the alternative climate change associated precipitation alternatives. They are more affected by multiple factors, such as land transfer, the water availability for agricultural sector and the deficit irrigation strategies. Also, the yearly expected precipitation change refers to the average precipitation changes in the region. However, most vegetables are in the Winter Garden region, which is in the west part of research region. The states of nature definitions do not fully reflect the precipitation changes in the Winter Garden as they are based on Edwards aquifer recharge.

Crop Irrigation Strategies

Crop irrigation strategies, including the deficit irrigation strategies, are the decisions made in the second stage of the model in the agricultural sector of FEW Nexus. It makes decisions on the actual amount of water applied to crops after the land shift and crop mix decision in the first stage of the model. In this subsection, we summarize results for two climate scenarios namely the IPSL-CM5A-LR GCM, RCP 8.5 in 2090s, which is the driest and hottest scenario, and the MIROC5 GCM, RCP 2.6 in 2050s, which is the wettest and second coldest scenario, as the example to exhibit the crop irrigation strategies (Table 7). Thought the two scenarios are under different population, we ignore the impact of population growth on irrigation strategies because it is too small. To make the comparison easier, we convert the total acres of crops under each category of irrigation strategy to the proportion of the irrigation strategies selected under each category. Generally, when the farmers realize it is a relatively drier year, the full irrigation strategies are preferred, rather than deficit irrigation to prevent the huge production loss, in all three scenarios. More full irrigation strategies are selected for the field crops as opposed to the vegetables. Also, the irrigation strategies for vegetables vary more across states of nature than those for crops. Across the scenarios, in the IPSL-CM5A-LR GCM, RCP 8.5 2090 scenarios, which has a lower expected precipitation level, deficit irrigation strategies are more selected, than the scenarios with the higher expected precipitation levels. The results are consistent with the findings by Keplinger (1998) and Keplinger and McCarl (2000).

Table 7: Crop irrigation strategies under different climate scenarios

Scenarios and Decades	Crop type	Strategy	HDry	MDry	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet
BASE 2015	Field crops	Full	99.6%	49.2%	95.5%	63.3%	17.0%	98.7%	1.3%	1.3%	2.0%
		3/4	0.3%	50.7%	4.4%	36.6%	82.9%	1.2%	98.5%	98.6%	97.8%
		half	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.2%
	vegetables	Full	89.9%	82.3%	90.5%	90.5%	51.4%	54.3%	4.2%	4.2%	22.5%
		3/4	10.1%	17.7%	9.5%	9.5%	48.6%	45.7%	95.8%	95.8%	77.5%
		half	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
IPSL-CM5A-LR RCP 8.5 2090	Field crops	Full	99.8%	28.7%	93.6%	51.4%	5.2%	98.6%	1.6%	1.6%	2.5%
		3/4	0.0%	71.1%	6.2%	48.4%	94.7%	1.2%	98.2%	98.2%	97.4%
		half	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
	vegetable	Full	50.5%	41.0%	74.4%	74.8%	4.4%	43.4%	2.6%	8.9%	9.2%
		3/4	18.2%	54.8%	21.4%	21.0%	64.1%	25.3%	66.0%	59.6%	59.3%
		half	31.4%	4.2%	4.2%	4.2%	31.4%	31.4%	31.4%	31.5%	31.5%
MIROC5 RCP 2.6 2050	Field crops	Full	100.0%	57.4%	97.0%	64.0%	27.1%	99.4%	1.4%	1.4%	2.0%
		3/4	0.0%	42.6%	3.0%	36.0%	72.9%	0.6%	98.6%	98.6%	97.9%
		half	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	vegetable	Full	84.1%	85.6%	97.6%	83.7%	59.5%	43.8%	7.8%	7.8%	38.6%
		3/4	13.5%	11.6%	0.0%	13.9%	13.8%	22.6%	58.5%	59.3%	60.0%
		half	2.4%	2.8%	2.4%	2.4%	26.7%	33.6%	33.7%	32.9%	1.4%

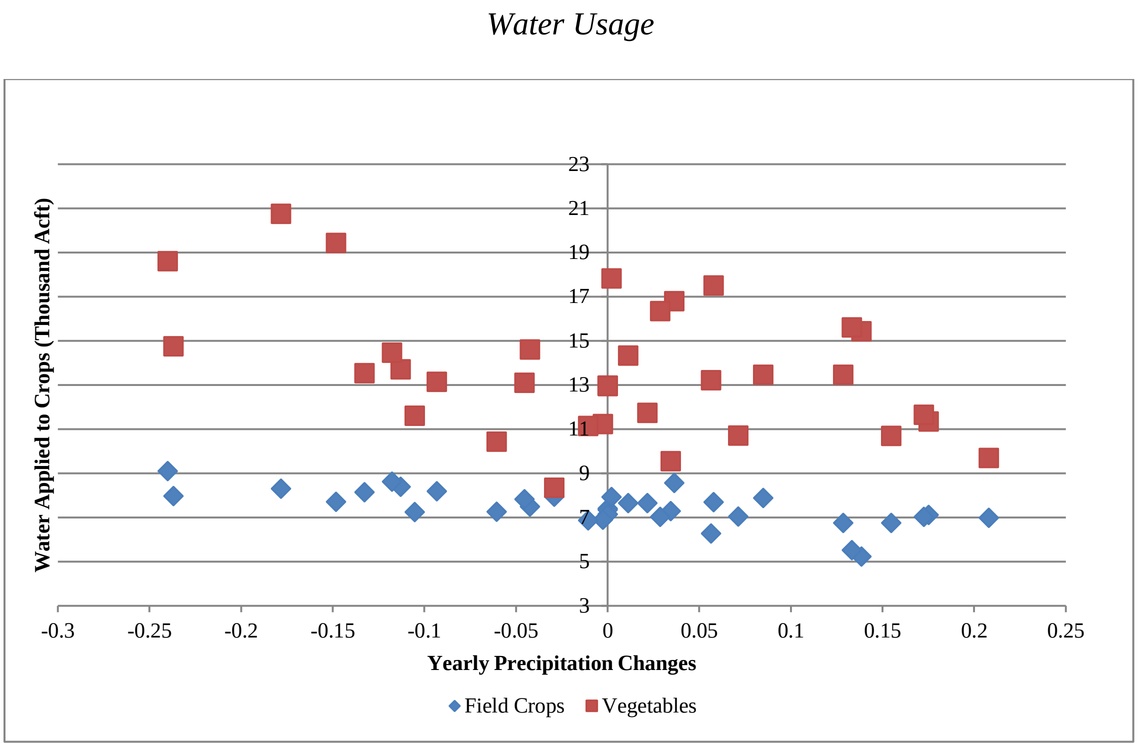

Figure 18: Water applied to crop land vs yearly precipitation changes

Although more deficit irrigation strategies are selected in the drier scenarios, it still needs more total water to achieve productive soil moisture levels (Figure 18). In terms of water used by irrigation, the average water usage by vegetables is more affected by the precipitation level than the field crops. However, the extra amount applied to the crops is much smaller than the decrease of precipitation. In turn, we still get observe the lower production indices in the drier scenarios, as shown in Figure 14.

Concluding Comments

In this chapter, we examined agricultural sector performance in a cooperative Food-Energy-Water Nexus setting as it was affected by climate change and population growth. We find within this study climate change has large implications for the agricultural sector. Population growth does increase stress from water competition but the effect is small.

The agricultural share of regional welfare is small being dwarfed by the municipal, industrial and electrical components. Furthermore, the absolute value of agricultural sector welfare does not change much across the alternative population growth scenarios, but increases when the climate is wetter. We find in an FEW Nexus context, historical agricultural ground water usage is reduced in the interest of increases in the municipal and other sectors, due to a higher use value outside of agriculture. But we find regionally this only occurs largely for groundwater aquifers other than the Edwards Aquifer. Agriculture retains its water rights in the river and Edwards Aquifer settings allowing continued irrigation.

Climate change is the dominant factor that impacts agricultural water usage. Agriculture needs more water in the drier cases but climate change diminishes its ability to access such water. Additionally, although it is not very obvious, population growth results in more water being taken away from agricultural sector.

In terms of climate change the expected agricultural production level is higher in the wetter MIROC5 scenarios than in the alternative drier scenarios. We find that field crop production increases more in the wetter scenarios but decreases less than other crops in drier scenarios. While vegetables exhibit the opposite case with larger decreases in the drier scenarios, but lesser increases in the wetter scenarios. This occurs because almost all of the field crops are planted as dryland crops, which strongly benefit from increased precipitation, while about one third of the vegetables are grown under irrigation land which is limited by the water resource. Livestock have a similar but less varying trend.

More irrigated land transfers to dryland with population growth. But compared with climate change effect, the amount transferred due to population growth is small. The benefit of more precipitation to dryland field crops leads to more irrigated land converted to dryland with more water sensitive crops (e.g. corn) being planted in wetter climate scenarios. While in the drier climate scenarios, conversions to sprinkler irrigated land and drought tolerant crops are preferred. Little cropland transferred to pasture since the region is not dry enough. The land transfer result is more complex than considered in previous research (Mu et al. 2013; Mu et al. 2018), as we introduced transferring furrow land to sprinkler irrigated land.

In terms of agricultural water use adjustments deficit irrigation strategies are preferred in the drier climate scenarios. While in a climate scenario, use of a full irrigation strategy is dominant in the drier states of nature to prevent huge losses in agricultural production. More deficit irrigation strategies are applied to the vegetables than the field crops. In terms of total irrigation water usage, both field crops and vegetables consume more water when the expected precipitation is less. Vegetable water consumption vary more responding to the expected precipitation level. But the increased irrigation water cannot offset the reduction in precipitation, in turn leading to a lower production level of field crops and vegetables under the drier climate scenarios.

Limitation and Future Research

There are some limitations of this research due to the model assumptions, data availability and method selection. Here we highlight important limitations.

First, water has a lower use value in the agricultural sector than in the other sectors and there is no water rights protection for groundwater from aquifers other than the Edwards with the model choosing to transfer usage. This leads agricultural groundwater use from Aquifers other than the Edwards to be greatly reduced in the interest of increasing water use in the municipal, industrial and other sectors. Also in those areas irrigated land transfers to dryland production. But in the real world, such coordinated action will not easily occur and may require substantial compensation and or moves toward agricultural protection. Model revisions could be undertaken to make the water movement less possible plus the value of cooperation will be examined.

Second, the Blaney-Criddle method and yield response factors we used to estimate the crop yield responses to climate change is not state of the art and a more sophisticated method could be used.

Third, the model could be expanded to consider exploiting regional aquifers that have brackish or saline water. Also the model could be expanded to include more accurate yield estimations for deficit irrigation and for the yield results of irrigation using saline water.

Fourth, the model uses convex combinations of historical crop mixes as a reflection of constraints arising through unobserved resource limitations, such as seasonal labor, capital, and other resources. However, with technological progress and climate change, crop mixes might be altered. We could add new crop mix combinations, that could arise as a response to technological progress and climate change using results from studies such as Cho and McCarl (2017).

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CHAPTER III

THE EFFECTS OF POPULATION GROWTH AND CLIMATE CHANGE ON WATER PROJECT SELECTION: FOOD-ENERGY-WATER (FEW) NEXUS ANALYSIS IN SOUTH CENTRAL TEXAS

Introduction

Studies on the Food, Energy and Water (FEW) Nexus focus on the decision making at the intersection of the sectors that produce and use FEW products/resources (McCarl et al. 2017). Instead of only considering the effects on a single sector, FEW Nexus analysis considers resource allocation and its impacts across the Nexus. Such analysis aims to examine and make gains through coordinated action in turn increasing regional welfare and sustainability.

In this chapter, we examine Nexus decisions within a case study in South Central Texas where water scarcity is a key concern. The research region covers a large area of Texas including San Antonio and Corpus Christi. That area is projected to exhibit doubled population by the end of this century. This region is also projected to be drier and hotter under climate change, which will not only reduce surface water supply (Gurdak et al. 2009; IPCC 2014), but also reduce groundwater recharge and increase municipal water consumption (Chen, Gillig, and McCarl 2001). Such growth coupled with a drier and hotter future stresses the regional water situation. Therefore, this is a meaningful case study within which to examine possible FEW Nexus actions.

Regional water scarcity is receiving substantial attention. In its regional planning activities the Texas Water Development Board (TWDB) regional planning group has proposed a number of water projects (TWDB 2015a; TWDB 2015b). To the best of our knowledge, TWDB did not consider the effect of climate change on the potential desirability of these water projects.

But we believe it is an important factor cannot be ignored. In this chapter, we will report on a Nexus analysis of water project construction and operation as affected by both climate change and population growth. Our results show that both climate change and population growth affect water projects construction and operating decisions.

Compensation is also important for the water project decision makings. The empirical model we set up is a full coordinated action, Nexus cooperation model, which aims to maximize regional welfare across agricultural, energy, and water consumption interests. However to attain this cooperation it is likely that compensation still be needed and we analyze the magnitude of such compensation that may be needed.

