Cap and trade markets for groundwater: Efficiency and distributional effects of the permit allocation mechanism

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Abstract

Agricultural production on the Texas High Plains is heavily dependent on the Ogallala Aquifer, which accounts for approximately 95 percent of groundwater pumped. Rapid groundwater depletion has been observed in the Ogallala Aquifer, which is attributed to low recharge rates and high water withdrawals. In an effort to manage this limitedly-renewable water resource, High Plains Water Conservation District (HPWD) No.1 has established a rule to reduce pumping 1.25 acre-feet per acre per year for all groundwater users within HPWD.

This research evaluates the efficiency and distributional effects of a "cap and trade" mechanism for the HPWD region under alternative methods of allocating the allowable groundwater use: an equal distribution rule and a uniform percentage reduction rule. Marginal abatement curves are derived from producer profit functions, which include four irrigated and three rain fed crops. Optimal cropping choices, water use, water permit trades, and water permit prices are estimated simultaneously by maximizing producer profits. The relative efficiency of the programs are evaluated by comparing total producer profits.

The results shows that the equal distribution cap will result in a more efficient use of groundwater resources, while the uniform percentage reduction cap will result in less wealth redistribution.

Keywords: Cap and Trade; Water Markets; Groundwater

JEL Codes: Q15, Q18, Q2, Q38

Chapter 1 Introduction

General Problem

The Ogallala Aquifer is one of the largest groundwater resources in the world. It is located beneath the central United States, including the states of South Dakota, Wyoming, Nebraska, Colorado, Kansas, Oklahoma, New Mexico and Texas. It underlies around 174,000 square miles and is the lifeblood of this region, providing the majority of water for agricultural, industrial and urban use (U.S. Geological Survey 2008).

Local agricultural production is heavily dependent on the groundwater with approximately $20 billion of Agricultural production per year in the United States being sustained by the groundwater resource of the Ogallala Aquifer (Qi and Scott 2010). However, rapid groundwater depletion has been observed in many regions of the Ogallala Aquifer. The rate of water withdrawal is much higher than the rate of recharge. Recharge to the Ogallala Aquifer is small, varying from 0.07 to 0.7 inches per year across the region (Nativ 1988; Stovall 2001), while about 1.7 billion gallons of groundwater is withdrawn per day from this aquifer to meet agricultural and urban demands (Maupin and Barber 2005). Due to the limited recharge, the Ogallala Aquifer has been regarded as an essentially nonrenewable water reservoir. Estimates have indicated that about 30-50% of groundwater from the Ogallala Aquifer has already been pumped (Nativ and Smith 1987a; Segerra and Feng 1994).

Rapidly diminishing groundwater reserves have the potential to drastically reduce the future economic contribution of agricultural production in the region, as irrigated production will likely be forced to convert to dryland production or be given up altogether.

The Ogallala Aquifer was discovered in the 1890's, at which time it was used for limited agricultural production due to the high cost of pumping and inefficient irrigation technologies (US Department of Commerce 1937). After World War II, advances in irrigation technology and decreased pumping costs made large scale irrigation possible. In particular, center pivot irrigation technology met the great demand for irrigation water in this region, making a barren agricultural land known as "Great America Desert" one of the most productive agricultural regions in the United States (Peterson and Marsh 2003).

Efforts have been made to conserve water by improving technologies and irrigation system. Low Energy Precision Application (LEPA) center pivot irrigation systems and Subsurface Drip Irrigation (SDI) are regarded as the most effective way to increase the rate of groundwater utilization. Unfortunately, recent reports show that even though utilization of such technologies improves the efficiency of water use, they do not result in conservation of groundwater. Rather, farmers have been able to produce both more extensively and more intensively. (Michael 2013)

Farmers withdraw water under an existing water right rule that is used to manage the groundwater. A well-defined water right system decides the water they extract and the conservation measures. Water rights in Texas are defined by the Rule of Capture, also known as absolute ownership. The Rule of Capture indicates that the first person to "capture" groundwater owns that resource. The landowner has the right to “take all the water they can capture under their land and do with it what they please, and they will not be liable to neighboring landowners even if in so doing they deprive their neighbors of the water’s use”(Potter 2004). The Texas court also modified the Rule of Capture with “(1) willful waste (2) malicious harm to a neighbor (3) subsidence” (Potter 2004).

However, the Rule of Capture potentially encourages inefficient use of the groundwater resource. Groundwater in the southern portion of the Ogallala Aquifer is a common pool resource, which leads inevitably to “the tragedy of the commons” (Hardin 1968). Contrary to achieve the best benefit of the whole group, individual seeks to maximize their own gains. As groundwater moves from one well with a higher water table toward one with a lower water table. Farmers are incentivized to pump as much water as possible before their neighbors. No liability to water use will accelerate groundwater depletion. The Rule of Capture is the oldest doctrine so it is not suitable for the water shortage. It doesn’t embody the value of water and slow the depletion of Ogallala Aquifer.

The fundamental solution to extend the life of Ogallala Aquifer is decreasing water use and increasing water utilization. In an effort to manage water resources, within the framework of the existing water right doctrine, the state of Texas has established regional Groundwater Conservation Districts (GCDs), which are “a local unit of government authorized by the Texas Legislature and ratified at the local level to manage and protect groundwater” (Lesikar 2002). The High Plains Water

Conservation District No.1 (HPWD) is the first water conservation district created in March 1951, Texas (Anderson 2010). The district serves an area of 11,850 square miles including all of Bailey, Cochran, Hale, Lamb, Lubbock, Lynn, Parmer, and Swisher Counties, and parts of Armstrong, Castro, Crosby, Deaf Smith, Floyd, Hockley, Potter, and Randall Counties (HPWD 2013 annual report). Since 1951, the HPWD developed management strategies and set desired future conditions (DFW), which are defined in Title 31, Part 10, §356.10 (6) of the Texas Administrative Code as "the desired, quantified condition of groundwater resources (such as water levels, spring flows, or volumes) within a management area at one or more specified future times". The Texas legislature, through House bill1763, requires groundwater conservation districts to set their desired future conditions at every five years and can be done sooner than that(Smith 2012). High Plains Underground Water Conservation District No.1 has approved a rule of "50/50 Management Goal": to ensure that in 50 years at least 50 percent of the remaining Ogallala Aquifer groundwater is available for future use (Postel 2010).

To achieve that goal, the High Plains Underground Water Conservation District enacted revisions to management goal in 2011. The revisions established production limits on pumping by all groundwater users within HPWD. Allowable production rate began with 1.75 acre-feet per contiguous per acre per year for 2012 and 2013, it dropped to 1.5 acre-feet per contiguous per acre per year for 2014 and 2015. For 2016 and subsequent years, the allowable production rate drops to 1.25 acre-feet per contiguous per acre year (Smith 2012).

The manner in which farmers use groundwater depends on the property rights governing the resources. To achieve efficient allocations, a well-defined property right should include three characteristics: (1) exclusivity, (2) transferability and (3) enforceability (Tietenberg and Lewis 2011). Under the maximum withdrawals at 1.5 acre-feet per contiguous per acre per year, the total water usage is reduced. While farmers still pump as much water as they can, because conserved water may be taken by neighbors. However, the transferable property right allows them change water right from one owner to another, water will transfer from lower value to higher value uses so that water will create more benefit and all farmers will be better off. So water market can be a preferred way of water reallocation.

