water

MDPI

Article

Food, Fracking, and Freshwater: The Potential for Markets and Cross-Sectoral Investments to Enable Water Conservation

Margaret Cook [1,*] and Michael Webber [2]

1 Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 301 E. Dean Keeton St. Stop C1786, Austin, TX 78712-1173, USA
2 Department of Mechanical Engineering, The University of Texas at Austin, 204 E. Dean Keeton St. Stop C2200, Austin, TX 78712-1591, USA; webber@mail.utexas.edu
* Correspondence: margaretcook@utexas.edu; Tel.: +1-361-779-5276

Academic Editor: Miklas Scholz
Received: 20 November 2015; Accepted: 18 January 2016; Published: 30 January 2016

Abstract: Hydraulic fracturing—the injection of pressurized fluid, often water, to increase recovery of oil or gas—has become increasingly popular in combination with horizontal drilling. Hydraulic fracturing improves production from a well, but requires a significant amount of water to do so and could put pressure on existing water resources, especially in water-stressed areas. To supply water needs, some water rights holders sell or lease their water resources to oil and gas producers in an informal water market. These transactions enable the opportunity for cross-sectoral investments, by which the energy sector either directly or indirectly provides the capital for water efficiency improvements in the agricultural sector as a mechanism to increase water availability for other purposes, including oil and gas production. In this analysis, we employ an original water and cost model to evaluate the water market in Texas and the potential for cross-sectoral collaboration on water efficiency improvements through a case study of the Lower Rio Grande Valley in Texas. We find that, if irrigation efficiency management practices were fully implemented, between 420 and 800 million m^3 of water could be spared per year over a ten year period, potentially enabling freshwater use in oil and gas production for up to 26,000 wells, while maintaining agricultural productivity and possibly improving water flows to the ecosystem.

Keywords: water-energy nexus; hydraulic fracturing; water market; water policy

1. Introduction

Dwindling water supplies, change in climate, and increased demand on resources due to population and industry growth have led to increased water stress worldwide [1]. More recently in Texas, hydraulic fracturing, a technique that requires a significant amount of water to improve fuel production from low permeability source rock, has become increasingly popular in combination with horizontal drilling, especially for shale formations. Hydraulic fracturing involves the injection of pressurized fluid composed of water, sand, and proprietary chemicals to increase extraction rates and recovery of oil or gas. This intensive water requirement can inhibit production in places with low water availability such as drought-prone South and West Texas. With continued scarcity of water that has the potential to restrict production, shale oil and gas fracturing companies have sought water leases and sales in these areas.

To assess the feasibility of investments in water savings, this paper conducts an analysis of the water market in Texas and the impact of the water demand for hydraulic fracturing in that market. Those trends and price impacts are relevant to the prospects for innovations in water efficiency since understanding the underlying dynamics is useful for identifying the potential for engineering solutions to mitigate the various water-related challenges. Because oil and gas companies have significant capital to invest, because they require large quantities of water to fracture wells, and because they are willing to pay a higher price for water than water purchasers in other sectors, they can stimulate the water market, altering the current allocation of water and the implementation of management practices used for efficiency, reuse, or recycling.

This paper does not explore possibilities for using brackish, saline, or reuse water for hydraulic fracturing, rather it examines the hypothesis that freshwater savings enabled by improving irrigation efficiency in the agriculture sector would make significant volumes of water available for other purposes. The agriculture sector makes a good candidate for investments in water efficiency because it uses significant volumes of water for a small overall portion of economic activity, and often has outdated, inefficient equipment. Thus, the agricultural sector is the focus of this analysis.

We hypothesize that if the energy sector makes cross-sectoral investments in water-efficient irrigation systems for agriculture, water could be made available for oil and gas production, potentially increasing the amount of water available for ecosystems and other uses over time. This paper examines this hypothesis with an original water and cost model that is developed and demonstrated for the Lower Rio Grande Valley in the Southern tip of Texas.

1.1. Water Availability and Allocation Policies in Texas

The 2010 United States census revealed that, over the last ten years, Texas received the largest increase in population of any state [2]. In the same period, Texas also suffered more weeks of exceptional drought (the worst drought classification given by the National Drought Mitigation Center) than any other state [3]. Between 2011 and 2014, water supplies in Texas dwindled. Surface water levels reached their twenty-year low between February and October 2013 and again in 2014 as shown in Figure 1. Similarly, water levels in the Ogallala Aquifer in Texas have sharply decreased over the past 60 years [4]. The US Geological Survey reports depletion at 150 to 400 feet across the Texas portion of the aquifer [4]. This water scarcity is a motivating context for the research presented in this manuscript.