Background and Data Source

Current Situation

Our research region is located in the South Central Texas containing San Antonio and Corpus Christi plus points in between. This area contains 4 river basins (Guadalupe/Blanco, San Antonio, Nueces/Frio and San Antonio-Nueces). The region also has access to several aquifers (Edwards Aquifer- San Antonio Segment, part of the Edwards-Trinity Aquifer, a segment of the Carrizo-Wilcox Aquifer, part of the Gulf Coast Aquifer and a few other minor aquifers). The terrain in South Central Texas is higher in the north and west part of the region and then falls as we traverse South and East, which causes the rivers to flow from the northwest to the southeast. The terrain, geology, river flow, location of key aquifers and aquifer recharge/discharge characteristics result in the upstream region predominantly using groundwater with the sources being the Edwards and Carrizo-Wilcox Aquifers. The downstream region near the principally rely on more on surface water.

As the seventh-most populous city in the United States, and the second-most populous city in Texas, San Antonio has about 1.5 million people who consume about 212 thousand acre feet of water for municipal water usage. An additional 0.2 million acre feet water is demanded for municipal and industrial usage in nearby areas. Other regional cities, such as New Braunfels in Comal County, San Marcos in Hays County, also have high population density and water demand. While they are located nearby the Guadalupe-Blanco Rivers, they cannot greatly increase reliance on its limited surface water sources. The major water sources for the Metro San Antonio-San Marcos region are the Edwards Aquifer, Edwards-Trinity Aquifer, Carrizo-Wilcox Aquifer and the Guadalupe/Blanco- San Antonio River (Figure 19).

The Edwards Aquifer provides over 86% of the municipal water for San Antonio-San Marcos Region. But due to its character as a karst aquifer, the water level in the Edwards Aquifer highly depends on regional precipitation and the aquifer rapidly discharges through springs and pumping. The groundwater elevation is highly related to the recharge of that year, and falls down quickly in low recharge years. Simultaneous concerns over a) increasing water demands, b) stochastic, widely variable recharge, c) rapid discharges of excess water and d) protection of endangered species led to the establishment of the Edwards Aquifer Authority (EAA) in 1993. The EAA is charged with managing the water in the Edwards Aquifer and maintaining minimum spring flows to protect habitat for endangered species in the aquifer fed springs (Patoski 2018). In discharging its management duties the EAA allocated water use rights and promulgated trading of Edwards Aquifer water.

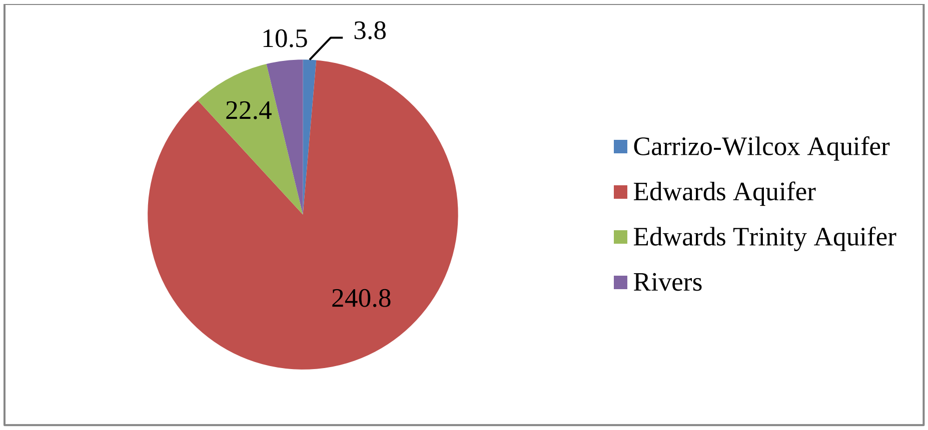


Figure 19: San Antonio Municipal Water Sources (Thousand Acre feet)

The stochastic water supply and EAA imposed pumping limits constrain water supply from the Edwards Aquifer. San Antonio- San Marcos are located in proximity to the San Antonio River and is also somewhat close to the Guadalupe River. However, the waters of these rivers are fully allocated plus they are not active water trading markets and the volumes are relatively low there is little chance for San Antonio - San Marcos region to greatly expand its diversion of water from these sources. Also potential expansion of groundwater supplies from the proximate Edwards-Trinity Aquifer and Carrizo Wilcox aquifers are limited. Therefore, the region needs for a sufficient and reliable local water sources raises the water scarcity issue and leads to the proposal of relatively expensive projects by the TWDB.

Projected Population Growth

The Texas Demographic Center (2018) projects rapid population growth for South Central Texas (Table 2). By 2090s, regional population is expected to double relative to the population level in 2015. This certainly contributes to the regional water scarcity issue and the need for planning.

Table 8: Population Growth Rate Based on the Level of 2015

	2030	2050	2070	2090
Metro San Antonio	16.2%	40.4%	67.1%	98.8%
Regional	16.4%	41.6%	70.9%	106.2%

Climate Change

Climate change also affects the water situation. Regionally the climate is projected to become more arid and hotter. These drier conditions are projected to directly reduce surface water availability and are also likely to decrease the recharge to aquifers (Gurdak et al. 2009; IPCC 2014). Moreover, based on our analysis and the findings in Chen, Gillig, and McCarl (2001), the increased temperature is also projected to decrease recharge to the Edwards Aquifer.

On the consumption side, the temperature and the number of hot days without significant rainfall (more than 0.25 inches) has a significant positive effect on municipal water consumption, while precipitation has a significant negative impact (Griffin and Chang 1991). Similar results were found by Chen, Gillig, and McCarl (2001).

Water Project Plans

Due to the water scarcity situation and population growth pressures, the Texas Water Development Board (TWDB) regional planning group proposed a number of water projects that could help mitigate the regional water scarcity (TWDB 2015a; TWDB 2015b). The water projects are designed to support municipal, industrial and agricultural sector water usage, with most of them designed for municipal usage. Generally, the water projects can be classified as groundwater transfers (Ground), surface water transfers (Surface), off-channel reservoirs (OCR), aquifer storage and recovery endeavors (ASR), saltwater desalination and other projects (Outside). The number of water projects in each category is listed in Table 9.

Table 9: Total Available Water Project Numbers

Water Project Type	Surface	Ground	ASR	OCR	Outside
Total Available Project Numbers	4	34	7	5	7

Among the planned water projects, there are 5 water projects for which at least one phase has been built and in operation. These include CzoSAWS (a groundwater transferring project, transferring water from Carrizo aquifer to serve San Antonio Water System (SAWS) entity in San Antonio), CzoSSLGC (a groundwater transferring project, transferring water from Carrizo aquifer to serve Schertz-Seguin Local Government Corporation (SSLGC) entity in metro San Antonio), SanAntonioASR (a ASR project, storing Carrizo aquifer water in Edwards Aquifer to serve San Antonio when needed), WellsRanch (a groundwater transferring project, transferring Carrizo Aquifer water near the border of Guadalupe and Gonzales county to serve multiple entities in metro San Antonio), KerrvilleExistASR (an ASR project, storing Guadalupe river water in Edwards-Trinity Aquifer to server Kerr county when needed). All of these five water projects supply water to municipal interests.

Other Data Sources

The integrated model covers the agricultural sector, electricity and power plants water usage, industrial, municipal, mining and other sectors water usage (details discussed in the Methodology section). To specify it we used data from multiple sources. For example, the hydrology part was specified using data from WRAP (Wurbs 2003), SWAT (Arnold et al. 2013) and the ground water model GAM. These models were set up using data sets developed by USGS, TWDB and Texas A&M University. Current water pumping and diversion data were drawn from TWDB database (TWDB 2016) and TCEQ database (TCEQ 2018); water project plans were summarized from TWDB regional water plans (TWDB 2015a; TWDB 2015b); agriculture crop and livestock budgets were drawn from the Texas A&M AgriLife Extension (Texas A&M Agrilife Extension 2017); current level of crop and livestock production and land usage data were from USDA Quickstat (USDA 2018). For more details about data specification, please see the data part of the model documentation.

Economic Issues

Other than the economic issues we discussed in Chapter II, there are several other important economic issues that arise in FEW studies. These are public goods, compensation transfer, investment incentives and characteristics of major investments including asset fixity.

Public Goods

A wide variety of potential strategies include major investments have been proposed to cope with the water scarcity in the region. However, some but not all of these strategies require major public commitments. In particular, some of the investments constitute public goods and are simply too expensive to be developed by individuals. This includes building off channel reservoirs (OCR), transferring water from water surplus regions to water deficit regions, and aquifer storage and recovery (ASR). Therefore, these water projects need direct capital investments or assistance from public agencies (government, NGO or other groups) (IPCC 2014; Fan et al. 2017; McCarl et al. 2016). However, some ways of addressing water scarcity such as reducing the cooling water usage by power plants may place a burden on certain parties while they may benefit other parties. This raises the discussion of compensation transfer and investment incentive.

Compensation Transfer and Investment Incentive

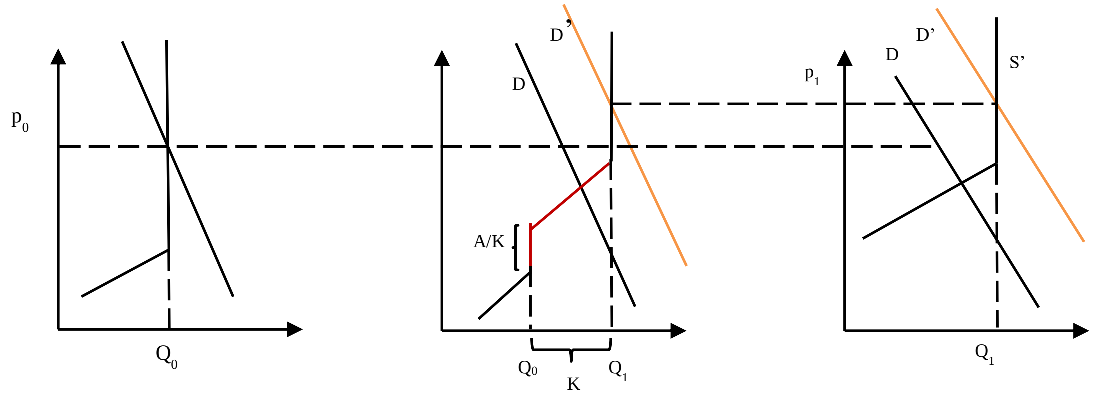
FEW Nexus decisions are motivated by the potential for total regional social welfare gains through coordinated actions and while they might benefit total regional welfare but damage the welfare for one party or sector. This means that there are a number of FEW actions that are not Pareto optimal failing to make all parties better off. Some parties, in particular ones that bear the cost of the investment, may find operating under the investment while conserving water and benefiting the whole region raises their individual operating and debt costs making them worse off. This means in the absence of compensation they have little incentive to invest.

However, incentives can be developed through some form of transfer payment where one compensates the implementing party for any welfare laws (Just, Hueth and Schmitz 2008; McCarl and Yang Forthcoming). For example, implementing irrigation water conserving practices such as moving from furrow to sprinkler irrigation or adopting more water conserving crops and ultimately abandoning irrigation may decrease revenues or increase costs to agriculture but at the same time save water and avoid the need for the construction of highly expensive water projects. This implies the need for some sort of a water transfer payment and can be facilitated through some sort of direct cost sharing, some form of a water market or some other means. There are many different ways to increase the incentive of FEW actions. For more discussion, please see McCarl and Yang (Forthcoming)

Asset Fixity

Asset fixity is a concern introduced by D. G. Johnson (1950) and G. L. Johnson (1956) when analyzing the investment projects, and then be developed and used in many studies (Edwards 1959; Johnson, Quance and Abel 1973; Gardner 1992; Chambers and Vasavada 1983; Wang et al. 2019). Asset fixity is important because once the investment project is built, it is fixed in one place with certain service area and the limits the scope of its operations during its economic life. In this research, once a water project is built, it is generally limited in terms of where it can draw water from, what customers it conserve and the characteristics of its overall capacity and operating conditions.

The impact of asset fixity of the water projects could be illustrated by Figure 2. The two period framework is set up following Tietenberg and Lewis (2009) and Wang et al. (2019). In the first period (Panel a), the total amount of water could supply to the region is Q_0 with the price p_0. Now suppose that there is a water project that can be built that would expand the local water supply. When the demand for water increases, we suppose there is not enough water to satisfy that expansion. In this case new water projects are then considered. For the existing water supply and water projects, the fixed cost is sunk. Only the O&M and variable cost will be charged as the marginal cost. While for the new projects, the fixed cost, O&M cost and variable cost will all be counted into the model when making the decision of building the water project, in turn making the cost higher than the exist water supply. The new demand curve and the aggregated supply curve of existing water supply and new water projects are then passed to the second period in Panel c to determinate the new price and quantity.



Panel (a) existing plant

Panel (b) add new capacity and demand

Panel (c) new demand and supply

Figure 20: Visual representation of impact of asset fixity over two time periods.

Methodology

Coupled with the climate change, rapid population growth will increase water demand and stress the water scarcity in this region. The situation has already stimulated much regional debate and interest with a regional planning group as part of the TWDB water planning effort proposing a number of water projects. In this analysis we will add projects into the regional model to examine climate change and population growth effects on water project adoption and other actions. To do this we incorporated data of water project water yield, water sources and destination, capital cost and operating cost into the model. The fixed volume independent costs are entered as the objective function coefficient for a binary variable that permits the choice of whether or not to build/operate the water projects. The operating and maintenance variable costs are charged against the continuous variable giving the amount of water supplied by the water projects. The variable identifying the amount of water to be pumped is limited by the capacity which is also a term on the binary variable as to whether or not the water project was constructed.