Specific Problem

Given the policies that have been implemented for the purpose of postponing groundwater use for irrigated agriculture, this research aims to evaluate the efficacy of a market solution for allocating the allowable groundwater. One such market-based mechanism is that of marketable permits, or “cap and trade.” A cap and trade mechanism establishes a desired level of abatement and sets a maximum total usage – the “cap” – over the area targeted by the policy. The total usage is then allocated to the productive entities, who may trade portions of their allocation as it benefits them. In the case of this research, the cap is a mandatory maximum amount of water that can be used in the study area for a fixed compliance period. A specific maximum quantity of water withdrawals are allocated to each user such that the sum of those withdrawals are equal to the cap. Since, some farmers inevitably achieve desired yields under allowance or find it easier or cheaper to reduce water use while others are constraint by the maximum allowance, trade takes place. The water trade market encourages farmers whose allowances cannot meet the demand can buy water right from farmers that have excess allowance. Allowance trading enables farmers to design their own compliance strategy based on their individual circumstances while still achieving the overall groundwater use reductions required by the cap (cap and trade essential).

Cap and trade mechanisms result in a more efficient outcome than a simple standards policy, which is the implementation of water use fee. In idealized circumstances, both water use fee and cap and trade have the same outcomes, but in reality, cap and trade can achieve the environmental standard more efficiently. First, cap and trade has the advantage of reducing some the uncertainty about achieving the environment target (Baumol and Oates, 1988). A water use fee imposes a fee on per acre foot water pumped, the quantities of water use reduced are dependent on the set of fee. If the fee is set too low, farmers are likely to pay the fee and continue to use more water; if the fee is set too high, the cost will affect the profits and local economics. Conversely, cap and trade sets the quantities of water use and let the market decide the price, there is no doubt of accomplishing the environmental target (Baumol and Oates, 1988). The second advantage of cap and trade over fees is that market adjusts the price automatically and growth without increasing water use. In contrast, the fixed fee faces the problem of economic growth and inflation (Baumol and Oates, 1988). For authority, frequent increases in water use fee to attain the water standards are likely to be administratively infeasible (Frank 2014). One of the potential disadvantages of cap-and-trade is that the cost may be far higher than the benefits of water trade without limit on the price of allowances. However, this problem is easily solved by putting an upper limit on the price of allowances (Frank 2014)).

Cap and trade mechanisms have been proven highly successful in reducing emissions on a large scale. The U.S. Sulfur Dioxide (SO_2) Emissions Trading Program has achieved a significant level of environmental protection in a cost-effective manner (NAPA 1998). Such successful results have led policy makers to consider the application of cap and trade markets to other environmental and resource problems, such as water pollution. The tradable loads program in the grassland drainage area California has already achieved significant improvement in regional water quality by establishing selenium discharge caps and trade market (Austin 2000).

Furthermore, many water cap and trade mechanisms have been implemented to deal with water scarcity problems and improve water allocation in many countries. For instance, the Nebraska Natural Resources Districts (NRDs) were established to manage the water allocations in the portion of the Republican River Basin that lies in Nebraska, they developed water allocation plans including water drilling moratoria and groundwater pumping limits in 2004. The irrigation allocations have been reduced 5-7 inches per year on certified irrigated acreage for all local NRDs over the past 25 years (Palazzo and Brozovi´c 2010). The Council of the Australian Government (COAG) set a Murray-Darling Cap to limit water diversions in 1993, it aims to keep a balance between the quantities of available water and the security of their water supply. The cap made water a more valuable resource, also protected and enhanced the riverine environment eventually (Maziotis 2010). In Chile,the National Water Initiative established in 2004 focusing on water marker and trade (National Water Commission, 2007b) and intensified more water conservation behavior. The National Water Code (WC) granted transferable water-use rights (WUR) which allowed people to have a certain water flow of river with a cap and could transferred among sectors such as from agricultural to industry (Maziotis 2010). Similar project were implement in New Mexico called Central Arizona Project (CAP) which was intended to divert waters from the upper Gila River and tributaries in New Mexico to downstream users in Arizona (McCann 2015)

Different from the above water programs which are surface water reallocation in order to meet the demand efficiently, in this study, the cap and trade mechanism is applied in groundwater which is defined as finite, depletable resource. It aims at reducing the amount of water withdrawn from the Ogallala Aquifer at a given level by maintaining it in the aquifer (Johnson 2009).

Objective

Under the 50/50 management goal, the local Ground water districts are faced with the evaluating and analyzing new polices to achieve the 50-year time horizon goals as well as keeping economy growth. The main objective of this study is to analyze the impacts of setting the “cap” of 1.5 acre-feet per contiguous per acre per year on the aquifer and the economy of the northwest Texas.

The specific objectives are aim at estimating market price and comparing the welfare affects under the uniform 1.5 acre-feet per contiguous per acre per year for all farmers and a reduction of quotas based on a previous year’s usage level.

Chapter 2 Literature Review

As the world’s largest groundwater reservoir, the Ogallala Aquifer sustains approximately $20 billion in Agricultural production per year in the United States (Bian, 2015), including most of water used for irrigation in Texas High Plains. In order to reduce the depletion of this nonrenewable resource, several public policies have been instituted, which focus on restricting water use while giving little consideration to efficiency and social welfare. However, population growth and climate anomalies required more judicious management of water to achieve long term efficiency and sustainability.

This chapter reviews and groups the prior studies into three parts. The first part provides a descriptive analysis of the Texas Rule of Capture and of common resources studies. The second part summarizes the policy and economic implications of water control. The third part examines the efficiency of tradable water markets. Generally, this literature review summarizes relevant previous research to support this study.

The overdraft of many aquifers can be attributed to their common-pool nature. Most groundwater management is concentrated on the misallocation of resources resulting from the uncontrolled use of a common property resource. Since the early 1960’s, researchers have investigated the optimal allocations of common resources. Brown and Deacon (1972) used economic optimization models to analyze an aquifer under conditions of economic growth and inequality of groundwater withdrawal and consumption. Brown and Deacon concluded that if water users do not pay pumping taxes, the depth of groundwater will be greater than the optimal value at each point in time and the marginal value of water will increase over time. Oscar Burt's research supports the same conclusions. Burt (1964) determined the optimal temporal allocation of water over time, and then examined the implications of groundwater storage control. Burt (1964) showed that the ultimate solution to groundwater control is increasing pumping cost. Burt (1970) expanded his research on institutional restrictions, considering several options. The first option is unrestricted optimization – pricing by a central agency under an optimal decision rule – which is that groundwater will be used at a level of marginal revenue equal to marginal cost and price. This option is regarded as the most desirable from the viewpoint of economic efficiency. The second option is non-pricing by a central agency, in which the water price would be decided by market forces. The final option is a compromise rationing by the central agency.

Groundwater management in the Texas High Plains is profoundly affected by the existing water rights system. Water rights in Texas are defined by the Rule of Capture, also known as absolute ownership which states that the first person to "capture" groundwater owns that resource. The landowner has the right to "take all the water they can capture under their land and do with it what they please, and they will not be liable to neighboring landowners even if in so doing they deprive their neighbors of the water's use"(Potter 2004). The rule of capture makes it difficult for farmers to conserve water: farmers have to pump as much water as possible to protect their own share, which inevitably leads to "the tragedy of the commons" (Hardin 1968). Instead of pursuing the benefit of the whole group, individuals seek to maximize their own gains.

Osborn (1973) used an input and output model to analyze the direct, indirect and induced economic impacts of the depletion of the Ogallala Aquifer in the Texas High Plains from 1970 to 2020. This study showed that the Ogallala Aquifer would be economically exhausted if all farmers focused on profit maximization. Even worse, the economy would suffer. The recommendation from Osborn's research was that management policies be implemented to maintain the economy and conserve water, even though the Ogallala Aquifer will inevitably be exhausted.