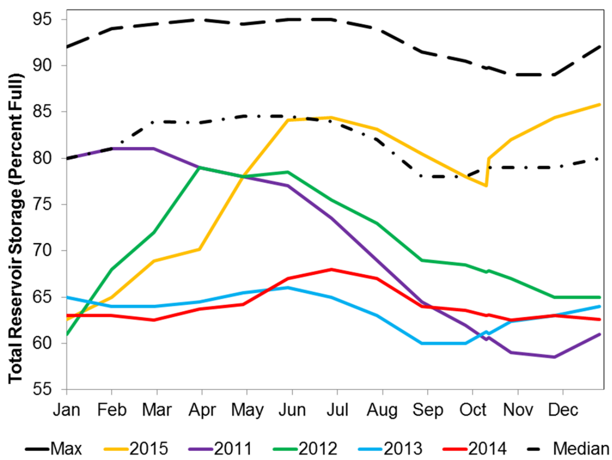

Figure 1. Reservoir levels across the state of Texas remained below median levels between 2011 and 2014. Between February and October 2013, water levels remained at the lowest levels in twenty years. Water levels in 2014 then decreased to the lowest levels in twenty-five years again between January and June of 2014. Maximum and median levels are calculated for 1990–2014 [5].

1.1.1. Surface Water: Prior Appropriation

Access to water is exacerbated by water scarcity as well as water allocation policies. Texas surface water is allocated under the Doctrine of Prior Appropriation, where a permit to withdraw water is based not on land ownership but on the point in time at which the permit or "water right" was acquired [6]. The system is often simplified as "first in time, first in right" because, upon application, a permitting authority gives a water right holder a priority date and an allocation amount that resides with the water right as long as it remains valid. Thus, water shortages fall on those who last obtained a legal right to use the water, unlike under Riparian water law, common in eastern states, in which shortages are shared equally among landowners adjacent to the water source. Because appropriative rights exist separate from land ownership, they can be bought, sold, leased, or transferred, forming the basis for a surface water market.

However, there are limitations. Interbasin transfer is allowed but restricted. Users must apply for and receive a water right or amendment to a permit [7]. The right is then junior in priority to rights granted before the time the application is accepted [7]. Moreover, the priority system is often termed "use it or lose it" because rights holders must use their entire volume or lose their right to it. The system often encourages wasteful water use. A market would allow potentially unused water to be leased to another water user under the original water right, creating an economic incentive to conserve where one might not have existed previously [8]. A lease of water allows the lessor and lessee to agree on a short- or long-term transfer of a surface water right [9]. However, unlike a sale, the lease allows the original water right holder to retain the underlying water right. At the end of the lease term, the water right reverts back to the water right holder [9]. A change in use, location, or amount of water diverted would require an authorized surface water right permit amendment from TCEQ [8–10].

Water rights in the Lower Rio Grande, below the Falcon-Amistad reservoir, differ from those on other rivers in that they are allocated on an account basis in which the Water Master, the arbitrator of water rights in this basin, records withdrawals and subtracts use from allocated accounts [11]. Rights for municipal uses are set at one priority level in which allocations renew on a yearly basis while irrigation rights are set at another level in which balances carry forward into the next year [11]. Thus, irrigation accounts are more constrained than municipal accounts [11]. Surplus in the Falcon-Amistad reservoir for any given month is allocated to the irrigation users [11].

1.1.2. Groundwater: Rule of Capture and Groundwater Conservation Districts

In contrast to its governance of surface water, the state of Texas does not incorporate permitting or judgments on reasonable use of water into its groundwater policy. Groundwater in Texas follows the Rule-of-Capture, attributing the right to withdraw groundwater to the landowner residing above that water and providing that, absent malice or willful waste, landowners can withdraw as much water as they want without incurring liability, even if that withdrawal will inhibit access to water by neighboring landowners [12]. However, a groundwater conservation district (GCD) authorized by the Texas Legislature can protect and manage groundwater resources to maintain supplies in the area [13]. These districts have the ability to require permits and to place reasonable restrictions on water withdrawals or well location [14]. Unless restricted by a GCD or other authority, landowners may withdraw as much water as they need.