Model Scope

The EDSIMRGW_NEX model will be employed as the analysis tool with which we can examine the effects of climate change and population growth on water project selections. EDSIMRGW_NEX as discussed in Chapter III is a regional hydrological and economic simulation model, which simulates regional agricultural and electricity production water allocation between agriculture, cooling, fracking and M&I plus electricity usage. It also simulates water flows, groundwater usage, aquifer elevation, spring flow, pumping costs, water project development, cooling retrofits and new power plant construction in the research region. The model and its previous versions (RIVERSIM, EDSIMR and RIVERSIMG) has been used into analyze the FEW Nexus related issues, such as water use tradeoffs between agriculture and municipal use (Dillon et al. 1993; Chen et al. 2001; Ding 2014), and water project selection (Gillig et al. 2001; Cai 2009).

EDSIMRGW_NEX is a mathematical programming model which incorporates a two-stage stochastic decision making procedure (Ferguson and Dantzig 1956; Dantzig 2010). Generally, the model contains an uncertain water supply in the form of 9 states of nature representing amount of water availability and aquifer recharge. Water project construction, crop mix, livestock mix, electrical cooling retrofits, and irrigated land transformation to dryland decisions are made in advance of time when the water availability is unknown (stage 1), while operational decisions like water project operation, irrigation water application, municipal water withdrawal and power generation are set given knowledge of state of nature. For example, the entities or government have to decide whether to build the water projects and which the water projects will be built in the first stage before they know future water flow and aquifer information. They then decide if the water project will be operated and how much proportion of the water project will be operate in the second stage after they know the state of nature of that year.

EDSIMRGW_NEX is a single, typical year equilibrium model with within year disaggregation on a monthly scale. The initial status of items such as reservoirs is set to the probability weighted average of the ending status. We allow drawdown of the aquifer water table, but limit the yearly drawdown of Edwards Aquifer to be no more than 0.5 feet to get the sustainable development and project the endangered species. Due to the complexity and time consumption of solving a long term dynamic model, we use EDSIMRGW_NEX as a recursive model when estimating the effects of climate change and population growth on the Nexus. We set the initial status of available land, aquifer water table, water projects and power plants as same as the ending status of those items in the last decade of same climate scenarios to present the dynamic process. Based on asset fixity, we also assume once water projects, power plants and cooling system retrofits are built, they will exist in that place for all subsequent model runs. For more details of model structure, please see the model documentation. Water project setup in the model

As we mentioned above, water construction is a decision that appears in the first stage of the model and is made independent of state of nature. On the other hand the decision to use that project in terms of the volume of water moved through it appears in the second stage of the model and there is dependent upon the stochastic state of water availability and recharge. Mathematically, let's denote $Build_{project}$ as a binary decision variable telling whether the water project is constructed, and $ProjectWater_{project,customer,sector,month,son}$ as the continuous variable of how much water is supplied to the customers in each sector from the water project in each month. Then two more constraints should be added into the model as following

$$ProjectWater_{project,customer,sector,month,son} \leq CAP_{project,customer,sector,month} \times (Build_{project} + exist_{project}) \quad \forall project, customer, sector, month, son \tag{1}$$

where $exist_{project}$ is the binary parameter that indicates if the water project already has been constructed($exist_{project} = 1$) or not ($exist_{project} = 0$). $CAP_{project,customer,sector,month}$ is the capacity (maximum water yield) that the water project can provide to the designed customer and sector each month.

Equation (1) constrains that the water provided by the water project to all eligible customers and sectors could not exceed its designed capacity. $ProjectWater_{project,customer,sector,month,son}$ is then added into constraints supplying water to eligible customers and sectors in the model as part of meeting the demands for those customers and sectors $ProjectWater_{project,customer,sector,month,son}$ is also entered into the objective function and other constraints where needed . For example, $ProjectWater_{project,customer,sector,month,son}$ of the ASR and OCR projects are constrained by the water storage amount available by month, and $ProjectWater_{project,customer,sector,month,son}$of ground water transfer projects are limited by the water availability, aquifer elevation relationships, and drawdown limitations the source aquifers.

Analysis Design

To test the effect of population growth and climate change on water project selection, we set up multiple model runs. First, we ran the model under Base 2015 scenario, which does not include any population growth and climate change effects. The results of the scenario permit us to examine model validity by comparing the model results with observed data. We should note that the model depicts full Nexus cooperation and as such may deviate from real world situations.

Second, we ran the base scenarios with only population growth effect for selected decades, which are the Base 2030, Base 2050, Base 2070 and Base 2090 scenarios. The population growth rate from 2015 to 2050 is based on projections the Texas Demographic Center (2018). In particular we use the one where the population was augmented by immigration at by one half of the historically observed rate. We also added the assumption that the net population growth rate for 2070 - 2099 were assumed to be the same as that assume for the time period from 2030 to 2059. Comparing the result of these four scenarios with the Base 2015 result, the impact of population growth on the water projects selection will be identified.

Third, we ran climate scenarios with both climate change effects and population growth effects. A number of General Circulation Models (GCMs) have been used by the IPCC to simulate the climate change till the end of this century (IPCC 2013). Based on the advice of the Texas State Climatologist – Dr. John Nielson-Gammon and the consideration of extreme cases, we then chose to use IPSL-CM5A-LR (Dufresne et al. 2013) and MIROC5 (Watanabe et al. 2010) to test the climate effects in this region. IPSL-CM5A-LR predicts the driest and hottest scenarios among the suggested GCMs, and MIROC5 predicts the wettest case. In doing this, we employed all of the four Representative Concentration Pathway (RCPs) developed in IPCC (2013). The aggregated average of climate change variables for the study region are presented in Table 10 using the downscaled projected climate data by the GCMs from 2020 to 2090 (Maurer et al. 2007; U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center

2013). The average temperature increases in all eight different climate scenarios with different paces, and the overall precipitation decreases in most cases.

Table 10: Climate Change in South Central Texas

Panel A: Precipitation Change Based on Average Precipitation during 1981-2016					
GCMS	**RCP**	**2030s**	**2050s**	**2070s**	**2090s**
IPSL-CM5A-LR	RCP2.6	-4.24%	-0.26%	-6.06%	-2.92%
(Driest)	RCP4.5	-13.27%	-14.83%	-11.31%	-11.77%
	RCP6.0	0.22%	-23.70%	3.62%	5.79%
	RCP8.5	12.86%	-4.53%	-17.82%	-24.02%
MIROC5	RCP2.6	-9.33%	20.81%	17.51%	7.13%
(Wettest)	RCP4.5	1.11%	17.26%	5.65%	13.86%
	RCP6.0	8.50%	2.16%	15.47%	3.44%
	RCP8.5	13.32%	-1.07%	-10.53%	2.86%
Panel B: Temperature Change Based on Average Temperature during 1981-2016					
GCMS	RCP	2030s	2050s	2070s	2090s
IPSL-CM5A-LR	RCP2.6	7.54%	8.30%	7.19%	6.84%
	RCP4.5	10.01%	11.67%	12.55%	13.49%
	RCP6.0	6.16%	11.47%	11.88%	14.81%
	RCP8.5	7.18%	15.22%	21.81%	31.02%
MIROC5	RCP2.6	6.75%	6.44%	6.70%	7.25%
	RCP4.5	8.08%	10.41%	10.94%	12.72%
	RCP6.0	4.83%	8.74%	11.21%	13.24%
	RCP8.5	8.00%	13.31%	18.96%	23.89%

Considering all cases for climate change (GCMs crossed with RCPs), and population growth alternatives we set up 32 alternative climate change scenarios. Comparing results of climate scenarios with base scenarios, the climate change effect on the water projects selections and operation will be identified.

In order to compare the welfare changes with and without water projects, we set up the same model runs as above but without water project involved into the model (base 2015, base scenarios with population growth, climate scenarios with population growth and climate effects). The welfare difference with and without water projects involved in the respecting scenarios are then compared to find the potential compensation transfer among the Nexus parties.

Results

Water Projects Selection Under Current Situation

We first examine the water projects selection in the base 2015 scenario without any population growth and climate change effect implemented. Six new ground water projects, Aransasblend, GulfCoastBeevilleConvert, SurfacewaterSanPatricio1, BeeSanBrackishStevensWell, NueNWBrackishStevensWell and SanPatricioblend are built under this scenario (Table 11).

- Aransasblend is a ground water project that mixing the brackish water from the Gulf Coast Aquifer with fresh water to support the municipal water usage in Aransas County.
- GulfCoastBeevilleConvert is a ground water project that pumps water from Gulf Coast Aquifer to support Bee County municipal water usage.
- SurfacewaterSanPatricio1 is a surface water project, which transfers Nueces river water to the San Patricio County for municipal water usage.
- BeeSanBrackishStevensWell is a ground water project, which desalinates ground water pumped from Gulf Coast Aquifer in Bee and San Patricio counties with the Stevens water treatment plant, and in turn supplies water for municipal water usage in San Patricio County and City of Corpus Christi.

- NueNWBrackishStevensWell is a ground water project, which desalinates brackish water pumped from the Gulf Coast Aquifer in Nueces County using the Stevens water treatment plant and serves municipal water usage in Corpus Christi.
- SanPatricioblend is a ground water projects, which mixes the brackish water withdrawn from the Gulf Coast Aquifer with fresh water to serve municipal interests in San Patricio County.

With the other five projects already built in this region before 2015, there are 11 operating water projects in the Base 2015 scenario. However, only the six of the projects are fully operated across all the states of nature in the Base 2015 scenario. In particular Aransasblend, BeeSanBrackishStevensWell and NueNWBrackishStevensWell are operated in all of the states of nature (Table 12). Other projects are operated in some states of nature, but not in others. This operation pattern is quite different from the operation patterns observed in the real world. There are several potential explanations for this.

First in the real world, it takes years to build and test in order to operate the water project. The decision makers may need to make the forecast ahead and start to build the project to guarantee the projects can be operated on time. But in the model, we simply made the model to be built and operated in the same period, without considering the time gap between building and operating the water projects.

Second in the real world, the transaction cost across the Nexus sectors is high and the compensation transfer among different sectors is important to get the incentive to build water project. But in this stage of model, we set up an ideal model to maximize the regional welfare with transaction cost and compensation transfer as internalized cost, which will not affect the regional welfare and decision making. This leads to the selection bias between the model and real world.

Third based on the project water yield, cost and targeted customer information in Table 13, it seems the water projects for San Antonio more expensive to operate than other alternatives, though it does not charge any fixed cost as it is sunk for the existed projects. Additionally, it is not necessary to run the water project to increase water supply for The City of San Antonio in current situation. But the water projects for Aransas, Bee, San Patricio Counties and City of Corpus Christi are needed. TWDB may have overestimated the increase in water demand for The City of San Antonio with higher prices stimulating reduced consumption levels. Also, it might because of The City of San Antonio has sufficient budget to implement the water projects ahead to mitigate the water scarcity pressure, but other cities and counties are constrained by the capital resource.

Table 11: New built and initial exist water project in Base 2015

Water Project	Project Type	Sector	Initial Exist	2015
Aransasblend	Ground	Municipal	0	1
GulfCoastBeevilleConvert	Ground	Municipal	0	1
SurfacewaterSanPatricio1	Surface	Municipal	0	1
BeeSanBrackishStevensWell	Ground	Municipal	0	1
NueNWBrackishStevensWell	Ground	Municipal	0	1
SanPatricioblend	Ground	Municipal	0	1
CzoSAWS	Ground	Municipal	1	0
CzoSSLGC	Ground	Municipal	1	0
KerrvilleExistASR	ASR	Municipal	1	0
SanAntonioASR	ASR	Municipal	1	0
WellsRanch	Ground	Municipal	1	0

Table 12: Water project operation in Base 2015

Project	HDry	MDry	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet
Aransasblend	1174	1174	1174	1174	1174	1174	1174	1174	1174
BeeSanBrackishStevensWell	24000	24000	24000	24000	24000	24000	24000	24000	24000
GulfCoastBeevilleConvert	340	340	340	340	340	340	0	340	0
NueNWBrackishStevensWell	18000	18000	18000	18000	18000	18000	18000	18000	18000
SanPatricioblend	9209	9209	9209	9209	9209	9209	0	9209	0
SurfacewaterSanPatricio1	0	0	0	0	0	0	0	160	0

Table 13: Designed Water Yield, Cost and Energy Consumption of Selected Water Projects

	Customer	Sector	Water Yield (Acft/Year)	Annualized Fixed Cost (Million US$/Year)	O&M Cost (Million US$/Year)	Variable Cost (US$/Acft)	Energy Consumption (kwh/acft)
Aransasblend	Aransas County	Municipal	1174	1.13	0.147	100	478
GulfCoastBeevilleConvert	Bee County	Municipal	340	0.022	0.021	100	108
SurfacewaterSanPatricio1	San Patricio County	Municipal	1507	0.327	0.044	815	225
BeeSanBrackishStevensWell	San Patricio County, Corpus Christi City	Municipal	24000	11.935	6.733	54	878
NueNWBrackish StevensWell	Corpus Christi City	Municipal	18000	9.683	6.953	46	580
SanPatricioblend	San Patricio County	Municipal	28155	9.264	1.524	54	969
CzoSAWS	San Antonio	Municipal	62588	0	5.97	100	1402
CzoSSLGC	San Antonio	Municipal	17237	0	1.313	100	516
KerrvilleExistASR	Kerr County	Municipal	1120	0	0.448	100	100
SanAntonioASR	San Antonio	Municipal	2636	0	1.054	100	100
WellsRanch	San Antonio	Municipal	3400	0	0.526	100	707

Note: The fixed cost of water projects are annualized to a 20 years period to get the annualized fixed cost, based on the accounting rules.