Texas policy makers and researchers have realized the necessity of water management, especially, since the Texas High Plains region of the Ogallala Aquifer experienced low saturated thickness, low recharge rates and high water withdrawals (Johnson 2009).They have therefore focused on reforming policies to conserve water in the Ogallala Aquifer while maintaining social welfare and the regional economy.

An efficient water conservation policy should effectively conserve water and promote the regional economy. Johnson (2009) developed optimization models to evaluate the effectiveness of two policy alternatives and their potential effects on the economy of the Texas Southern High Plains. The two polices considered and compared in his research were 1) a water pumpage fee of $1 per acre foot, which was authorized by the Texas legislation in 2002 but has not yet been implemented, and 2) a pumping quota designed to ensure that in 50 years, at least 50 percent of the remaining Ogallala Aquifer groundwater will be available for future use. This 50/50 policy, as it came to be known, was authorized and has been implemented by the High Plains Underground Water Conservation District (HPWD). Johnson's results indicated that the 50/ 50 policy had shown a significant effect on extending the life of the aquifer, and had conserved more water than had the water pumpage fee. From a water management standpoint, the 50/50 policy is a more efficient and effective policy. However, the farmers' net incomes were much lower under the 50/50 policy, which negatively affected the regional economy.

Wheeler (2006) evaluated water conservation policies that limited drawdown of the Ogallala Aquifer in the Southern High Plains of Texas and in Eastern New Mexico over a sixty year planning horizon. The research aimed at identifying the most effective policies to conserve water. The policy alternatives included 1) a 0% drawdown policy, 2) a 50% total drawdown policy, 3) a 75% total drawdown policy, and 4) a 50% annual drawdown policy. Wheeler developed a county-level, nonlinear dynamic optimization model to determine the optimal level of saturated thickness and the net present value (NPV) of net returns per acre over a sixty-year planning horizon. The results indicated that the 0% drawdown policy conserved massive amounts of water but had detrimental effects on the regional economy. Both the 50% total drawdown policy and the 75% total drawdown policy conserved water, with the 75% total drawdown policy resulting in a slightly higher NPV of net returns than the 50% policy and the 50% total drawdown policy conserving 25% more water than the 75% total drawdown policy did. Wheeler noted that these two policies were more restricting in higher water use counties than in lower water use counties because the water restrictions were not binding constraints in lower water use counties: the aquifer drawdown level did not decline to 50% or 75% in low water use counties, even in the unconstrained scenario. Additionally, the 50% annual drawdown policy was not binding for low-water-use counties and the cost of implementing the annual policy was found to be greater than the cost of the total policies. Though this research showed that pumping quotas were more efficient than pump taxes, it also demonstrated that the water conservation came at the expense of the regional economy. These results suggest that allocated but unused permits in low water use areas could be traded to compensate the loss of NPV in high water use areas and allocate the ground water more efficiently.

Other states besides Texas also face aquifer overdraft issues. Feinerman and Knapp (1982) estimated the benefits of potential groundwater management in Kern County, California. This study investigated the magnitude of benefits from various forms of water management, such as pump taxes and quotas, as well as the welfare effects on groundwater users resulting from such management. Feinerman and Knapp evaluated the present value of annual net benefits of groundwater withdrawals under linear decision rules. The results illustrated that both quotas and pump taxes can be used to conserve groundwater, though users would benefit from quotas but suffer substantial losses under pump taxes.

These policies are designed to limit water use and restrict water transfer, and aim to prevent the aquifer from being exhausted rather than to allocate water efficiently. However, restriction is not the only way to protect groundwater depletion. Policy makers could address groundwater shortages through stronger private property rights and water markets (Landry 2000).

Zekri and Easter (2005) estimated the potential benefits and losses of establishing water markets among farmers or between farmers and urban water companies in Tunisia. Farm models were used to estimate the opportunity cost of water per farm type, and an aggregate model was used to examine gains and losses to the regional economy. Results indicated that water trading among farmers would be quite limited and would have a limited impact on farmers' incomes. In contrast, the market between farmers and the urban water company would offer higher volumes of water trades to urban users because water company would be willing to pay higher prices.

A case study from Albuquerque, New Mexico indicated that in the presence of strong demand growth, controlled pumping improves social welfare by 22 percent and extends the use of water up to 20 years. Hansen (2012) applied a hydro-economic model to find the optimal pumping path and optimal price path. This research showed how efficient water prices can be used to achieve the optimal level of water pumping. Controlled water pumping and finding the optimal price prioritizes economic efficiency over status quo management. The efficient water allocation would provide decision makers with a solution to increasing water demand.

Vaux and Howitt (1984) applied an interregional trade model to California using regional supply and demand functions estimated for 1980, 1995 and 2020. They examined two water policy scenarios in California. The first scenario is to develop a new supply, which increases all water prices. The second scenario illustrates the adjustment of supply through the use of a market, which would benefit both urban and agricultural regions through trade. The results showed that water transfers can be substituted for new supplies to the extent that less than 10000 ac ft of new capacity could be justified by 2020. The work also demonstrated that trade would lead to the premature drawdown of groundwater resources in the absence of management, which might create excess supply capacity for urban region.

Several forms of water markets have been applied to manage groundwater, including cap and trade mechanisms. The cap and trade approach is considered a cost effective and equitable way of reducing irrigation consumptive use. Thompson, Supallala and Martin (2009) evaluated the merits of a cap and trade mechanism by estimating its effects on the republican Basin in Nebraska. Optimization models were applied to compare the optimal use of water with trading (cooperative solution) to the optimal use of water without trading (uncooperative solution). The results illustrated that trading would significantly reduce the cost of controls to reduce consumptive use, and that economic gains from trade would be split between buyers and sellers based on the selling price, which represented the increasing welfare of farmers. Although the cap and trade mechanism led to increased total consumptive groundwater use for a given cap, the cost per unit in consumptive use was lower than for the uncooperative solution. This implied that the cap should be set slightly lower to achieve the environment goal if the cap and trade mechanism was to be implemented.

Palazzo (2009) evaluated the welfare impacts of alternative spatial water management policies on individual farmers in the Nebraska portion of the Republican

River Basin. To analyze the distribution and magnitude of welfare gains from market-based allocation of irrigation water, Palazzo implemented a spatial field level model. The research concluded that tradable permit water allocations lead to a significant welfare gains. Moreover, under a tradable permit policy the total cost of reducing water use to the current NRD allocation can decrease by nearly 40 percent across the watershed. Furthermore, Palazzo generated field level marginal abatement cost curves for water allocation reduction, which showed that marginal abatement costs varied for users in the basin. The heterogeneity of marginal abatement cost distributions allowed that farmers with lower marginal values sell permits to buyers with higher marginal abatement cost, the equalized marginal abatement costs could generate a large reduction in total abatement cost relative to current restriction policies. Reducing the total abatement cost can be regarded as a gain in welfare. Under frictionless tradable permit policy, several trading schemes were analyzed to compare welfare effects and economically feasible solutions, including trading by basin-wide, trading by NRD, trading by county, trading by township. Because the total abatement cost is the profit loss in water use constriction, the reduction in total cost of abatement would increase the farmer's welfare. If trading is unrestricted throughout the basin, the total abatement cost would reduce nearly 45 percent, which means the welfare gains from trading are highest but it would be infeasible politically.