Because groundwater is a property right, it can be bought, sold, or traded. Under the Rule-of-Capture, groundwater is a common-pool resource. By economic principles, due to knowledge that neighbors might exploit or sell the shared water beneath their land, no single user has an incentive to conserve water for later use [15]. Landowners are instead inclined to over-exploit their groundwater resources [15]. Regulations by GCDs allow water use and potential marketing while limiting over-exploitation. They can also limit a market by requiring permits or levy fees for water exported out of the district [16–18]. While statewide water trades are made more difficult, the rules do not inhibit market activity on the regional level within a district.

The Edwards Aquifer Authority is an example of a functioning groundwater market [16]. No water can be withdrawn from the aquifer without a permit [16,19]. There are limitations to the system, though. To address third-party effects of groundwater transfers, a groundwater right holder cannot sell or lease more than fifty percent of their irrigation rights [16].

1.2. Water Use for Hydraulic Fracturing in Texas

Shale deposits are thin, sometimes relatively impermeable, layers of rock that contain significant quantities of natural gas or petroleum liquids and often cover a wide area underground. Hydraulic fracturing in combination with horizontal drilling has enabled economic extraction of the natural gas and petroleum liquids from the shale.

Texas has several shale plays, shown in Figure 2. The Energy Information Administration (EIA) estimates the Eagle Ford Shale holds about 4.3% of the nation's total natural gas reserves and about 7% of the nation's total oil reserves [20]. As shown in Figure 3, Texas experienced increased levels of oil and gas production in the decade between 2005 and 2015. Some analysts expect continued growth.

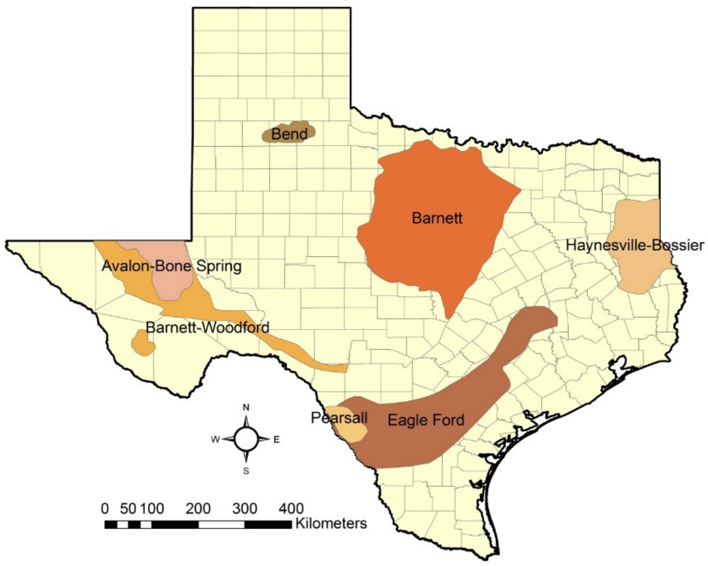

Figure 2. There are several shale plays in Texas: the Avalon-Bone Spring, Barnett, Barnett-Woodford, Eagle Ford, Haynesville-Bossier, and Pearsall shales. Most of these shales are in drought-prone areas. (Map created by the authors based on data from [21,22]).

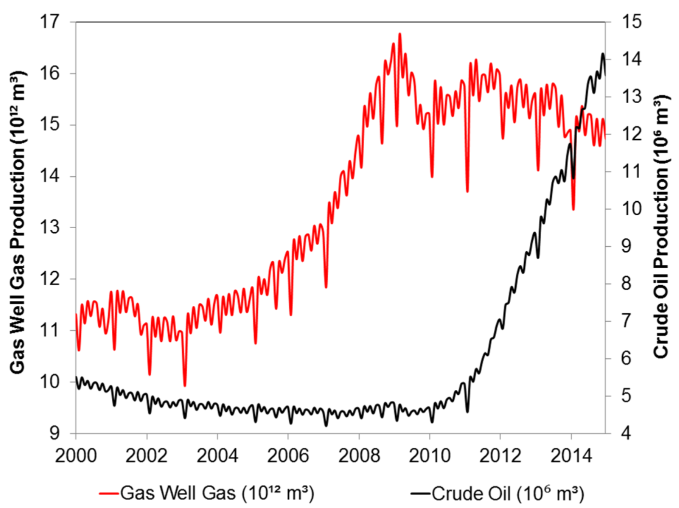

Figure 3. While gas production began to increase in the early 2000s in Texas, this study captures water transactions prior to 2009 due to the increases in oil production beginning in 2009 and 2010. (Figure created by the authors based on data from [23]).