Table 14: Net Welfare for each sector with and without water project running (Million US$)

	With Water Projects	Without Water Project	Difference
Agricultural	140.0	140.0	0.0
Electricity	2291.1	2316.0	-24.9
Municipal	1501.0	1362.9	138.1
Industrial	145.2	137.3	8.0
Mining	1.0	1.0	0.0

The net welfare gain with and without water project operation was compared to find the parties who get benefits from the water projects. We find the municipal and industrial sector benefit from running the water projects, while the electricity sectors lost welfare (Table 14). The welfare changes of agricultural and mining sector is too small to be presented in the table, which is just caused by the changes of pumping cost. As water projects are built, power demands are incurred and the electricity sector needs to augment production and possibly build more power plants to provide enough power for the water projects. The price of electricity is also raised due to the new power plants.

The welfare changes for these three sectors are then decomposed to the customers' surplus, producers' surplus and authority's surplus, presented in Table 15. The consumers' surplus from municipal and industrial sectors reflects gains arising from the construction of the water projects due to the lower market price and more supply. While the electricity consumers’ surplus decreases due to the higher price in the market. The authorities' for all three sectors gain from water projects due to rents to their capacity. Producers' surplus from all three sectors decreases due to the water projects for different reasons. The producers' surplus loss from municipal and electricity sector is majorly because of the new built water projects and power plants, and also affected by the changes of marginal cost and pumping cost. The producers' surplus loss from industrial sector is due to the changes of demand quantity and marginal cost, though the water projects decreases the pumping cost.

Table 15: Decomposed Welfare changes of Municipal, Industrial and Electricity Sectors in Base 2015 Scenarios

	Net Benefit	Consumer's Surplus	Producers' Surplus	Authority's Surplus
Municipal	138.06	135.26	-0.20	3.00
Industrial	7.97	1.28	-0.06	6.75
Electricity	-24.88	-77.86	-3.97	56.94

Water Projects Selection with Only Population Growth Effects

Now we examine the effects of population growth under constant climate on the selection of water projects. In that case, population growth causes more water projects to be built (Table 16). In particular the model chooses to produce the TWATrinity, GulfCoastBeevilleField and CRWAWellsRanch projects to cope with the level of population growth that is projected to occur by 2030. When meeting the projected population by 2050 the two projects discussed above plus the NuecesBlend project are constructed. When the population growth reaches the level projected for 2070 yet another project is added which is the Forestar water project. In the 2090 period, four more water projects are constructed to meet the increased water demand arising due to population growth, including ExpandedCzoSAWS, HCPUA, GBRACzo and BWSSWSC. The basic information of the water projects are listed below.

- TWATrinity is a project that pumps water from Edwards Trinity Aquifer in Comal County to serve the municipal water usage in Hays County where the San Marcos City is.
- GulfCoastBeevilleField is a ground water project which pumps ground water from Gulf Coast Aquifer in Beeville Field in Bee County to serve the municipal usage in Bee County.

- The CRWAWellsRanch water project is a ground water project pumping from the Carrizo Aquifer in Guadalupe and Gonzales Counties to server the municipal water usage in the urban areas within Bexar, Guadalupe, Hays and Comal Counties.
- NuecesBlend is a ground water project, which blend the Gulf Coast aquifer brackish water in Nueces County with fresh water and serve the municipal usage for Nueces County.
- Forestar is a ground water project, which transfers water from Carrizo Aquifer in Lee County, which is outside of our research region, to meet municipal demand in Hays County.
- ExpandedCzoSAWS is a ground water project, which pumps water from Carrizo Aquifer in Bexar County and serves the municipal water usage in the City of San Antonio, Medina County and other regions of Bexar County.
- HCPUA is a ground water project, which pumps water from Carrizo Aquifer in Caldwell and Gonzales Counties, and serve the municipal water usage in Bexar, Wilson, Guadalupe, Hays, Comal, Caldwell Counties.
- GBRACzo is a ground water project that pumps water from Carrizo Aquifer in Gonzales County and serve the municipal sectors in Caldwell, Guadalupe and Hays counties.
- BWSSWSC is a ground water project that pumps the brackish water from the Wilcox Aquifer in Wilson County, and desalinates the water to serve the municipal water usage in Wilson County.

Table 16: New built water projects to meet population growth as projected for various periods

Project	Project type	Customers	Exist	2030	2050	2070	2090
Aransasblend	Ground	Bee County	1				
GulfCoastBeevilleConvert	Ground	San Patricio County	1				
SurfacewaterSanPatricio1	Surface	San Patricio County, Corpus Christi City	1				
BeeSanBrackishStevens Well	Ground	Corpus Christi City	1				
NueNWBrackishStevens Well	Ground	San Patricio County	1				
SanPatricioblend	Ground	San Antonio	1				
CzoSAWS	Ground	San Antonio	1				
CzoSSLGC	Ground	Kerr County	1				
KerrvilleExistASR	ASR	San Antonio	1				
SanAntonioASR	ASR	San Antonio	1				
WellsRanch	Ground	Bee County	1				
TWATrinity	Ground	Hays County		1			
GulfCoastBeevilleField	Ground	Bee County		1			
CRWAWellsRanch	Ground	Guadalupe County Bexar County Hays County Comal County		1			
NuecesBlend	Ground	Nueces County			1		
Forestar	Ground	Hays County				1	
ExpandedCzoSAWS	Ground	Bexar County San Antonio Medina County					1
HCPUA	Ground	Bexar, Wilson, Guadalupe, Hays, Comal, Caldwell Counties					1
GBRACzo		Caldwell, Guadalupe and Hays counties					1
BWSSWSC	Ground	Wilson					1

The operational details for these projects are presented in

Table 17. Some water projects are fully operated in all the decades after it is built, such as Aransasblend and BeeSanBrackishStevensWell projects. Other water projects are fully operated in some states of nature, but are not operated under all states of nature. In particular SurfacewaterSanPatricio1 and GulfCoastBeevilleConvert projects are operated in some states of nature. But they are not always operated in the dry scenarios. This is because the state of nature is set based on the recharge level of Edwards Aquifer, but not everywhere of the research region has the same pattern of precipitation and water flows as the Edwards Aquifer recharge. And the main water sources of some areas in the research region are mainly from the ground water, which is not significantly affected by the states of nature outside of the effects on the Edwards aquifer. TWATrinity is fully operated in most periods except in the 2070s, as in that case the Forestar project is built in 2070 and is able to supply the water demands for water to Hays County.

GulfCoastBeevilleConvert and GulfCoastBeevilleField projects are only operated in the 2030s, not any other period after that do it to its higher withdrawal in pumping cost. This might be limited by the ground water sources or San Patricio and Bee Counties do not need the extra water supply after 2030s.

More water projects are built to serve municipal interests in Hays and Comal Counties. But no water projects are built and dedicated to the City of San Antonio directly until 2090s. Two of exist water project built in the real world, CzoSSLGC and WellsRanch, are operated during the 2090s of the base scenario, both serves the municipal water usage in the City of San

Antonio. This implies that the City of San Antonio does not need the extra water supply from water project until the 2090s. Between the conservation effects induced by higher prices and the reduced load from the competitive cities in the face at compile the City of San Antonio is able to meet its needs.

Table 17: Water Project Operation in Base Scenarios

Decades	Projects	HDry	MDry	Dry	DNormal	Normal	WNormal	Wet	MWet	HWet
2030	Aransasblend	1174	1174	1174	1174	1174	1174	1174	1174	1174
	BeeSanBrackishStevensWell	24000	24000	24000	24000	24000	24000	24000	24000	24000
	CRWAWellsRanch	9554	9554	9554	9554	9554	9554	9554	9554	9554
	GulfCoastBeevilleConvert	340	340	340	340	0	340	0	340	340
	GulfCoastBeevilleField	1174	1174	1174	1174	1457	1174	1457	1174	1174
	NueNWBrackishStevensWell	18000	0	18000	18000	18000	18000	18000	18000	18000
	SurfacewaterSanPatricio1	0	160	0	0	0	0	0	160	0
	TWATrinity	5000	5000	5000	5000	5000	5000	5000	5000	5000
2050	Aransasblend	1174	1174	1174	1174	1174	1174	1174	1174	1174
	BeeSanBrackishStevensWell	24000	24000	24000	24000	24000	24000	24000	24000	24000
	CRWAWellsRanch	10355	10355	10355	10355	10355	10355	10355	10355	10355
	NueNWBrackishStevensWell	18000	18000	18000	18000	0	18000	18000	18000	18000
	SurfacewaterSanPatricio1	0	0	160	0	0	0	160	160	0
	TWATrinity	5000	5000	5000	5000	5000	5000	5000	5000	5000
2070	Aransasblend	1174	1174	1174	1174	1174	1174	1174	1174	1174
	BeeSanBrackishStevensWell	24000	24000	24000	24000	24000	24000	24000	24000	24000
	CRWAWellsRanch	10355	10355	10355	10355	10355	10355	10355	10355	10355
	Forestar	41660	41660	41660	41660	41660	41660	41660	41660	41660
	NueNWBrackishStevensWell	18000	18000	18000	18000	18000	18000	18000	18000	18000
	SurfacewaterSanPatricio1	0	0	160	0	0	0	0	0	160
2090	Aransasblend	1174	1174	1174	1174	1174	1174	1174	1174	1174
	BWSSWSC	1120	1120	1120	1120	1120	1120	1120	1120	1120
	BeeSanBrackishStevensWell	24000	24000	24000	24000	24000	24000	24000	24000	24000
	CRWAWellsRanch	10355	10355	10355	10355	10355	10355	10355	10355	10355

Table 17: Continued

Decades	Projects	HDry	MDry	Dry	DNormal	Normal	WNormal	Wet	MWet	HWet
2090	CzoSSLGC	17237	17237	17237	17237	17237	17237	17237	17237	17237
	ExpandedCzoSAWS	27738	27738	27738	27738	27738	27738	27738	27738	27738
	Forestar	45000	45000	45000	45000	45000	45000	45000	45000	45000
	GBRACzo	15000	15000	15000	15000	15000	15000	15000	15000	15000
	HCPUA	32563	32563	32563	32563	32563	32563	32563	32563	32563
	NueNWBrackishStevensWell	18000	18000	18000	18000	18000	18000	18000	18000	18000
	SurfacewaterSanPatricio1	160	0	160	160	0	160	160	0	0
	TWATrinity	5000	5000	5000	5000	5000	5000	5000	5000	5000
	WellsRanch	3400	3400	3400	3400	3400	3400	3400	3400	3400

Table 18: Net Welfare for each sector with and without water project running (Million US$)

Decades	Sector	With Water Projects	Without Water Project	Difference
2030s	Agricultural	130	130	0
	Electricity	2822	2928	-106
	Municipal	1755	1549	206
	Industrial	198	182	16
	Mining	1	1	0
2050s	Agricultural	140	140	0
	Electricity	3583	3583	0
	Municipal	2088	1802	286
	Industrial	237	205	31
	Mining	1	1	0
2070s	Agricultural	130	130	0
	Electricity	4339	4339	0
	Municipal	2543	2044	499
	Industrial	287	234	53
	Mining	1	1	0
2090s	Agricultural	150	150	0
	Electricity	5186	5189	-3
	Municipal	3086	2148	938
	Industrial	343	268	75
	Mining	1	1	0

The welfare of population growth scenarios with and without water projects are then calculated by comparing the welfare of each sector in the base scenarios with water project and the base scenarios runs without allowing water projects to be built or operated (Table 18). Similar results are found here as the base 2015 scenario. Although the water projects are all designed for the municipal sector, the industrial sector benefits from them due to lower water prices. But the electricity sector loses welfare in the 2030 and 2090. This is because when more water projects are operated, they use substantial electricity for conveying the water in pumping it (Table 32 in Appendix) and this raises electricity prices. Even though the municipal sector pays the power plants by the market price of electricity, it still cannot cover the cost of building new power plants to increase the electricity supply. So it only raises the cost of power plants and leads to a loss within the electricity sector when the water projects operate.

Table 19: Decomposed Welfare changes of Municipal, Industrial and Electricity Sectors in Base 2015 Scenarios

Sector	Decades	Net Benefit	Consumers' Surplus	Producers' Surplus	Authority's Surplus
Municipal	**2030**	206.10	298.61	-27.68	-64.83
	2050	286.22	243.03	-22.16	65.36
	2070	499.18	801.05	-118.98	-182.89
	2090	937.51	2213.47	-281.80	-994.17
Industrial	**2030**	15.58	8.95	-0.17	6.80
	2050	31.43	16.99	-0.26	14.70
	2070	52.82	32.47	-0.41	20.76
	2090	74.74	49.87	-0.53	25.40
Electricity	**2030**	-24.88	-77.86	-3.97	56.94
	2050	-105.98	-1.54	3.94	-108.38
	2070	0.01	-0.75	1.61	-0.85
	2090	0.04	-1.75	2.73	-0.94

The decomposition of the welfare changes is listed in Table 19. Again, the municipal and industrial consumers obtain most of the benefit from water projects in all cases. While the consumers' surplus decreases in all cases due to the higher price of electricity. The producers in the municipal and industrial sectors incur a loss in all cases, due to the new construction cost of water projects. The electricity producers' lose in under the 2030 population growth scenario, but gain under the other scenarios. This is because the new power plants cost cannot be covered by the increased electricity price in 2030, but could be covered in the other scenarios. The authority's surplus of municipal sector losses more with population growth and more water projects are built due to the mitigation of water scarcity by the water projects.