Luitel et al. (2013) evaluated the implementation of a proposed cap and trade model on groundwater management in the Texas Southern High Plains. A non-linear dynamic optimization model was developed to estimate the changes between a status quo scenario and the cap and trade mechanism under 50/50 management policy in saturated thickness, water applied per crop acre and net revenue per acre. The results suggested that the cap and trade mechanism could be a useful tool to conserve groundwater efficiently in Texas Southern High Plains.

While different assumptions and models were used in these studies, some general conclusions resulted. First, without restriction management, the Ogallala Aquifer will be quickly exhausted. Second, groundwater management policies may inevitably hurt the regional economy, even though pump quota polices, such as the 50/50 policy, are more efficient than pump taxes in the majority of research. Finally, the water market may offer opportunities to compensate the economic loss and social welfare.

In light of the discussion above, there are a limited number of studies that combined the water quotas and water market together, which could creatively extend the life of Ogallala Aquifer while at the same time minimizing the impact on the regional economy and social welfare. Moreover, unlike other aquifers in previous research, the Ogallala Aquifer in the Texas Southern High Plains is attributed as low saturated thickness, low recharge rates and high water withdrawals (Johnson 2009). The unique hydrologic parameters may produce different conclusions compared to prior research. Additionally, an efficient water market could work for both surface and groundwater management, but only groundwater marketing is considered here, and no surface water conjunction and recharge are assumed.

Chapter 3 Conceptual Framework

How to allocate groundwater efficiently is a natural resource economics problem. The unique hydrologic characteristics of the Southern Ogallala Aquifer and the distinctive water law in Texas make the analysis of groundwater allocation more complicated. In order to properly evaluate the effectiveness of water policy and the efficiency of water markets, it is imperative to understand related production and economic theories.

This research aims to increase social welfare under water conservation policy. Welfare economics provides the basic theory to evaluate economic policies in terms of their well-being effects associated with the allocation of resources (Timothy 2002). A famous concept called Pareto efficiency, which is usually applied to maximizing social welfare, occurs when it is impossible to make one individual better off without any deleterious effects on others (Tietenberg and Lewis 2012 chapter 3).

This chapter is divided into four sections. The first section briefly reviews the concepts of nonrenewable resources and static efficiency. Property rights doctrines and water markets are discussed in the second section. The method by which quota policy is used to conserve groundwater is explained in the third section. The last section models the profit-maximizing function to evaluate the efficiency and distributional effects of a cap and trade mechanism.

Nonrenewable resource and static efficiency

A nonrenewable resource is one for which the natural replenishment is so slow that it does not renew itself at a sufficient rate for sustainable economic extraction in meaningful human time frames (Tietenberg and Lewis 2012 chapter 6). Groundwater resources are never strictly nonrenewable. However, the Southern Ogallala Aquifer is viewed as "fossil water," by definition, a nonrenewable resource which is being recharged at a very slow rate (Schneider 2003). According to most research, withdrawals from the Ogallala Aquifer are at least 10 times greater than the current natural recharge rate, which could naturally be ignored (Kerr Center, 2004).

The fact that the water resource is being used without restriction implies that the Ogallala Aquifer will inevitably decline toward economic exhaustion (Johnson 2009). Economic exhaustion is defined as the depletion of a resource to the point at which the cost of extraction is greater than the value of the extracted resource (Johnson 2009). Another type of resource exhaustion is physical exhaustion; It occurs when the last unit of the resource has been removed (Das 2004). In most situations, economic exhaustion occurs before physical exhaustion as the cost of the last unit of a resource is too high to extract. In the case of groundwater use, economic exhaustion is encountered when the marginal cost of applying groundwater to agricultural production is more than the marginal value product of the irrigated crop. When economic exhaustion occurs, agricultural production will transition from irrigated to rain fed production; whereby crop production and the regional economy would suffer significantly (Terrell 1998).

It is critical to define the Ogallala Aquifer as a nonrenewable resource since it determines how to allocate groundwater effectively. Several economic theories and models are defined to manage the nonrenewable resource. David Ricardo, on his research about pricing of exhaustible resources, argued that the price of a nonrenewable resource should increase over time (Ricardo D. 1951). The theory of natural resource allocation, generally starting from the famous "Hotelling Rule" (Harold Hotelling 1931), states that the price of the resource – determined by the marginal net revenue from the sale of the resource – increases at the rate of interest over time. It is viewed as the most socially and economically profitable extraction path of a non-renewable resource, since the increasing price reflects the increasing scarcity of the resource (Gérard 2007).

The efficiency of resource allocation can be analyzed by static efficiency and dynamic efficiency. If the resources are allocated over n time periods, dynamic efficiency is satisfied when the present value of net benefits is maximized over the n periods (Tietenberg and Lewis 2012 chapter 3). Static efficiency is reached when economic surplus, which is the sum of consumer surplus and producer surplus, is maximized by the resource allocation at a single point in time. It is also consistent with the Efficiency Equimarginal Principle: social net benefits are maximized when the social marginal benefits from an allocation equal the social marginal costs (Tietenberg and Lewis 2012 chapter 3).

In the case of applying groundwater in agricultural production, an allocation of groundwater is said to satisfy the static efficiency when the marginal benefit of using the last unit of water is equal to the marginal cost of that unit of water at a single point in time.

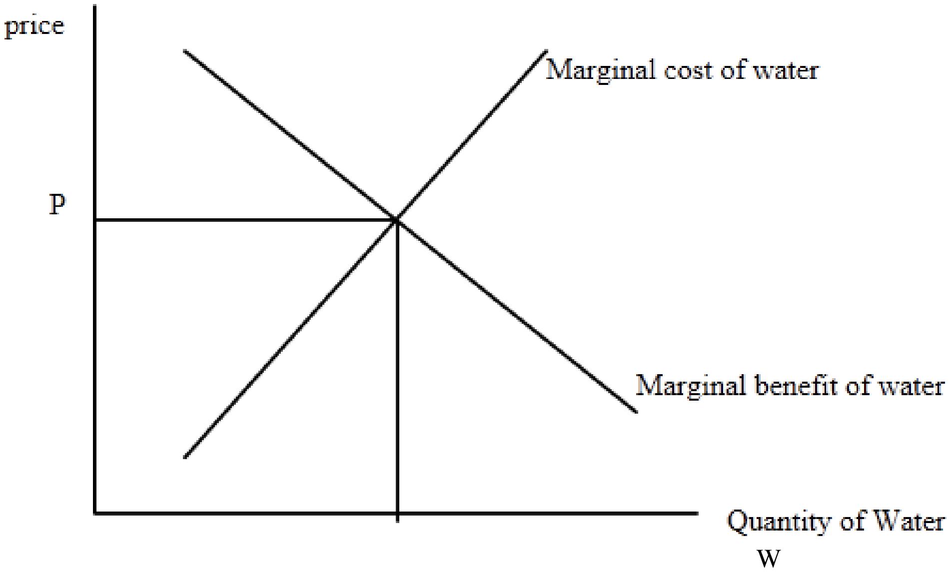

Figure 1 the optimal quantity of groundwater use

In Figure 1, the marginal cost of water curve (MC) has a positive slope, which means the additional cost of extraction increases as the quantity of water extracted from the aquifer increases. The marginal benefit of water curve (MB) follows the law of diminishing marginal returns, which means that marginal benefit of water use decreases for additional units of water extracted from the aquifer. The static efficiency is represented by the intersection of MC and MB corresponding to W, where the social surplus is maximized.

Water Market and Property right

Water markets refer to the temporary or permanent transfer of water between users for an agreed-on price (Avioli 2013). It is viewed as an efficient and effective means of reallocating a scarce natural resource from an economic standpoint. The biggest advantage that a water market has is the automatic response to water scarcity by experiencing a higher price. Such markets stimulate water conservation and allow water to flow to high-valued users (Avioli 2013).