Hydraulic fracturing requires a significant amount of water to extract gas or liquids. In the area surrounding the Eagle Ford Shale formation, for example, total water consumption is expected to increase from 7.15 million m^3 (5800 ac-ft) in 2010 to 55.2 million m^3 (44,800 ac-ft) in 2020 due to oil and gas drilling [24]. That water demand is the equivalent of supplying the total per capita water needs of 13 million people in 2010 and 104 million people in 2020. Because the water might not be available due to prior allocation for other purposes, such as irrigation, these projections for high water use introduce a vulnerability and potential hindrance to increased hydraulic fracturing in Texas. Oil and gas producers would have to purchase previously allocated water rather than acquiring a right to access it. Moreover, in certain areas of the state, water use for hydraulic fracturing has been banned or restricted. In the Barnett shale region, the City of Grand Prairie recently banned the use of municipal water for hydraulic fracturing. Similarly, in the Texas Panhandle, the Board of Directors of the High Plains Underground Water Conservation District Number 1, the officials governing water use in the Ogallala Aquifer in the area, approved limits on water use for hydraulic fracturing in July of 2011 [24]. In 2014, citizens of the City of Denton, TX voted to ban hydraulic fracturing from the city's limits. The ban was partially triggered by concerns over water [25–27].

For many other water-intensive sectors, the price of new water might be prohibitive. However, because of higher costs for other parts of the supply chain, and because water is used to produce an even higher-value product, water prices are unlikely to be a major hurdle for the oil and gas sector. To illustrate, in 2012, Breitling Oil and Gas paid $68,000 (a mere 0.2% of the $3.5 million spent to hydraulically fracture the well) to truck 13,000 m^3 of water from Oklahoma to its operations [24]. In the Permian Basin, the cost to drill and complete a well might be up to $20 million with the cost of water purchase, transportation, and disposal only amounting to less than 10% of that cost [28]. While a non-trivial expense, the majority of costs are not water-related, which means the price of water is not the key financial determinant in the total cost of a well.

Moreover, despite frequent drought in the Barnett Shale region in North Texas, Nicot *et al.* found that droughts do not seem to drive water use for hydraulic fracturing in that region of Texas as much as gas prices and economic activity do [29]. When water supplies are restricted, oil and gas producers can purchase water from other water user groups. Meaning, in the midst of water scarcity and added water restrictions from political forces, the lack of available freshwater might not stunt shale liquid and gas extraction. However, water purchases by the energy sector in areas of water scarcity, such as the Eagle Ford Shale region in South Texas and the Permian Basin in West Texas, could inhibit access for other water use sectors. Thus, water sales and leases by oil and gas operators intending to shore up water supplies for hydraulic fracturing could play an important role in the market for water in these water-stressed areas of the state.

1.3. Irrigation Water Use in Texas

The agriculture sector is one of the main economic sectors with which oil and gas producers might compete for water. In 2007, the agriculture industry in Texas had a statewide economic value of $4.7 billion [30]. In 2012, agricultural cash receipts totaled $2.2 billion for cotton, $1.2 billion for corn, and $594 million for grain sorghum [31]. The industry is also the largest water use sector in the state at over 50% of total water withdrawals [32]. Much of this water use is in three regions: the Lower Rio Grande Valley in South Texas, the Lower Colorado River area near the Texas Coast, and over the Ogallala Aquifer in West Texas and the Panhandle, as shown in Figure 4. Farms in the Lower Rio Grande Valley produce sorghum, upland cotton, sugarcane, watermelon, onions, grapefruit, and other crops and fruits [33]. Farms in the Lower Colorado River area produce many crops, but rice cultivation makes up the majority of the irrigated acreage [33]. Farms in West Texas and the Panhandle produce much of the upland cotton grown in the United States, as well as other crops including corn, wheat, and sorghum for grain [33].

Since 1970, due to use of improved technologies such as better sprinkler systems, including center pivot systems and low pressure sprinklers, Texas irrigation water use has become more efficient. However, there is still room for improvement. Only 3% of irrigated acres today use highly efficient subsurface drip irrigation [30]. About 19% of the state's irrigated acres still rely on less water-efficient forms of irrigation such as flood or furrow (parallel channels used to carry water to crops that are grown on the ridges between the furrows [34]), for which about half the water used is lost through evaporation or transpiration and does not reach the crops [30]. With management improvements in the irrigation industry, water can be used more efficiently.