Water Projects Selection with Population Growth and Climate Change Effects

Now we introduce climate change in conjunction with population growth. In these joint scenarios, the water projects selected are detailed in Table 20 and Table 21. The pattern of building water projects is influenced by climate change leading to the finding that the climate change effect will accelerate the need for expensive water projects.

In terms of climate change scenario effects on water project selection the scenarios fall into three classes. First, under the IPSL-CM5A-LR RCP 6.0 case, the NuecesBlend is built earlier in the 2030s, rather than during 2050s, but postponed into 2070s in the PSL-CM5A-LR RCP 4.5 case. This is not consistent with the overall precipitation changes projected by the GCMs. But the NuecesBlend is built in the Nueces County, which is not quite correlated with the overall change as Nueces County is at the coastline and the edge of the research region. Second, under the IPSL-CM5A-LR RCP 8.5 case, one more water project CRWASiesta is constructed. CRWASiesta is a surface water project, that transfers water the from Cibolo Creek tributary of the San Antonio River in Wilson County to meet water needs in Caldwell, Guadalupe, Bexar, Hays and Comal Counties. Third, the TWACzo project is built in 2090s under MIROC RCP 2.6 and IPSL-CM5A-LR RCP 8.5 cases, the HCPUA is built across all other scenarios during the 2090s. TWACzo is ground water project which pumps ground water from Carrizo Aquifer from Gonzales County and serve the municipal water usage in Comal and Hays Counties. Compared with HCPUA project, TWACzo has a smaller water yield and fewer destinations. It is selected because the CRWASiesta is constructed in the IPSL-CM5A-LR RCP 8.5 case and more existed water projects such as CzoSAWS are operated in that case.

Table 20: Number of Water Projects constructed by scenario

GCM	RCP	2030	2050	2070	2090
MIROC5	RCP2.6	3	1	1	4
MIROC5	RCP4.5	3	1	1	4
MIROC5	RCP6.0	3	1	1	4
MIROC5	RCP8.5	3	1	1	4
IPSL-CM5A-LR	RCP2.6	3	1	1	4
IPSL-CM5A-LR	RCP4.5	3	0	2	4
IPSL-CM5A-LR	RCP6.0	4	0	1	4
IPSL-CM5A-LR	RCP8.5	3	1	1	5

Table 21: New built water project in each period with climate change and population growth effects

GCMs	RCPs	Projects	2030	2050	2070	2090
IPSL-CM5A-LR	RCP2.6	GulfCoastBeevilleField	1			
		CRWAWellsRanch	1			
		TWATrinity	1			
		NuecesBlend		1		
		Forestar			1	
		ExpandedCzoSAWS				1
		HCPUA				1
		GBRACzo				1
		BWSSWSC				1
	RCP4.5	GulfCoastBeevilleField	1			
		CRWAWellsRanch	1			
		TWATrinity	1			
		Forestar			1	
		NuecesBlend			1	
		ExpandedCzoSAWS				1
		HCPUA				1
		GBRACzo				1
		BWSSWSC				1
	RCP6.0	GulfCoastBeevilleField	1			
		CRWAWellsRanch	1			
		TWATrinity	1			
		NuecesBlend	1			
		Forestar			1	
		ExpandedCzoSAWS				1
		HCPUA				1
		GBRACzo				1
		BWSSWSC				1
	RCP8.5	GulfCoastBeevilleField	1			
		CRWAWellsRanch	1			
		TWATrinity	1			
		NuecesBlend		1		
		Forestar			1	
		ExpandedCzoSAWS				1
		TWACzo				1
		GBRACzo				1
		BWSSWSC				1
		CRWASiesta				1
MIROC5	RCP2.6	GulfCoastBeevilleField	1			
		CRWAWellsRanch	1			
		TWATrinity	1			
		NuecesBlend		1		

Table 21: Continued

GCMs	RCPs	Projects	2030	2050	2070	2090
		Forestar			1	
		ExpandedCzoSAWS				1
	RCP2.6	TWACzo				1
		GBRACzo				1
		BWSSWSC				1
		GulfCoastBeevilleField	1			
		CRWAWellsRanch	1			
		TWATrinity	1			
		NuecesBlend		1		
	RCP4.5	Forestar			1	
		ExpandedCzoSAWS				1
		HCPUA				1
		GBRACzo				1
		BWSSWSC				1
		GulfCoastBeevilleField	1			
		CRWAWellsRanch	1			
MIROC5		TWATrinity	1			
		NuecesBlend		1		
	RCP6.0	Forestar			1	
		ExpandedCzoSAWS				1
		HCPUA				1
		GBRACzo				1
		BWSSWSC				1
		GulfCoastBeevilleField	1			
		CRWAWellsRanch	1			
		TWATrinity	1			
		NuecesBlend		1		
	RCP8.5	Forestar			1	
		ExpandedCzoSAWS				1
		HCPUA				1
		GBRACzo				1
		BWSSWSC				1

Water project operation is also affected by climate changes. The operational decisions in terms of water pumped under the driest scenario IPSL-CM5A-LR RCP8.5 is presented in Table 22. Here we find the operation level in the IPSL-CM5A-LR RCP8.5 scenario tends to be higher in each period. For example, the CRWAWellsRanch and Forestar projects have a smaller operation level than the base scenarios. The SanPatricioblend and CzoSAWS projects are operated during 2090s under the IPSL-CM5A-LR RCP8.5 case, rather than 2090s under the base scenarios.

Again all of the water projects are designed for municipal usage, but the electricity and industrial sectors also benefit. This should be considered as the Nexus cooperation and the potential compensation transfer between sectors.

Table 22: Operation Status of Water Projects under IPSL-CM5A-LR RCP85 Scenarios

Decades	Projects	HDry	MDry	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet
	Aransasblend	1174	1174	1174	1174	1174	1174	1174	1174	1174
	BeeSanBrackishStevensWell	24000	24000	24000	24000	24000	24000	24000	24000	24000
	CRWAWellsRanch	9571	9571	9571	9571	9571	9571	9571	9571	9571
2030	GulfCoastBeevilleConvert	340	0	340	340	340	340	0	340	340
	GulfCoastBeevilleField	1174	1457	1174	1174	1174	1174	1457	1174	1174
	NueNWBrackishStevensWell	18000	18000	18000	0	18000	18000	18000	18000	18000
	TWATrinity	5000	5000	5000	5000	5000	5000	5000	5000	5000
	Aransasblend	1174	1174	1174	1174	1174	1174	1174	1174	1174
	BeeSanBrackishStevensWell	24000	24000	24000	24000	24000	24000	24000	24000	24000
2050	CRWAWellsRanch	10355	10355	10355	10355	10355	10355	10355	10355	10355
	NueNWBrackishStevensWell	18000	18000	18000	18000	18000	0	18000	18000	0
	TWATrinity	5000	5000	5000	5000	5000	5000	5000	5000	5000
	Aransasblend	1174	1174	1174	1174	1174	1174	1174	1174	1174
	BeeSanBrackishStevensWell	24000	24000	24000	24000	24000	24000	24000	24000	24000
	CRWAWellsRanch	10355	10355	10355	10355	10355	10355	10355	10355	10355
2070	Forestar	41719	41719	41719	41719	41719	41719	41719	41719	41719
	NueNWBrackishStevensWell	18000	18000	18000	18000	18000	18000	18000	18000	18000
	SurfacewaterSanPatricio1	160	160	160	0	0	160	160	0	0
	TWATrinity	0	0	0	0	0	0	0	0	0
	Aransasblend	1174	1174	1174	1174	1174	1174	1174	1174	1174
	BWSSWSC	1120	1120	1120	1120	1120	1120	1120	1120	1120
	BeeSanBrackishStevensWell	24000	24000	24000	24000	24000	24000	24000	24000	24000
	CRWASiesta	2100	2100	2100	2100	2100	2100	2100	2100	2100
2090	CRWAWellsRanch	10355	10355	10355	10355	10355	10355	10355	10355	10355
	CzoSAWS	17164	17164	17390	17164	17164	17164	17164	17164	17164
	CzoSSLGC	17237	17237	17237	17237	17237	17237	17237	17237	17237
	ExpandedCzoSAWS	27738	27738	27738	27740	27738	27738	27738	27738	27738
	Forestar	45000	45000	45000	45000	45000	45000	45000	45000	45000

Table 22: Continued

Decades	Projects	HDry	MDry	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet
2090	GBRACzo	15000	15000	15000	15000	15000	15000	15000	15000	15000
	NueNWBrackishStevensWell	18000	18000	18000	18000	18000	18000	18000	18000	18000
	SanPatricioblend	14328	14342	14328	14342	14328	14328	14328	14328	14461
	TWACzo	9922	9922	9922	9922	9922	9922	9922	9922	9922
	TWATrinity	5000	5000	5000	5000	5000	5000	5000	5000	5000

Concluding Comments

The South Central Texas region is a water scarce region with high demand growth and climate change projections of a drier and hotter future. Such projections portend a more severe water scarcity problem in the future. The TWDB sponsored regional water planning group proposed a number of water projects for this region to cope with population growth and expanding water scarcity. Climate change is also a likely motivating factor behind development of these projects.

In this chapter, we used modeling to examine water project selection and the welfare changes of each sector. In the analysis we examined water project desirability under a base 2015 scenario then with scenarios on only future population growth and later on combined climate change and population growth.

Our results show that in the base 2015 scenario, the water projects chosen within the model differ from the projects that appear to be getting the most regional attention. In particular, the model selected water projects that serve cities in Comal and Hays County but not San Antonio. But most of the existing water projects under active construction of consideration are designed for San Antonio municipal usage. This may arise because: a) the non San Antonio oriented water projects are relatively more cheaper than those that could be used by San Antonio; b) Nexus benefits arise from cooperative decision-making in the region; c) we assume the cities have the same access to capital availability as does San Antonio; d) water scarcity induced higher prices stimulate reduced demand in San Antonio meaning that the future projections are somewhat higher than the model after price elastic response or e) some other forces are not considered within 'ideal' model.

Additionally we note that the existing San Antonio projects are not fully operated until the 2090s in the base scenario. Furthermore, in our analysis we find that although all of the water projects are designed for the municipal water usage, the industrial sector also benefits, which may because of the lower water pumping cost and the lower market price and higher supply consequently. Additionally we find the electricity sector loses when the water projects are built because more power plants are needed to supply the increased electricity due to the water project construction and the payoff from municipal sector does not cover the cost or the new water projects increase the electricity price in turn reduces the consumers' surplus.

The base scenarios with population growth effects show unsurprisingly that population growth stimulates additional water project construction and operation. In particular, the model chooses to produce the TWATrinity, GulfCoastBeevilleField and CRWAWellsRanch projects to cope with the level of population growth that is projected to occur by 2030. When meeting the projected population by 2050 the NuecesBlend project is constructed and the Forestar project are constructed for 2070. In the 2090 period, four more water projects are constructed to meet the increased water demand by population growth, including ExpandedCzoSAWS, HCPUA, GBRACzo and BWSSWSC.

We also find that climate scenarios further accelerate water project construction and operation. Compared with the base scenarios with only population growth effects, the water project building might be postponed or more water projects are needed. The higher level of operation of water projects are also needed in the drier scenarios, compared with the base scenarios.

Limitation and Further Research

In this chapter, we examined the impacts of population growth and climate change on water project construction and operation decisions. But there are limitations that characterize this research and could be improved. Here we choose to highlight three of them.

First, the construction and operation decisions of water projects are based on the expected return of water projects across nine states of nature. While in the real world, the decision-making might be based on some level of risk aversion to avoid the severe cases. In the future, we could add risk aversion coefficients into the model and examine how the risk aversion affects the decision-making in the Nexus Analysis.

Second, we only examine the population growth effect based on the one half of the historical immigration rate projection by the Texas Demographic Center which is on the low end. We then concluded the water projects for the City of San Antonio are underutilized. But water planners are likely considering a higher immigration rate and are thus planning for higher demand. In the future, we can run more scenarios using different immigration rates to test the impact of population growth on water projects selection.

Third, in this research, we assume all of the other Nexus sectors could cooperate with each other, but it might be not true in the real world. We will also compare the result with and without the Nexus cooperation among other sectors.

CHAPTER IV

DO ROAD BLOCKAGES NEGATIVELY AFFECT FOOD SECURITY AND POVERTY IN AFGHANISTAN: A PROPENSITY SCORE MATCHING APPROACH

Introduction

Food security, as one of the most important human needs, is at risk in Afghanistan (Messer et al. 2001). According to the World Food Summit (1996), a country is food secure, *"when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life".* This definition of food security has four dimensions: i) availability: sufficient food supply to cover the needs of population; ii) access: citizens have the ability or sufficient purchasing power to obtain food; iii) utilization: individuals have the ability to get sufficient calories and balanced nutrition; and iv) stability: ability to access food at all times, in spite of price changes or other factors affecting availability (Simmons 2013).