However, in reality, one limitation of the market arises from how it allocates common pool resources. Left it to itself, the market will over-use the free access resource, which is why the wide application of water markets has been slow to develop (Tietenberg and Lewis 2012). When the groundwater resource have a well-defined property right, the groundwater market can be efficient.

Property rights are defined as a bundle of entitlements defining the owner's rights, privileges, and limitations for use of the resource (Tietenberg and Lewis 2012 chapter 2). A well-defined private property right has the characteristics of exclusivity, transferability, and enforceability (Tietenberg and Lewis 2012 chapter 2). When individuals obtain a well-defined private property right to groundwater, they are willing to act in an efficient manner. Because all benefits and costs accrue the owner, the behavior of wasting water represents a personal financial loss. So the pursuit of profit is consistent with efficient allocation in a well-defined property right market (Griffin 2011).

The Texas water right doctrine – the Rule of Capture – rules landowners possess the right to access the groundwater below their land (al-Hmoud 1994), however they only own the water upon pumping it to the surface. Due to the hydrologic nature of the Southern Ogallala Aquifer, a landowner may, in using a well on their own land to pump groundwater, be extracting water underlying their neighbor's land. Therefore, this region of the Ogallala Aquifer can be viewed as a common pool resource as it isn't controlled by a single user and could be accessed by others with limited restriction. Because a landowner cannot prevent others from pumping the water below their land, the exclusivity requirement of a well-defined property right is not satisfied. Enforceability is also lacking as a landowner's right cannot be protected from the encroachment of his neighbor's pumping (Griffin 2011). Above all, the Southern Ogallala Aquifer lacks the necessary characteristics to build an efficient market system (Anderson and Hill, 1997, p.176).

Allocation of common pool resources is not efficient and generally not sustainable, because under unrestricted access, users treat groundwater as a free input and over-use occurs (wheeler 2005).

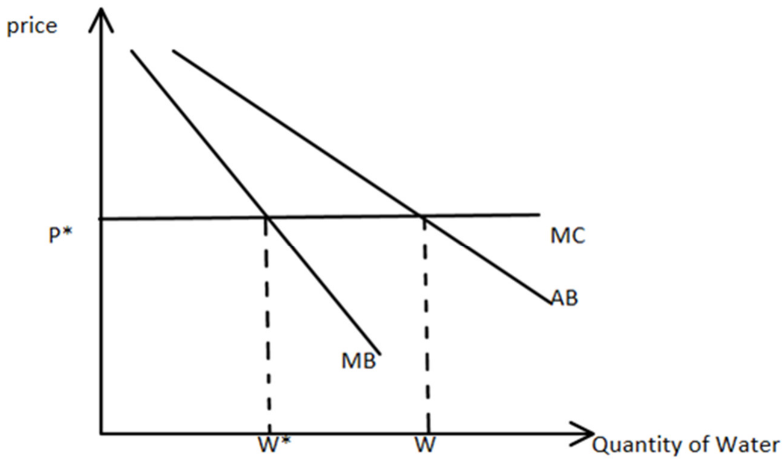

Figure 2 the quantity of groundwater pumped

Figure 2 shows the difference between groundwater irrigation use as a common pool resource and a level of efficient use, MB curve represents the marginal benefit of groundwater use. The AB curve represents the average benefit of groundwater use while MC represents the marginal cost of groundwater use. According to static efficiency, where marginal benefit equals marginal cost, shows the optimal quantity of water use (W*). However, in the presence of sufficient demand and unrestricted access to the common pool resource, individuals have incentive to expend further effort until total benefit equals total cost, where AB intersect with MC, implying a level of water use equal to W. The quantity of water use as a common pool resource (W) is much greater than the efficient level of water use (W*), so common pool resources inevitably lead to inefficient over-use. Farmers race to extract as much water as they can before their neighbors do.

Water Conservation Policy and Cap and trade mechanism

Institutions can play an important role in a water market system through controlling water price and overseeing water transfer (Tietenberg and Lewis 2012). Recognizing this role, Groundwater Conservation Districts (GCDs), first established in 1949, try to maintain a balance between protecting the private landowners' rights and the water resource. Most districts direct their efforts toward "preventing waste, collecting data, educating people about water conservation and preventing irreparable harm to the aquifer" (Lesikar and Kaiser 2002).

High Plains Underground Water Conservation District (HPWD) No.1, which was created in 1951, has approved a rule of "50/50 Management Goal." The rule ensures that in 50 years at least 50 percent of the remaining Ogallala Aquifer groundwater within the district is available for future use (Postel 2010).To achieve that goal, a revision was enacted in 2011 that established production limits on pumping by all groundwater users within HPWD. For 2016 and subsequent years, the allowable production rate is reduced to 15 inches per contiguous year (Smith 2012).

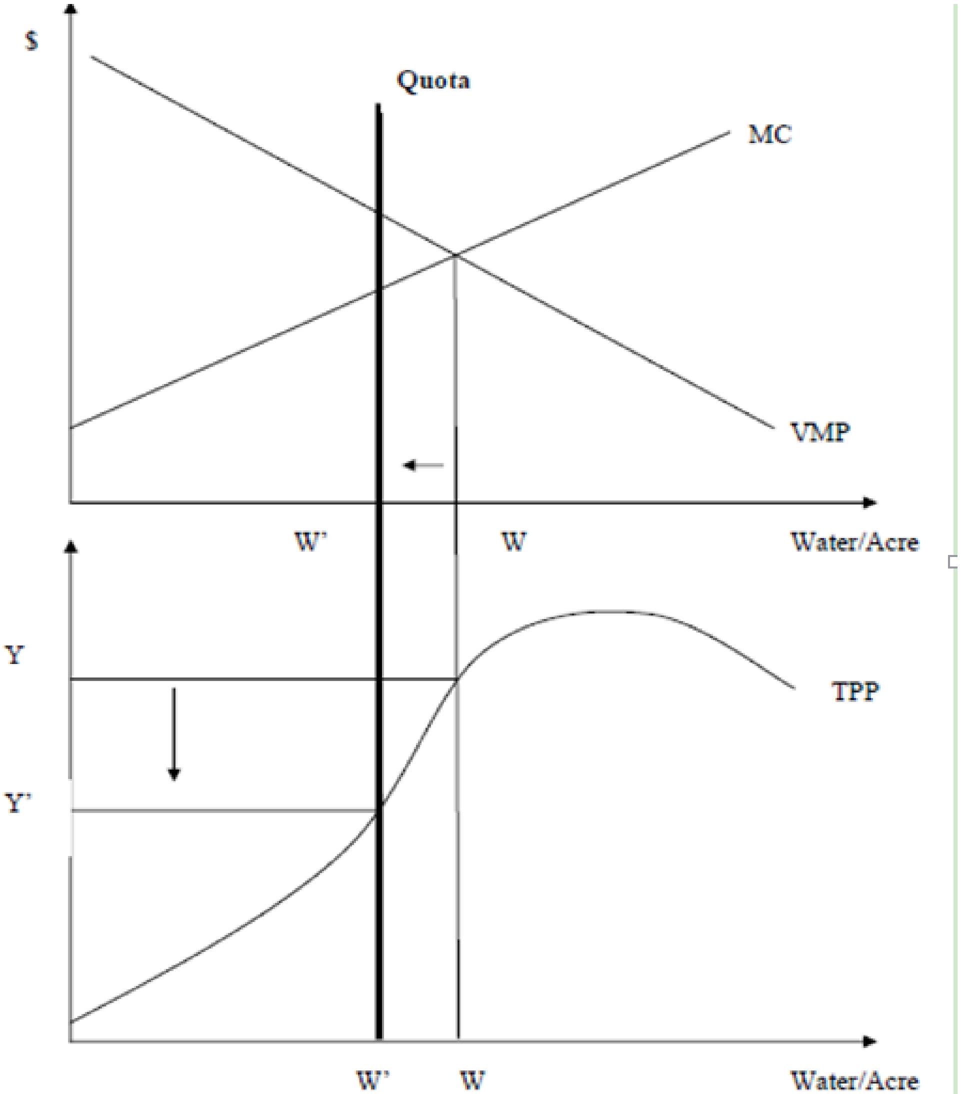
$
Quota
MC
VMP
W'
W
Water/Acre
Y
Y'
TPP
W'
W
Water/Acre