However, the assumption that all measures for water efficiency reduce water has been challenged by past research [35,36]. Huffaker and Whittlesey suggest increased efficiency leads to more overall use of water [36]. Improved management practices are preferred to improved technologies [35].

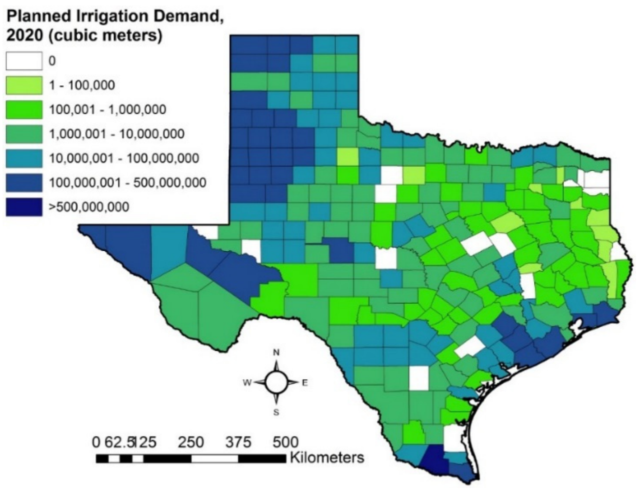

Figure 4. The irrigation water use in Texas by county is highest in in the northernmost part of the state (the Panhandle) and in the southernmost part of the state (the Lower Rio Grande River Basin). (Map created by the authors based on data from [22,37]).

Potential irrigation efficiency opportunities lie in use of best management practices (BMPs) such as furrow dikes, which are small dams for each ridge between a planted row of crops; gated and flexible pipe to prevent seepage in irrigation channels and furrows; recovery of irrigation runoff water (tailwater recovery); and brush management. The Texas A & M Agrilife Extension has also suggested improving irrigation scheduling; developing improved irrigation water management practices; adopting drought tolerant crop varieties; continuing conservation practices adoption; and improving irrigation conveyance systems [30]. Other practices include monitoring soil moisture and reducing evaporation [35]. This study focuses on application of Best Management Practices (BMPs).

As a major agricultural producer for Texas and the United States as a whole, the Lower Rio Grande Valley region consumes a large amount of water on irrigation—about 79% of total regional water use [37]. The counties with the highest irrigation water withdrawals in the valley, Cameron and Hidalgo Counties (shown in Figure 5 outlined in black), consume about 432–740 million m^3 (350,000–600,000 ac-ft) of water per year, respectively. Thus, the Lower Rio Grande Valley could be a prime candidate for large-scale irrigation efficiency improvements. Accordingly, some BMPs have already been implemented in some of the irrigation districts in the valley [30]. However, many BMPs, including brush management, crop residue management and conservation tillage, and tailwater recovery and reuse systems are not yet in wide-spread use [30].

Moreover, not all of the canals used to convey irrigation water are lined to prevent seepage. While these counties hold an opportunity for improvements in irrigation management and a potential for water savings, they are also adjacent to active shale production. The Eagle Ford Shale resides upstream of these two counties and underneath Webb, Maverick, and Dimmit Counties in the Rio Grande Basin, as shown in Figure 5 in purple. All five of the counties in the Lower Rio Grande Valley could benefit from future economic growth of the oil and gas industry; the counties in the Eagle Ford Shale could benefit due to increased oil and gas production and the neighboring counties due to water sales.