In Afghanistan, food security is a severe problem. Rosen, et al. (2015) indicated that 6.5 million people (20% of the total population) suffered food insecurity with a 45 million ton food gap in 2015. Over time the food security problem has improved, as the 1995 estimate that 15.8 million people (out of 17.6 million) were food insecure which is more than twice recent estimates. Based on the survey data used in this research, about 36% of the households in Afghanistan consume fewer than 2550 Cal per capita on average per day, (Note 2550 Cal is an estimate of the average calorie intake requirement for normal activities). Ensuring availability of sufficient food is a primary challenge for the Afghanistan government.

Poverty is also common in Afghanistan. According to the National Risk and Vulnerability Survey in Afghanistan (NRVA 2011), the average household income is around 149 thousand Afghan Afghani (AFN), which is equivalent to $1,918 US dollars (computed based on the April 2019 exchange rate). Furthermore since the average household size in Afghanistan is 7.5 people, this means income per capita is only 256 US$, much lower than the $1.25 US per day global poverty line given by the World Bank for 2008 (World Bank n.d.). Additionally people in Afghanistan are affected by social and climate shocks. More than 70% of Afghanistan households employ temporary coping strategies in the face of such shocks, such as reducing non-food expenditures, increasing household income sources, selling properties, decreasing food quality and quantity, borrowing money or begging.

Afghanistan has had substantial economic growth since 2002 and has received substantial help from international institutions and donor countries. But efficiently using financial and food aid in Afghanistan is a major challenge. Additionally road blockages are an issue with over 36% of households reporting obstructed access to the outside of village at least once in the 2011-2012 survey years. Roads may be blocked by the heavy snows and avalanches in the winter or by conflict and armed fire at any time of year. Poor road access, complicates further economic development, food security gains, and household income. This raises our interests to investigate the impact of road blockages on food security and income. In this paper, we investigate the impact of road blockages on food security, household income and the coping strategies using a propensity score approach.

In the remainder of the paper, the literature review is presented first, followed by the methodology and data used in this research. The results are then discussed. We present the conclusion of this research at the end.

Literature Review

International measures, such as The Global Hunger Index (GHI) (Von Grebmer et al. 2010; Von Grebmer et al. 2015), show Afghanistan is a food insecure country. The GHI is computed as the average of the proportion of the population that is undernourished in %, the prevalence of underweight children of age under five in % and the proportion of children dying before the age of five in %. The GHI score for Afghanistan (Table 23) shows that Afghanistan has suffered extreme food insecurity, especially during the period from 1995-2000. Even though the situation improved after 2000, there was still substantial hunger.

Table 23: Global Hunger Index (GHI) of Afghanistan, 1990-2015

Year	GHI Score	Global food insecurity Rank (from highest to lowest hunger level out of 117 countries)	GHI Score Based Hunger Alarm level
1990	47.4	21	Alarming (35.0-49.9)
1995	55.9	10	Extremely alarming (≥50)
2000	52.5	6	Extremely alarming (≥50)
2005	44.9	10	Alarming (35.0-49.9)
2015	35.4	8	Alarming (35.0-49.9)

Data Source: http://ghi.ifpri.org

Food security has a role in increasing conflict risk (Messer and Uvin 2005; Chen et al. 2016). When people suffer food insecurity, they may feel like they have nothing more to lose and have an incentive to fight for food, resources, equal rights, and political power (Cohen and Pinstrup-Andersen 1999). E. Messer, Cohen, and Marchione (2001) argue that food insecurity itself does not cause violent conflict directly, but raises the vulnerability to natural, economic and political conditions that in turn can trigger conflict. Therefore, addressing food security, and poverty are likely means of reducing the risk of violence.

In terms of methodology, we studied areas subject to road blockages and areas that were not subject to such blockages. To do this we used propensity score matching. The propensity score matching method was introduced by Rosenbaum and Rubin (1983), then has evolved over the year through multiple applications and extensions many researches (Hahn 1998; Heckman, Ichimura and Todd 1997; Imbens 2004). The propensity score matching method is widely used in testing the impact of treatment on poverty and food security problem. These include propensity score matching method studies addressing poverty and food security problems. For example, Mendola (2007) studied the impact of agricultural technology adoption on poverty reduction in rural Bangladesh; Becerril and Abdulai (2010) studied the impact of improved maize varieties on poverty in Mexico; Abebaw, Fentie, and Kassa (2010) studied the impact of food security program on household food consumption in Northwestern Ethiopia; Owusu, Abdulai, and Abdul-Rahman (2011) studied the impact of non-farm work on food security in Northern Ghana; Cunguara and Darnhofer (2011) studied the impact of improved agricultural technologies on household income in rural Mozambique; and Gitonga et al. (2013) studied the impact of metal silos on food security in Kenya. However, all of studies above are based on experimental results, using a treated and control group in a financial or extension setting. We could not find a study using observed of natural experiment data based on actual observations. In our case we will look at the effects of road blockage on food security and poverty problem using data from areas with and without blockages.

Methodology

Evaluating the impact of the presence or absence of treatment (road blockage) on an outcome is a form of a missing data problem (Heckman et al. 1997; Heckman et al. 1997), because individuals can only receive or not receive the treatment but not both. Let

$D = 1$ denote cases when the individual receives the treatment, and $D = 0$ when they did not. The total outcome (Y) for the individual could be calculated as

$$Y = DY_1 + (1 - D)Y_0$$

where Y_1 is the outcome when receiving the treatment, Y_0 is the outcome when not receiving the treatment. If the situations were not mutually exclusive the treatment impact (Δ) could be easily written as $\Delta = Y_1 - Y_0$, which would eliminate the missing data problem. However, in our case, no household could simultaneously be in both a group with a road blockage and the group without such a road blockage. Therefore, we cannot construct Δ directly to get the impact of road blockage.

Additionally, if the experiment is a randomized experiment, the impact of treatment can be calculated as the difference of outcome between the treated and control group (Heckman et al. 1997; Imbens and Wooldridge 2009). However, the road blockage cases are not random, because the treatment of road blockage is also affected by the social and geographic conditions. We then employ the propensity score matching (PSM) method to evaluate the impact of the blockages. Such an approach can control the bias of the impact of treatment effect due to the systematical difference between treated and control group.

Propensity Score Matching

Propensity score matching combines the propensity score estimation with a matching method that attempt to estimate the unbiased impact of treatment on outcome. Matching is the method to evaluate the impact of treatment by comparing the outcome of treated group and control group (Wooldridge 2005). Propensity score is used here to deal with the multiple dimensional covariates *X* and get a balanced unbiased result.

Propensity score is defined as the conditional probability of receiving the treatment given the covariates *X* (Rosenbaum and Rubin 1983). It could be written as,

$$e(x) = pr(D = 1|X = x) = E(D|X = x)$$

where e(x) is the propensity score, *D* is the treatment dummy variable and *X* is the set of covariates.

In order to estimate the difference in the mean outcome between treated and control groups, the *unconfoundedness* and *overlap* assumptions need to be satisfied (Imbens and Wooldridge 2009). They are called ignorable assumptions in Rosenbaum and Rubin (1983).

Unconfoundedness Assumption:

$$D \perp\!\!\!\perp (Y_0, Y_1)|X$$

The unconfoundedness assumption requires that the treatment is independent of the outcome excepting the effects arising through the selected covariates *X*, which implies that "beyond the observed covariates *X* there are no (unobserved) characteristics of the individual associated both with the potential outcomes and treatment" (Imbens and Wooldridge 2009). This has implications for the covariate (*X*) selections in two ways: 1) *X* should include items that assign the treatment and associated with the outcome *Y* (Rosenbaum and Rubin 1983). 2) *X* should not include items that are influenced by the treatment, which usually leads to the failure of unconfoundedness assumption (Wooldridge 2005; Imbens and Wooldridge 2009).

Overlap Assumption:

$$0 < pr(D = 1|X = x) < 1 \quad \forall\, x$$

implies that X does not cause either of the outcomes $D = 1$ or D = 0, which implies that the conditional distribution of X given $D = 1$ should be completely overlap the distribution of X given $D = 0$ (Rosenbaum and Rubin 1983; Imbens and Wooldridge 2009). However, using a logit or probit approach to estimate the propensity with the restriction of the probability strictly between zero and one will mislead the overlap assumption (Imbens and Wooldridge 2009). The normalized difference in the covariate between the treated and control group is a sensible way to test the overlap assumption, but not sufficient (Imbens and Wooldridge 2009). The normalized difference is defined as

$$\Delta_X = \frac{\overline{X_1} - \overline{X_0}}{\sqrt{S_0^2 + S_1^2}}$$

where $\overline{X_1}$ and $\overline{X_0}$ are the subsample mean of treated and control group, S_1^2 and S_0^2 are the sample variance of treated and control group.

Imbens and Wooldridge (2009) then suggested that matching without replacement could help improve the overlap in covariate distribution, no matter whether it is based on the propensity score or the covariates themselves. The improvement of overlap assumption will be larger when the control group is much larger than the treated group.

There are two steps to estimate the impact of treatment using the propensity score matching. First, the propensity score is estimated using the logit regression method, secondly, the treated and control group are matched by the propensity score using nearest neighbor matching, and the impact of treatment parameters are then calculated.

Average Treatment Effects on the Treated (ATT)

The most common parameter to evaluate the impact of treatment (*D*) on the outcome (*Y*) is the mean, and specifically the Average Treatment effects on the Treated (ATT) (Heckman et al. 1997). ATT is calculated as the difference between the mean outcome in the treated group (Y_1) and the mean outcome in the control group (Y_0) conditional on receiving treatment, which could be written as

$$ATT = E(Y_1 - Y_0 | X, D = 1) = E(\Delta | X, D = 1)$$

Data Description

The data for this study is collected from Afghanistan's Multi-Purpose Household Survey called the National Risk and Vulnerability Survey (NRVA 2011), which is implemented by the Afghanistan Central Statistics Organization (CSO) and covers 20,828 households across Afghanistan. We focus on data regarding road blockage, household income, food security and coping strategies in the survey.

Road blockage is a data item collected in the survey and refers to the binary observation of whether the road toward the community is blocked for all of the households in the community or not. The household is classified as being in the road blockage group if the *shura* of the community stated that the road was blocked at any time in the past year, otherwise, the household is classified as one that is not subject to a blockage (in the control group).

To develop information on food security of the household, the nutrition and calories intake is calculated based on the average daily amount of food consumed in the past week and the nutrients contained in each kind of food using information from USDA Food Composition Databases (2018). This was then adjusted by the age and gender of household members, the meals dining outside and the meals served to guests to get a per capita per day measure. For the details of the adjustments, please see the Appendices to this chapter.

For nutrition the NRVA survey covers about 90 different foods in 10 different categories, including bread and cereals, meat and fish, dairy and eggs, oil, vegetable, fruits, nuts, sugar and sweets, beverages and spices. The data for beverages and spices are omitted, because little energy and nutrition contained in spices and the survey does not contain any detail on the types of beverages. Nutritional measures used were total calories, protein, Vitamin A and iron.

Household income data were also needed. Income sources were considered as the sum over 4 categories: i) household income from agriculture, including the production and sales of field crops, orchard products and livestock; ii) household income from opium production and sales, iii) income from borrowing, begging, and zakat; iv) other income from non-agriculture sector, which covers all other income sources, e.g. manufacturing, services, trade and other waged labor.

Household reactions to exogenous situations were also considered including responses to climate and other natural circumstances, social and political conflicts, and the economic situation in the country (CSO 2014). The strategies selected by the household to cope with the shocks were grouped into 5 categories: i) reducing food quantities and qualities, ii) decreasing other expense, iii) Increasing borrowing, including purchasing food on credit, taking out loans and receiving help from others, iv) Increasing household income, including selling assets, renting or mortgaging out land, selling houses, lands or female livestock, working on relief programmes, joining the military, withdrawing children from school and increasing child labor, and v) no action. We counted the coping category as selected if one or more coping strategies in the responding category are selected.

Results

Summary Statistics of Unmatched Samples

The summary statistics of variables in the households subject to the road blockage (treated) and those who were not (control) groups weighted by the household weights projected by NRVA data are presented in Table 24.

For the household demographic information, the households in the region with no road blockages tend to be larger (HH size). Their household heads also exhibited better education (Head's year of schooling) and more time spent on off-farm employment (head is engaged in off-farm %) relative to the ones with road blockage. There is no significant difference on the gender and average age of the household heads among the two groups.

The food security indicators (Panel B of Table 24) showed no significant difference in per capita per day calories and protein intake between the two groups. In reference to USDA Recommended Dietary Allowances – RDA, an adult female needs 2200 Cal per day and an adult male needs 2900 Cal per day, and the per capita calories intake should be at least 2550 Cal to guarantee food security (National Research Council (US) 1989; USDA Agricultural Research Service 2018). The protein intake is also higher than the RDA level 56g per day per capita for both groups. The data shows that on average consumption the households in Afghanistan achieved a level of food security in 2011, and even exhibited a premium. But the survey results show about 36% of the household in Afghanistan consumes fewer than 2550 Cal on average per day across both the treated and control groups, and there is no significant difference in the proportion of the food insecure household between the two groups.