Figure 3 imposition of a water quota

Figure 3 illustrates the impact of a groundwater quota restriction policy on irrigated agriculture. As mentioned in figure 1, a farmer is maximizing profit where marginal cost intersect with marginal benefit corresponding to point W. It is also corresponding to the point on the TPP curve, showing the optimal (profit-maximizing) level of output Y for unconstrained water irrigation.

The quota restriction limits producers to a certain quantity on water extraction which constrains the water use to point W'. The shift from W to W' decreases the producers output to Y', which has negative impact on profit. Because individuals have different marginal abatement costs, the exact impact on individual producers varies.

Under the 50/50 policy, pumping caps could establish quantified private property rights in groundwater allocation. Given the improved definition of the groundwater right under the policy, a "cap and trade" mechanism could prove to be an efficiency-improving method to allocate the restricted groundwater withdrawals.

Economic Model

This paper assumes that the irrigated land is only dependent on groundwater, which has no access to surface water. Optimal cropping choices, water use, water permit trade and water permit prices are estimated simultaneously by maximizing farmers' profit. Assuming there are four irrigated crops (k=1, 2, 3, 4) and three rain fed crops (j=1, 2, 3). Each irrigated crop yield (Y_k) is assumed to follow a quadratic function, which depends on the amount of groundwater (W_k) applied (Equation 1).

$$Y_k = \beta_0 + \beta_1 W_k + \beta_0 W_k^2 \qquad (1)$$

$$\text{S.T.} \qquad 0 \le W_k \le W_k^* \qquad \text{k=1, 2, 3, 4} \qquad (2)$$

$$\sum_{j=1}^{4} W_k \le W \qquad (3)$$

Assuming that W_k is the amount of groundwater used for crop k; Y_k is the crop yield function of crop k. It follows the law of diminishing marginal returns, which implies $\frac{\mathrm{dY}_{\mathrm{k}}}{dW_k} \ge 0$ and $\frac{\mathrm{d}^2\mathrm{Y}_{\mathrm{k}}}{dW_k^2} \le 0$, so that there is a maximum crop yield (Y_k^*) possible corresponding to an optimal amount of groundwater use (W_k^*). Total water applied should be non-negative, and a farmer's optimal unconstrained water use is no greater than W_k^*(Equation 2), since pumping water from the ground has a cost, and applying more water would be inefficient. The total amount of groundwater applied is constrained by the water availability (Equation 3).

Following Palazzo (2009), a profit-maximizing water use model is established in a single time period for each individual producer. It is written as:

$$\pi = \sum_{K=1}^{4} [p_k Y_k (W_k) - C_k Y_k (W_k) - C_W W_k - F_k] + \sum_{J=1}^{3} [p_j Y_j - C_j Y_j - F_j] \qquad (4)$$

Where p_k is the price of irrigated crop k, p_j is the price of rain fed crop j, Y_k is the crop yield of irrigated crop k, Y_j is the crop yield of rain fed crop j, C_k is the variable production cost of irrigated crop k, C_j is the variable production cost of rain fed crop j, C_w is the cost for water use, F_k is the fixed cost of irrigated crop k, F_j is the fixed cost of rain fed cost.

The first portion of equation 4 is the sum of profit from each irrigated crop production, which is the sum of revenue ($p_k Y_k (W_k)$) minus variable production cost ($C_k Y_k (W_k)$), water cost ($C_w W_k$) and fixed production cost (F_k). The second portion of equation 4 is the sum of profit from each rain fed crop production, which is the sum of revenue ($p_j Y_j$) minus variable production cost ($C_j Y_j$) and fixed production cost (F_j).

A_k is the land used for the production of irrigated crop k, and A_j is the land used for the production of rain fed crop j. The land use for each crop must be non-negative (Equation 5 and 6) and total land use for production should no greater than the total land farmer available (A) (Equation 7).

$A_k \geq 0$ (k=1, 2, 3, 4) (5)

$A_j \geq 0$ (j=1, 2, 3) (6)

$$\sum_{k=1}^{4} A_k + \sum_{j=1}^{3} A_j \leq A \qquad (7)$$

Assuming the amount of groundwater applied is an important input that effects the profit, and the increasing of groundwater applied will increase the profit (equation 8).

$$\frac{\partial \pi}{\partial W} \geq 0 \qquad (8)$$

As stated earlier, under the 50/50 policy, farmers face the mandatory reduction on water use to 15 inches. So the reduction in water allocation would decrease the profit. The loss in profit is the cost of water restriction, which defined as the marginal abatement cost, it can be written as:

$$C(a) = \pi(W^*) - \pi(\hat{W}) \qquad (9)$$

$\pi(W^*)$ is the maximized profit under unconstrained water use, and $\pi(\hat{W})$ is the maximized profit under constrained water use ($W = \hat{W}$). It is worthy to note that the producer may transfer to rain fed crops when the profit of irrigation is close to zero. So, the upper bound on abatement cost is $\pi(W^*) - \pi(0)$.

Under the constrained water allocation, the total loss in profit of all producers are the sum of abatement cost. If trading is allowed among producers, equalizing marginal abatement costs across producers is a cost-effective way to reduce the loss in profit for all producers (Montgomery 1972, Hanley et al. 2001).

Chapter 4 Methodology and Procedure

Introduction

The procedure to analyze the economic impacts resulting from implementation of "50/50 policy" is presented as following steps. The first step uses the production data and cost data to estimate the profit function and to calculate the optimal amount of groundwater use for each crop. Then according to the crop choice and water availability, unique demand and supply functions for each farmer are created during the procedure. A hypothetical water market is built by following the rules that is created for trading, then farmers are allowed to sell or buy water.

Two methods are used to build the rules under the 50/50 water policy, the first one is the 15 inches permits for all farmers and another one is a reduction quotas depended on previous years' usage level. Finally, two methods will be compared by evaluating the economic welfare of farmers.

Study area

The study area consists of night counties located within the High Plains

Underground Water Conservation District (HPWD) and Groundwater Management Area (GMA) 2. They are Hale, Floyd, Lamb, Lubbock, Parmer, Crosby, Swisher, Bailey and Deaf Smith counties. Figure 4.1 highlights the geographic location for study area counties within yellow line. And the light blue area is the Groundwater Management Area 2, red highlight area is the HPWD boundary (HPWD 2015).