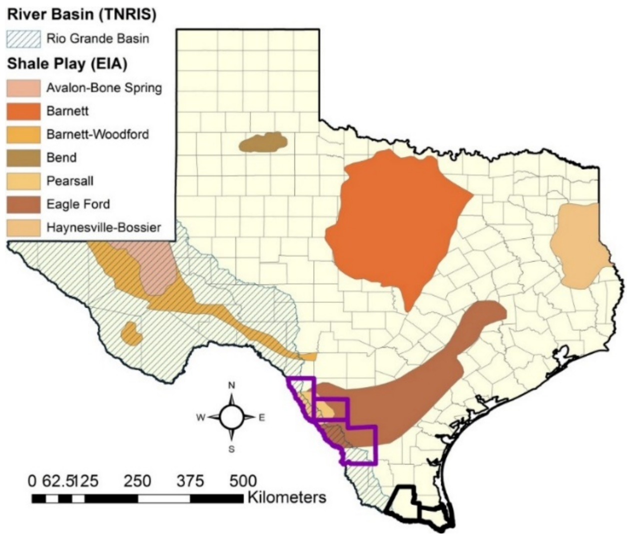

Figure 5. Two shale plays overlap with the Rio Grande River Basin, the Barnett-Woodford and Eagle Ford shales. Webb, Maverick, and Dimmitt counties are outlined in purple, and Cameron and Hidalgo counties are outlined in black. (Map created by the authors based on data from [21,22,29]).

1.4. Adoption of Irrigation Efficiency Practices

While BMPs might save water, irrigators or irrigation districts might be unwilling to implement them. Many factors affect adoption of water efficiency mechanisms, particularly water price and farm finances, education, policy, and water availability. Farmers are also likely to implement irrigation efficiency mechanisms on low quality land or if yield potential increased [38].

Water price has a direct impact on demand and secondary impact on choice of efficiency measure and capital investments [38,39]. Similarly, purchasing water in water markets or other similar alternatives is cost effective compared to subsidies for investments in improved irrigation efficiency [40]. Past research has indicated irrigation water conservation subsidies are unlikely to reduce water use [41]. However, farms in southern Alberta have experienced challenges in implementing economic instruments to manage irrigation water because, as a concept, they have little support in the irrigation industry [42]. Moreover, where cost of water is small percent of total farm budget in Western Australia, investment is slow [35].

Capital for long-term investment in irrigation efficiency might not always be available [39]. Colorado irrigators, for example, implemented when practical or economical, and in Canada, surveys of two irrigation districts showed that farmers often did not implement water efficiency measures because of financial reasons [35]. Mechanisms that are easier to implement and provide demonstrable effects often have financial rather than sociological barriers while ones that require farmers to learn new skills also have sociological barriers like education [35].

Improved control and farmer education is needed for increased participation in irrigation management [43]. A study in India found that training and education of farmers, in addition to "changes in government policies such as rules and regulations, pricing, institution building and infrastructure development" is needed to encourage adopting water efficient cultivation methods [44]. Other research has shown farmers that adopt water efficiency mechanisms earlier are often younger, more educated, more cosmopolitan, higher income, have larger farm operations, and receive primary sources of information about the technologies or management practices [35,39,45]. Farmers that have trialed a mechanism are also more likely to adopt [39]. Ultimately farmers are risk averse; mechanisms involving existing knowledge and skills are adopted before options that require costly, complex innovations [34]. A study in sub-Saharan Africa recommended investment in clear education for adopters of drip irrigation, focusing on repairs and maintenance [46].

In Australia, considerable uncertainty about long term access to water impedes irrigation investment [35]. A study in India found that "adoption of water-saving irrigation will not improve farmers' livelihoods despite its importance in reducing water scarcity problems at regional scale" [44]. "Unequal water distribution among farms, dissatisfaction with Water Authority operators, and high water fees and charges" created obstacles for farmer participation in irrigation management [35]. Conservation might also reduce return flows [38]. It is important to keep these water availability concerns in mind when recommending water efficiency strategies.

2. Analysis

2.1. Assessing The Water Market in Texas

In Texas, formal water markets have been slow to develop. Water is rarely traded across Texas due to the large size of the state and the lack of natural or man-made conduits for large water transfers like those in California [47]. Where water is traded, local markets prevail, specifically in the Lower Rio Grande Valley (in the Southern tip of Texas), over the Edwards Aquifer (in central Texas), and in the Texas Panhandle. Other markets exist through local water trusts. Despite the drawbacks to the current water trading system, water transfers have occurred in Texas for decades.

Usual transactions occur within the agriculture sector or from agriculture to non-agriculture users [47]. According to the Western Governors Association, Texas traded a total 3.5 billion m^3 between 1988 and 2009 at an average 10 million m^3 per transfer [48]. Trades increased between 2007 and 2009 resulting in 185 million m^3 of transfers over those three years [48]. However, the ongoing drought in Texas triggered and increases in demand from various water use sectors, including oil and gas, has increased demand for water transfers across the state. During the drought in 2011, users sold or leased more than 2.1 billion m^3 [48]. Figure 6 shows water transactions between 1987 and 2008 and between 2009 and 2014. The two time periods show the difference in area and price of water transactions, particularly the water trading that occurred in areas that also experienced an increase in oil and gas production after 2009—the Eagle Ford Shale, Permian Basin, and Anadarko Basin. The figures do not include all transactions that occurred in the state during this time period.