On the micronutrients[5], we find that in both groups, the average intake of Vitamin A is much lower than RDA level and the group with road blockage did not get enough iron (RDA levels are 800 mg for Vitamin A and 13 mg for iron).

[5] Here we use Iron as the example of mineral and Vitamin A as the example of vitamin.

Panel C of Table 24 presents data on income and the income components. Total household income (Household Income) for households without road blockage is significantly higher than it is for those with road blockage, and lower proportion of households below the global poverty line. If the road is blocked, the household exhibit more income from agriculture, but much less from opium sale. The households with road blockage also tended to borrow more and have less income from non-agriculture sectors.

The potential coping strategies and the percentage of households employing each are summarized in Panel D of Table 24. Note that the coping strategies are not mutually exclusive, which means that the households may undertake more than one strategy. Decreased non-food expenditures is the strategy most likely to be picked no matter whether the road is blocked or not. Reduced food quantity and quality, and increased borrowing are the second most chosen coping options. Least likely are actions to increase household income. Overall, if the roads towards outside of the community are blocked at any time in the past year, the household are more likely to utilize the coping strategies.

Table 24: Descriptive statistics of unmatched sample

	Is Road to outside of the community blocked at any time in the past year?			
	No (N=11,624)	Yes (N=6,515)	t-test Δx	Sig.
Panel A: Household Characters				
Household Size	7.434	6.948	-0.486	***
HH Head Gender (%)	0.996	0.997	0.001	
HH Head Age	39.663	39.431	-0.232	
Head's Year of Schooling	3.744	2.070	-1.673	***
Head is engaged in off-farm (%)	0.773	0.617	-0.156	***
Panel B: Nutrition Intake				
Food Insecurity HH %	36.28%	36.60%	0.31%	
Energy intake per capita per day (Cal)	3093.56	3122.49	28.94	
Protein per capita per day (g)	102.99	105.44	2.45	
Iron per capita per day (mg)	13.63	12.27	-1.36	***
Vitamin A per capita per day (RAE, mcg)	369.79	234.18	-135.62	***
Panel C: Income Components per household				
HH below global poverty line (%)	83.19%	89.85%	6.67%	***
Household Income	163147.53	117218.39	-45929.14	***
HH Income from Agriculture Sector	31097.70	37716.95	6619.24	***
HH Income from Non-Ag Sector	125580.41	71350.07	-54230.34	***
Borrow	2887.85	7582.23	4694.37	***
HH Income from Opium Sales	3581.56	569.15	-3012.41	***
Panel D: Coping Strategies				
Did not do anything to compensate	22.782%	23.838%	1.056%	
Decreased non-food Expenditures	42.28%	45.19%	2.91%	***
Reduced Food Quantity or Quality	32.76%	39.29%	6.54%	***
Increased Borrowing	31.33%	39.72%	8.39%	***
Increased HH Income	13.03%	23.44%	10.42%	***

Notes: HH stands for household. N is the number of observations before inflated by the survey weights, but all other numbers in the table take account of the survey weights.
Sources: Authors' own calculation based on NRVA 2011 survey data
* Significant at 5%;
** Significant at 1%;
*** Significant at 0.1%

Propensity Score Matching

In order to estimate the effects of road blockage on food security, household income and the coping strategy selection, we first estimated how the propensity score for the selected covariates is affected when the access road to the community is blocked. A valid propensity score estimation requires that the covariates are exogenous and the unaffected by the treatment to satisfy the *unconfoundedness* assumption. The household size, household head's gender, age, year of schooling and whether the household head is engaged in off-farm work are selected as the covariates to estimate the propensity score. The selection of independent variables follows the work of Abebaw, Fentie and Kassa (2010) and Cunguara and Darnhofer (2011).

Although the normalized differences in the selected covariates between the treated and control group is not a sufficient indicator for the overlap assumption, they were calculated as the pre-tested of propensity score estimation and matching (Table 25). The absolute values of the normalized differences are all around a quarter or below, which implies that the sample is well balanced under this criterion.

Table 25: Normalized Difference in Covariates between Treated and Control Group

Variable	Normalized Difference
Household Size	-0.1113
HH Head Gender (%)	0.0116
HH Head Age	-0.0136
Head's Year of Schooling	-0.2505
Head is engaged in off-farm (%)	-0.2432

The Logit Model is then used to estimate the propensity score of road blockage and the result is presented in Table 26. The percentage of correctly predicted household is around 60%, the pseudo R-squared is around 0.04 and the Wald χ^2 test get a very large value. These imply that the goodness-to-fit of the model is good enough. All of the variables we selected significantly affect the propensity score. The larger size of households and the households with the household head has more years of schooling or an off-farm job tend to live in the area without any road blockage, while the households with a female household head are more likely to live in the area with road blockage.

Table 26: Result of Logit Model

	Estimate	z value	Sig.
Intercept	-0.201	-8.90	***
Household Size	-0.065	-142.81	***
HH Head Gender (%)	0.432	19.55	***
HH Head Age	0.001	9.93	***
Head's Year of Schooling	-0.063	-216.02	***
Head is engaged in off-farm (%)	-0.653	-236.98	***
% Predicted correctly	59.7%		
McFadden's pseudo R-squared	0.04		
χ^2	153099.8		***

Notes: HH stands for household.
* Significant at 5%
** Significant at 1%
*** Significant at 0.1%

The treated and control group are then matched by the propensity score. The density of propensity score of treated (road blockage) and control group (no road blockage) after matching are then plotted to visually testing the overlap assumption. The two distributions are almost identical (Figure 21), which indicates a good satisfaction of the overlap assumption.

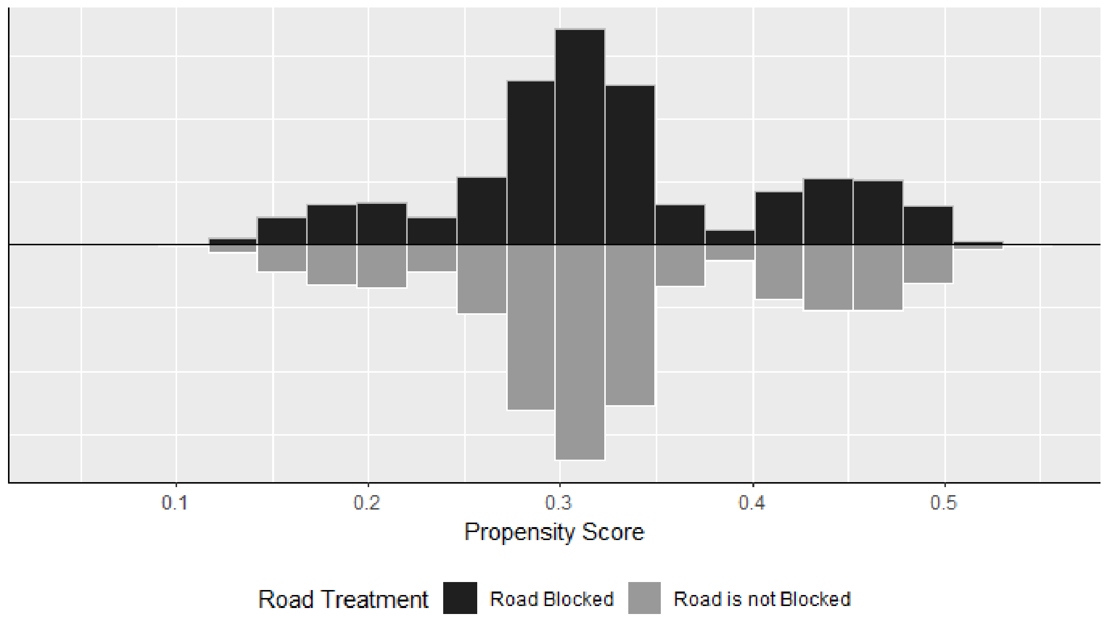


Figure 21: Propensity Score Distribution of Matches

The Impact of Road Blockage

As argued by Heckman, Ichimura, and Todd (1997), the most common parameter to evaluate the impact of treatment on interested outcome is the Average Treatment effects on the Treated (ATT). We then calculated the ATT effects of road blockage on food security, household income and household coping strategies.

Table 27: ATT effects of Road Blockage on Food Security

	Coefficients	T statistics	Sig.
Food Insecurity HH %	2.37%	3.44	***
Energy intake per capita per day (Cal)	-45.05	-2.52	*
Protein per capita per day(g)	-0.52	-0.79	
Iron per capita per day (mg)	-1.41	-14.44	***
Vitamin A per capita per day (mcg)	-136.12	-18.56	***

* Significant at 5%
** Significant at 1%
*** Significant at 0.1%

In terms of general food security, more households are food insecure in the road blockage area than in the unblocked area. Road blockage has significant negative effects on the minor nutrition of microelements we measured namely Iron and Vitamin A, but the ATT effect on calorie intake is only significant at the 5% level and the reduction of protein intake is not significant (Table 27). This implies that compared with the households without road blockage, the households in road blockage areas get less minor nutrition but not calories and protein on average. To further examine the effects of road blockage on food sources, we computed data and results for major food groups Table 28 and Table 29).

In the road blocked region, the calories and protein come more from the breads and cereal (Table 28 and Table 29), which are cheaper and easier to store, but have less microelements and vitamins. This shows smaller calorie intake from all other sources, such as meat, fishes, vegetables and fruit, and smaller protein intake from all other sources excepting oil in the road-blocked group.

The finding implies that the road blockage in Afghanistan changes the diet structure of the household. Conversely when the roads are unblocked, households exhibit a better and more balanced diet.

Table 28: ATT Effects of Road Blockage on Calories Source (Cal)

Calories Source	Coefficients	T statistics	Sig.
Breads and Cereal	135.12	9.91	***
Legume and Nuts	-12.50	-6.75	***
Vegetables	-24.32	-22.11	***
Fruit	-45.77	-17.40	***
Meat	-20.57	-12.49	***
Dairy Products	-3.22	-1.91	.
Sugar	-49.27	-20.54	***
Oil	-24.52	-5.72	***

* Significant at 5%
** Significant at 1%
*** Significant at 0.1%

Table 29: ATT Effects of Road Blockage on Protein Source (g)

Calories Source	Coefficients	T statistics	Sig.
Breads and Cereal	4.96	9.69	***
Legume and Nuts	-0.99	-8.31	***
Vegetables	-1.38	-18.61	***
Fruits	-0.69	-15.57	***
Meat and Fish	-2.15	-10.71	***
Dairy Products	-0.25	-2.11	*
Sugar and Sweets	-0.03	-3.37	***
Oil	0.01	6.48	***

* Significant at 5%
** Significant at 1%
*** Significant at 0.1%

Next we examined road blockage in Afghanistan effects on household income and income components (Table 30). The effects of road blockage on overall household income are large and negative dominantly arising from effects on non-agricultural income. This is likely because road blockage restricts access of household members to many off-farm jobs. The impact of road blockage on household income from agricultural sector is small and only significant at the 5% level. This likely reflects the fact that owned or rented land is usually nearby and the blocked road does not cut off access although it may affect the sales price or access to the market. Road blockage also decreases the income from opium perhaps due to the limited access to outside and perhaps an endogeneity between conflict and opium enforcement.

Road blockages also increase the borrowed amount perhaps due to its reduction on the overall household income. However, the increased borrowed money will increase the financial risk of the households in the future, and may leads to the vicious circle of financial problem, in turn possibly increasing the risk of conflict.

Table 30: ATT effects of Road Blockage on Household Income Components

	Coefficients	T statistics	Sig.
HH below global poverty line (%)	4.62%	9.85	***
Household Income	-24,652.87	-13.42	***
HH Income from Agriculture Sector	-2,102.48	-2.27	*
HH Income from Non-Ag Sector	-22,795.73	-14.89	***
Borrow	4,740.77	12.11	***
HH Income from Opium Sales	-4,495.43	-12.46	***

* Significant at 5%
** Significant at 1%
*** Significant at 0.1%

We also test the ATT effects of road blockage on coping strategies (Table 31). We find that households in the road blocked region are more likely to: a) reduce their food quantity or quality and b) increase the amount of borrowing, which are consistent with what we found above. Additionally we find that households in the road blocked region are more willing to: a) find new income sources or sell household properties to increase household income; and b) reduce non-food expenditures. Selling household properties is also not a good signal for society security, which may increase the risk of conflict in the future.

Table 31: ATT effects of Road Blockage on Copying Strategy Selection

	Coefficients	T statistics	Sig.
Did not need to do anything to compensate	0.92%	1.495	
Decreased Non-food expenditures	2.64%	3.663	***
Reduce Food Quantity or Quality	4.88%	6.994	***
Increase Borrowing	8.58%	12.372	***
Increase HH Income	8.49%	15.158	***

* Significant at 5%
** Significant at 1%
*** Significant at 0.1%

Concluding Comments

In this paper, we investigate how blocked roads in Afghanistan impact food security, household income, and household coping actions. The data we used arose from the National Risk and Vulnerability Survey 2011 Afghanistan Multi-Purpose Household Survey (NRVA 2011), which covers 20,828 households. We employed a propensity score matching method to evaluate the impact of road blockage on food security, household income and coping strategies.

We found that road blockages increase the proportion of households that are food insecure although we find blockages do not have a significant impact on protein intake. Road blockages also have significant negative impacts on micronutrient consumption (Iron and Vitamin A) with a less significant impact on calories intake. To understand those results we further examined road blockage effects on food sources. There we found households with road blockage exhibit consumption patterns with more bread and cereals, but less meat, vegetables, fruits and other foodstuffs. This underlies the micronutrient results as bread and cereals contain relatively less vitamins and microelements than do meat and vegetables.