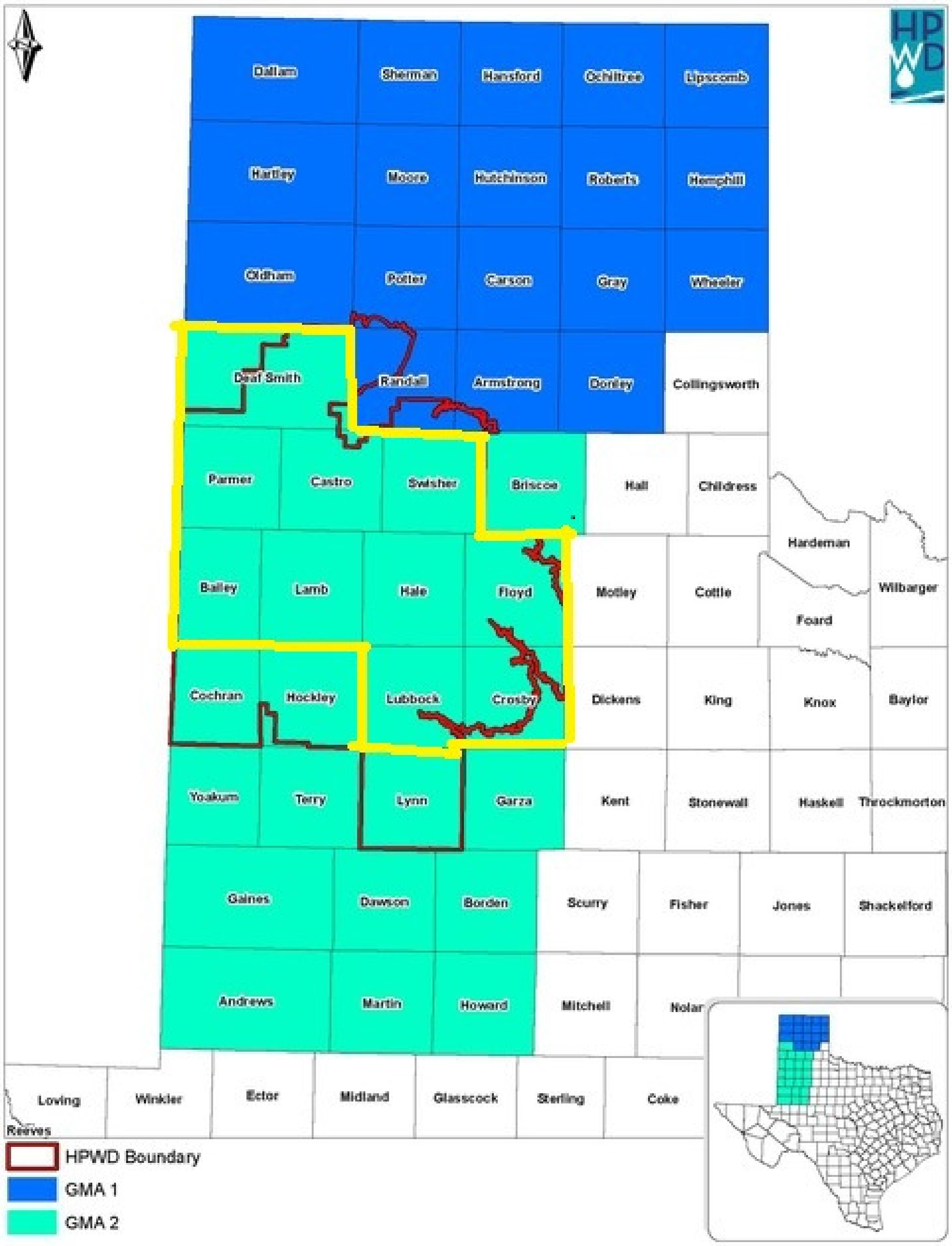

Figure 4.1 study area counties (HPWD 2015)

http://www.hpwd.org/gmas/

Although the GMA#2 consists twenty three counties, the study area is limited to the night high groundwater use counties in GMA#2. Irrigation groundwater use in these counties account for 50% of all groundwater use in GMA#2 area, and for majority counties in study area, groundwater is the only source for irrigation (TWDB, 2013).

Year	County	Population	Irrigation	Irrigation Ground Water	Irrigation Surface Water
2013	GAINES	18,820	360,353	360,353	0
2013	CASTRO	8,026	349,217	349,217	0
2013	HALE	35,626	330,563	330,365	198
2013	LAMB	13,780	271,563	271,563	0
2013	DEAF SMITH	19,337	223,246	223,246	0
2013	PARMER	9,963	222,847	222,847	0
2013	TERRY	12,651	206,105	205,364	741
2013	LUBBOCK	292,005	156,610	156,414	196
2013	YOAKUM	8,184	151,408	151,408	0
2013	FLOYD	6,248	140,753	140,753	0
2013	HOCKLEY	23,563	138,242	138,242	0
2013	SWISHER	7,684	134,191	134,191	0
2013	DAWSON	13,847	118,586	118,586	0
2013	CROSBY	5,974	112,604	111,818	786
2013	COCHRAN	3,013	109,500	109,500	0
2013	BAILEY	7,140	89,383	89,383	0
2013	LYNN	5,761	87,787	87,787	0
2013	MARTIN	5,331	41,967	41,967	0
2013	BRISCOE	1,541	28,531	28,531	0
2013	ANDREWS	16,491	18,398	18,398	0
2013	GARZA	6,510	11,384	11,384	0
2013	HOWARD	36,077	4,992	4,992	0
2013	BORDEN	657	4,056	4,056	0
total		558,229	3,312,286	3,310,365	

Table 4.1 2013 Water use survey historical summary estimates in GMA#2 by county, Texas Water District Board
http://www.twdb.texas.gov/waterplanning/waterusesurvey/estimates/

The majority of the data is collected from the Texas Alliance for Water Conservation (TWAC), which was initiated in 2004 to conserve water for future generation by reducing the depletion of groundwater while maintaining economic growth (TAWC 2015).

Thirty-five representative site are chosen from the Texas Alliance for Water Conservation (TAWC) project covering 6000 acres, and they were monitored closely for use of irrigation water, crop yields, and input costs. A wide range of observations and field records has been obtained from the TAWC sites from 2005 to 2014(TAWC 2015),

This study assumes that each field is viewed as an individual farmer and gets involved into water market. It is assumed that farmers want to maximize their profits when they make their decisions response to water policy. So they may be willing to buy or sell water in order to pursuit profit.

The crops considered in this study include corn, cotton, grain sorghum and wheat. As the largest crop production states in United States, Texas cotton production contributes billions of dollars to the state’s economy (NASS 2014). Cotton is the leading crop in study area. As another main crop, corn is the most water intensive crop. A recent study found corn generates more than \$3.5 billion to the High Plains region, and irrigated corn accounts for approximately 65-70 percent of the state’s corn production (CPAT 2015). Texas is the 2nd largest producer for sorghum as well, the cash value to farmers is \$315 million, which generates \$1.065 billion for Texas (Smith and Anisco 2014).During the 2013-2014 wheat production season, and

Texas producers planted 6.0 million acres of wheat, according to the National Agricultural Statistics Service (NASS). The cash value to farmers is $288 million, generating $973 million for the Texas economy.

Specific data

Several source were used to provide data for prices, production cost, yields, acreage and irrigation.

Production function: The production function is assumed to follow a quadratic function which relied on water irrigation. The total irrigation inches and yield for each individual farmer are collected from TAWC field summary data set. Parameters for each crop were estimated in Microsoft Excel where Y is crop yield, X is total irrigation, X^2 is total irrigation square. The production function is directly depended on water irrigation, so if no irrigated water applied, the crop yield indicates the dryland yield. It is assumed that if irrigation water used is increased, this would lead to an increase in crop production.