Road blockages were also found to increase the proportion of households below the global poverty line and reduce household income, especially income from non-agricultural employment and opium. The households experiencing road blockage also exhibit additional borrowing and selling of household properties, which will increase the financial risk of the household in the future and get into the vicious circle of borrowing and return.

The obvious implication is that lowering the incidence of road blockages would help in reducing food insecurity and boost incomes. This would involve improvement of transportation infrastructure reducing vulnerability to winter factors and better controlling conflict related blockages, in turn avoiding hunger, poverty and the enhanced incidence of conflict.

Limitation and Future Research

The average treated effects on the treatment (ATT) estimated by propensity score matching is used to measure the difference between the treated and control group. However, it might be desirable to focus more on households with food insecurity and low income problems rather than the average of all households. This implies that using downside risk measures for food security and income might be more suitable. In the future, we could extend our analysis, using methods such as quantile regression, to examine downside risk. Secondly, the propensity score matching cannot explore the causal relationship between road blockage and food insecurity and poverty problems. We just simply assume that road blockage would cause the food insecurity and poverty without any testing. But there might be some bi-directional causal relationships, which need to be tested in the future. Third, there are other interesting topics we can extend our work on, such as the impact of road blockage on local commodity prices and health problems.

CHAPTER V

CONCLUSIONS AND FUTURE RESEARCH

Conclusions

In this dissertation, we did an economic examination of agricultural and water projects decisions under the Food-Energy-Water (FEW) Nexus. This was done in a water scarce region where the water scarcity will be exacerbated by both climate change and population growth. We also analyzed how road blockages impact food security, household income and coping strategies in Afghanistan.

In Chapter II (the first essay), we examine how the agricultural sector in a cooperative Food-Energy-Water Nexus setting is affected by climate change and population growth. We find within this study that climate change has large implications. Population growth does increase stress from water competition but the agricultural effect is small. The absolute value of agricultural sector welfare does not change much across the alternative population growth scenarios, but increases when the climate is wetter.

The results show climate change is the dominant factor that impacts agricultural water usage, agricultural production level, land transfers, and water management decisions. In the drier cases, agricultural sector needs more water for irrigation, and full irrigation is dominant to protect production. The land transfer from furrow to the sprinkler irrigated land is common. In terms of crop mixes, drought tolerant crops are preferred under the drier climate scenarios. We also find that the Nexus coordination reduces agricultural groundwater use due to comparative water use values. But the agricultural production level in drier cases is lower than that in the wetter climate cases due to the less precipitation. Although not a very large effect with population growth, more water is taken away from agricultural sector, and more irrigated land transfers to dryland.

In Chapter III (the second essay), the impact of climate change and population growth on water project construction and operation decisions is analyzed. The desirability of water projects under a base 2015 scenario is considered than an examination is done on how future population growth affects this followed by an analysis of joint climate change and population growth is examined.

In the base 2015 scenario, we find the water projects chosen within the model differ from the projects that appear to be getting the most regional attention. In particular, the model selected water projects that serve cities in San Patricio, Bee and Aransas Counties and the City of Corpus Christi, but not the City of San Antonio. However today most of the existing water projects being implemented are designed for San Antonio municipal usage only. This may arise because: a) the current projects largely meet future needs under the current situation; b) the alternative San Antonio oriented water projects are relatively more expensive than those chosen in our modeling place but in the model the reduced water demands release water resources that could be used by San Antonio but this may not be being considered, c) Nexus benefits arise from cooperative decision-making in the region but the amount of coordination assumed is not being considered; d) we assume the cities have sufficient access to capital availability but this may not be the case with City of San Antonio having more access; e) water scarcity induced higher prices stimulate reduce demand in San Antonio meaning that the future projections are somewhat higher than the model after price elastic response; or f) some other forces are not considered within our 'ideal' model. Also we note that the results show existing San Antonio projects are not fully operated until the 2090s in the base scenario meaning the current projects supply adequate water for a substantial time period.

Furthermore, in our analysis we find that although all of the water projects are designed for the municipal water usage, the industrial sector also benefits, which may because of the lower water pumping cost and the lower market price and higher supply consequently. Simultaneously we find the electricity sector loses when the water projects are built because more power plants are needed to supply the increased electricity due to the water project construction but that the payments from the municipal sector does not cover the cost and the new water projects increase the electricity price in turn reduces the consumers' surplus.

The base scenarios with population growth effects show unsurprisingly that population growth stimulates additional water project construction and operation. At least one more water project in each selected decade is constructed to meet the increased water demand by population growth. We also find that climate scenarios further accelerate water project construction and operation. Compared with the base scenarios with only a population effect, the water project building might be expedited, postponed or more water projects are needed. The higher level of operation of water projects are also needed in the drier scenarios, compared with the base scenarios.

In Chapter IV (the third essay), we investigate the food security and poverty problem in Afghanistan from a special perspective: how do blocked roads impact food security, household income, and household coping actions. We conduct this investigation using propensity score matching method. The investigation indicates that road blockages increase the proportion of households that are food insecure. Road blockages also have significant negative impacts on micronutrient consumption (Iron and Vitamin A) with less significant impact on calorie intake, and no impact on protein intake. We further examined road blockage effects on calories and protein sources. There we found households with road blockage exhibit consumption patterns with more bread and cereals, but less meat, vegetables, fruits and other foodstuffs. This underlies the micronutrient results as bread and cereals contain relatively less vitamins and micronutrients than do meat and vegetables. Road blockages also increase the proportion of households below the global poverty line and reduce household income, especially income from non-agricultural employment and opium. The households in the road blockage group also exhibit additional borrowing and selling of household properties, which will increase the financial risk of the household in the future and get into the vicious circle of borrowing and return. The obvious implication is that lowering the incidence of blockages would help in reducing food insecurity and boost incomes. This would involve improvement of transportation infrastructure reducing vulnerability to winter factors and better controlling conflict related blockages, in turn avoiding hunger, poverty and the enhanced incidence of conflict.

Limitations and Future research

Naturally, there are limitations that characterize this research and could be improved in the future. Here we choose to highlight some of them.

In **Chapters II and III**, water has lower values in the agricultural sector than the other sectors and there is no water rights protection for the groundwater with the model choosing to transfer usage. This leads the agricultural groundwater from Aquifers other than Edwards Aquifer to be greatly reduced in the interest of increasing water use in the municipal, industrial and other sectors. Also the irrigated land transfers to dryland production. But in the real world, such coordinated action will not easily occur and may require substantial compensation and or moves toward agricultural protection. Model revisions could be undertaken to make the water movement less possible plus the value of cooperation will be examined. After the revision, we will also compare the result with and without the Nexus cooperation among other sectors

Also in those chapters, the Blaney-Criddle Method and yield response factor was used to estimate the crop yield responding to climate change but this is not state of the art and a more sophisticated method could be used. Additionally the model could be expanded to consider exploiting regional aquifers that have brackish or saline water. Also, a more accurate yield estimator for deficit irrigation yield and irrigation using saline water could be added into the model.

Moreover, the model only use the convex combination of the historical crop mix data to reflect unobserved resource limitations, such as seasonal labor, capital, and other resource availability. However, with technological progress and climate change, limiting factors and crop mixes could be changed. We thus could extend the model adding new crop mix combinations based on studies such as Cho and McCarl (2017).

In terms of water projects, the construction and operation decisions of water projects are modeled as if the decisions are based on maximizing the expected return while in the real world, some level of risk aversion is likely important. In the future, we could add risk aversion into the model and examine how it affects decision-making.

Also for our population growth scenarios we used the middle growth scenario developed by the Texas Demographic Center which is based on an assumption of one half of the historical immigration rate. But water planners may be considering a higher immigration rate and are thus planning for higher demand. In the future, we can run additional scenarios to test the impact of alternative population growth assumptions on water projects selection.

In Chapter IV, we used the average treated effects on the treatment (ATT) and propensity score matching approach to test the impact of road blockage on Afghanistan food security and poverty. However, it may be desirable to focus more on households with food insecurity and low income problems rather than the average of all households. This implies that using a downside risk measure of food security and income might be more suitable and we could extend our analysis to examine downside risk. Secondly, the propensity score matching cannot explore the causal relationship between road blockage and food insecurity and poverty problems. But it might be the bi-direction causal relationship, which could be tested in the future. Third, there are other interesting topics we can extend our work on, such as the impact of road blockage on local commodity prices and health problems, etc.

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APPENDIX A

APPENDIX TABLES FOR CHAPTER III

Table 32: Electricity Consumption by Water Project (GW·h)

GCM	RCP	2015	2030	2050	2070	2090
BASE	BASE	0.60	14.03	9.35	52.23	79.75
MIROC5	RCP2.6	0.00	6.60	13.24	52.31	79.74
	RCP4.5	0.00	11.01	9.36	52.31	79.74
	RCP6.0	0.00	6.62	14.22	52.31	104.16
	RCP8.5	0.00	9.63	9.36	52.23	79.76
IPSL-CM5A-LR	RCP2.6	0.00	12.65	9.36	52.31	79.73
	RCP4.5	0.00	14.05	9.37	52.23	79.75
	RCP6.0	0.00	6.61	15.76	52.85	90.28
	RCP8.5	0.00	14.80	9.35	52.30	93.64

Table 33: Designed Water Yield, Cost and Energy Consumption of Selected Water Projects

	Water Yield (Acft/Year)	Fixed Cost (Million US$)	O&M Cost (Million US$/Year)	Variable Cost (US$/Acft)	Energy Consumption (kwh/acft)
GulfCoastBeevilleField	1457	0.4	0.102	101	429
GulfCoastBeevilleConvert	340	0.022	0.021	100	108
CRWAWellsRanch	10629	3.872	3.783	71	448
ExpandedCzoSAWS	27740	5.656	0.74	100	72
HCPUA	35690	34.761	16.154	125	1138
TWACzo	15000	23.399	8.179	125	2238
TWATrinity	5000	2.183	0.341	135	1203
GBRACzo	15000	17.595	5.831	100	1153
Forestar	45000	32.413	14.041	100	1833
WellsRanch	3400	0	0.526	63	707
CzoSAWS	62588	0	5.97	100	1402
CzoSSLGC	17237	0	1.313	29	516
Aransasblend	1174	1.128	0.147	100	478
SanPatricioblend	28155	9.264	1.524	54	969
NuecesBlend	707	0.387	0.084	100	680
BeeSanBrackishStevensWell	24000	11.935	6.733	54	878
NueNWBrackishStevensWell	18000	9.683	6.953	46	580
BWSSWSC	1120	1.411	1.321	84	350
SurfacewaterSanPatricio1	1507	0.327	0.044	815	225
CRWASiesta	5042	5.757	2.747	75	1186
SanAntonioASR	2636	0	0.7908	100	100
KerrvilleExistASR	1120	0	0.336	100	100

APPENDIX B

APPENDIX TABLES FOR CHAPTER IV

We calculate household food nutrient sufficiency by adjusting needs accounting for the age and gender of household members, the meals dining outside and the meals consumed by guests. The Recommended Dietary Allowances (RDA) per capita is defined as the average nutrients RDAs of one adult female and one adult male, and adjust the weights of other household members by their ages and gender based on the recommended dietary requirement provided by National Research Council (US) (1989)

Table 34: Recommended Dietary Allowances (RDAs) and Adjustment Index for Calories and Protein Intake

	Age	**Calories (Cal)**	**Protein (g)**	**Calories Index**	**Protein Index**
Infants	0.0–0.5	650	13	0.255	0.230
	0.5–1.0	850	14	0.333	0.248
Children	1–3	1300	16	0.510	0.283
	4–6	1800	24	0.706	0.425
	7–10	2000	28	0.784	0.496
Males	11–14	2500	45	0.980	0.796
	15–18	3000	59	1.176	1.044
	19–24	2900	58	1.137	1.027
	25–50	2900	63	1.137	1.115
	51+	2300	63	0.902	1.115
Females	11–14	2200	46	0.863	0.814
	15–18	2200	44	0.863	0.779
	19–24	2200	46	0.863	0.814
	25–50	2200	50	0.863	0.885
	51+	1900	50	0.745	0.885

Data Source: RDAs refer to *Recommended Dietary Allowances: 10th Edition* (National Research Council (US) 1989). The Index was calculated by the authors based on RDAs level for each group.

Table 35: Recommended Dietary Allowances (RDAs) and Adjustment Index for Vitamin A and Iron

	Age	Iron (mg)	Vitamin A (mcg RAE)	Iron Index	Vitamin A Index
Infant	0-0.5	0.27	400	0.021	0.5
	0.5-1	11	500	0.846	0.625
Children	1-3	7	300	0.538	0.375
	4-8	10	400	0.769	0.5
	9-13	8	600	0.615	0.75
Males	14-18	11	900	0.846	1.125
	19-50	8	900	0.615	1.125
	51+	8	900	0.615	1.125
Females	14-18	15	700	1.154	0.875
	19-50	18	700	1.385	0.875
	51+	8	700	0.615	0.875

Data Source: RDAs refer to *Fact Sheet for Health Professionals* (NIH 2018) .The Index was calculated by the authors based on RDAs level for each group.