Cost function: Due to the data availability, the primary source for cost function is from KSU Farm Management guide. Cost is crop specific including fixed cost, variable cost related with water irrigation and variable cost related with crop yield. Fuel and labor costs as well as machinery repair, depreciation, and interest expenses are presented by projected Kansas Custom Rates for specific field operations. Seed, fertilizer, herbicide, and insecticide/fungicide costs are based on historical data. But some modifications have to be made because of the different hydrologic characteristic between Kansas and Texas. The cotton cost is supposed to be a little higher in Texas.

Commodity price: Prices for corn, wheat, cotton, and grain sorghum are obtained from Texas Historical Estimates, United States Department of Agriculture (USDA). Due to the market price fluctuation, five-year (2010-2015) average prices are used for calculation.

Profit function: Total revenue is calculated by multiplication on price and yield. The difference between revenue and cost is the profit function for each crop. This study assumes producers desire to maximize profits, so they must choose the optimal amount of groundwater use where profit is maximizing. The water irrigation positively affects the production yield, and the profit is depended on the production yield.so the water irrigation and crop choice reflect the profit-maximizing decision.

Marginal profit function: The marginal profit is defined as the difference between the marginal revenue and the marginal cost of producing one additional unit of output, which is an important parameter for the supply and demand function.

One methods to build the rule is to reduce quotas based on previous year's usage level. And the specific reduction is depended on the policy. In order to satisfy the 15 inches constraint, the target total inches is multiplication on 15 inches and actual acreage for irrigation. The actually total irrigation inches is multiplication on actual irrigation inches and irrigation acreage. The difference between actual total irrigation and target irrigation over actually irrigation indicates the reduction quotas for each individual farmers.

Several rules are followed to create individual farmer's demand and supply function. In a water market, individual farmer could be a seller or a buyer. We assume that farmers are desire to maximize their profit, so the irrigation water applied will be no greater than the optimal irrigation water use. It is assumed that if market price is higher than the marginal profit for each unit, then farmers are willing to sell water to maximize profit. If market price is lower than the marginal profit for additional unit, the farmers are willing to buy water to maximize profit. And the sum of all individual demand function is the market demand function, the sum of all individual supply function is the market supply function. The equilibrium point on market demand and supply curve is the market price and water quantities, which is used to compare the benefit under 50/50 water policy.

Chapter 5 Results and Conclusion

Under the 50/50 management goal, the local Ground water districts are faced with the evaluating and analyzing new polices to achieve the 50-year time horizon goals as well as keeping economy growth. The main objective of this study is to analyze the impacts of setting the “cap” of 1.5 acre-feet per contiguous per acre per year on the aquifer and the economy of the northwest Texas.

The specific objectives is to:

- Determine the characteristics of conservation method alternatives which could keep economic growth under 50/50 policy.
- Create rules for trading and estimate market price
- Compare the farmers’ welfare under the different conservation method alternatives.

To achieve the objectives of this research, the economic welfares of two water conservation method alternatives are evaluated along with a simulated water market.

Uniform 15 inches permits: this methods alternatives limits each farmer’s water use to 15 inches per year, so that the aquifer cannot exceed 50 percent. Under this premise, farmers could trade the water to maximize their profit.

19 percent quota reduction based on a previous year’s usage level: this methods alternatives limits each farmer’s water usage to 81 percent of previous year’s water usage. This methods can conserve the same amount of water as uniform 15 inches permits.

395 observations are selected as the representative observations from the study area, they have a diverse crop mix, total crop acreages are 27453 acres in both dryland and irrigated, including 1.3% dryland sorghum, 6.5% irrigated sorghum, 3.3% dryland

wheat, 6.1% irrigated wheat, 9.7% dryland cotton, 52.5% irrigated cotton and 20.6% irrigated corn.

Corn is the most water intensive crop, the optimal amount of irrigation water use is 23 inches. 31.51% of the total irrigation is applied by corn, and the mean water applied is 18.08 inches, which is about 53.2% greater than the average water applied in total area. If each farmer could apply the optimal water on irrigation corn, 115151.4 inches of water would be applied each year. Cotton is the most widely planted crop, which occupied 62.24% of the study area. The optimal amount of water use is 21 inches, and the mean water applied is 11.07% inches. Wheat and sorghum are least intensive crops, which only use 10% of the total irrigation water, which a

According to the data, the lowest profits per acre are dryland production, while the irrigation production gains higher profits per acre. The most profitable crop is corn, which profit per acre is 40% greater than the average profit per acre in study area, and the least profitable crop is wheat, which accounts for 0.6% of the total profit. Cotton is the second profitable crop, which contributed 68.7% of total profit due to the largest growing acreage.

Under the water conservation policy, the water use is limiting to uniform 15 inches per acres for each farmer, which means farmers with unconstrained water use above the 15 inches must reduce their water use to meet the allocation. If farmers could apply the optimal amount of water to maximize profit in unconstrained policy, 86% of irrigated sorghum acres, 77% of irrigated wheat acres, 87% of irrigated corn acres and 66% of cotton acres are constrained by the 15 inches permits.

Another conservation alternative is 19 percent quota reduction based on a previous year's usage level, which means no matter how much water you used before, all farmers are constrained by the policy.

In order to reduce the profit lost for farmers, a water simulated market is built to trade their permits between each other. Some trading rules are created to make it feasible. First, no transaction cost and market management cost are considered in the simulated market. Second, a market price is given for each trading units in the market. Third, the dryland production are given no permits at water allocation. Finally, farmers get the permits for free, the total amount of permits is equal to the total irrigated acreage multiplied by the 15 inches.

The permit price and trading patterns for different conservation alternatives are estimated.

For uniform 15 inches permits, the market price is $3.91 per inch. Sorghum and wheat are the net sellers, and corn and cotton are buyers. The wheat and sorghum profit are increased by 50% and 150%.Wheat and sorghum profit a lot from the trade, because the maximum profit inches for sorghum is 13 inches, which is lower than the permit, so sorghum farmers get more profit by selling permits. And what has the lowest price, when the market price is higher than marginal profit, wheat farmers are willing to sell up to 75% of their permits, which is 12 inches. A 17% increase of cotton profit is benefit from the huge irrigated acreage.

For 19% quota reduction based on a previous year's usage level, the market price is calculated as $10.91per inch. Due to the high market price, sorghum and wheat are moving to dryland production, the total yield for sorghum and wheat degrease 48% and 2% at the same time. But the profit for sorghum and wheat increase by 77% and 119%.

As the main buyers, both corn and cotton has a slightly increase in profit because of the excessive price.

Under the different conservation policies, there are several important results summarized as follows:

1) There are some options for farmers when they face the restriction and market:
    a) When the market price is lower than the marginal profit (marginal abatement cost), farmers are willing to buy permits to increase pumping to maximize profit.
    b) When the market price is higher than the marginal profit (marginal abatement cost), farmers are willing to sell permits to move to dryland production.
2) Farmers are better off under the simulated market, the total profit is even higher than the unconstrained market. And sorghum and wheat farmers gain from the market, both of the conservation alternatives have little impact on corn farmers. As the major buyer, cotton farmers have a huge demand for water, but the increasing water cost counteract the profit from growing more cotton.
3) Compare the uniform 15 inches method to 19 percent reduction method, the uniform 15 inches have a 6.6% higher than 19 percent reduction method has.

And under 15 inches policy, farmers could produce more crops, up from 3% in 19 percent reduction policy.

Possible extension of this paper is that a dynamic model is needed to further study the impact of trading on farmers' welfare. Because the groundwater is an unrenewable resource, dynamic model could explain the marginal user cost more clearly.

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