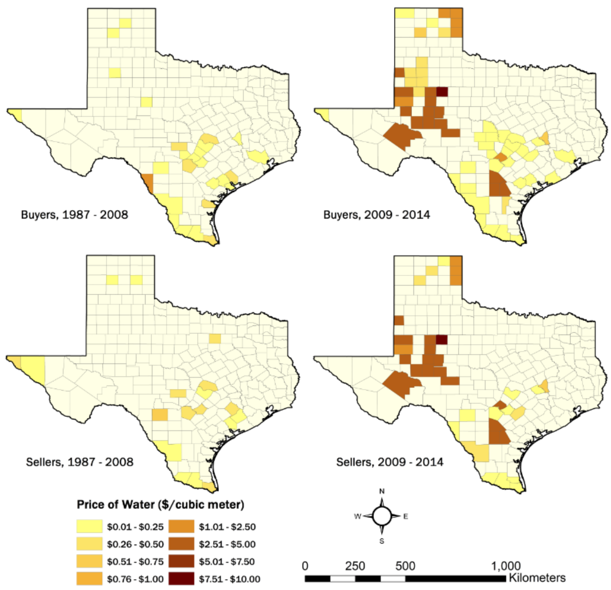

Figure 6. Water transactions across the state of Texas often occur in local markets in the Lower Rio Grande Valley below Falcon Dam, in the Edwards Aquifer area, and in Northwest Texas. Between 2009 and 2013, transactions increased in South and West Texas and in the Panhandle due to the increase water demand for hydraulic fracturing. Data were compiled from various sources including private operators and [12,22,24,49–67].

To assess the water market in Texas, we curated and integrated various public and private datasets including hard data from governmental entities and soft data such as interviews with water marketers, local or state agencies, and landowners. We also surveyed the existing market literature, as well as press releases for water sales across the state. This determination is difficult since the state only keeps record of water leases or sales in the Rio Grande basin. Thus, this figure does not include all water transactions in the state between 1987 and 2014 as not all transactions are reported to the various databases we evaluated.

2.2. Assessing Volume and Cost of Improved Irrigation Efficiency

In this study, we incorporate data from a Texas Water Development Board (TWDB) evaluation of BMPs. The four examples used in this section are furrow dikes (small dams for each ridge between a planted row of crops); gated and flexible pipe to prevent seepage in irrigation channels and furrows; recovery of irrigation runoff water (tailwater recovery); and brush management. Past studies have shown the furrow dike system, for example, is a cost-effective management practice for producers in the Southeastern U.S. that positively impacts natural resource conservation, producer profit margins, and environmental quality [68]. Figure 7 shows the ranges in potential water savings available per area covered, σ_W ($m^3/km^2 \cdot$ year), for these four irrigation water-saving practices as reported by the TWDB. The BMPs also range in cost of implementation. Figure 8 shows the varying cost of implementation per irrigated acre for four irrigation water-saving practices, C_{area} (km^2/year). The data shown in Figures 7 and 8 are used as inputs for Equations (1)–(3).

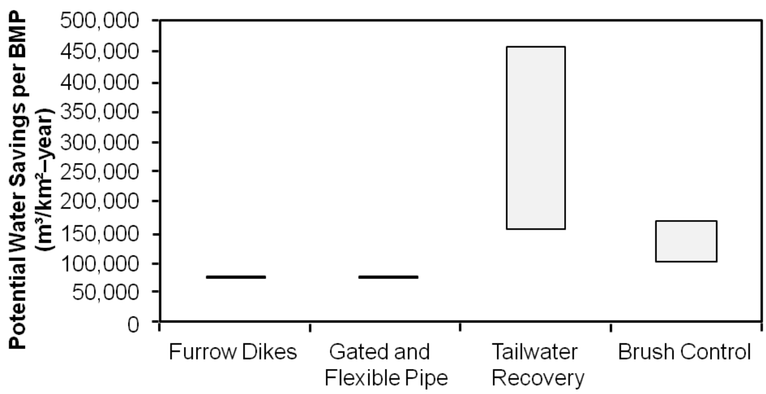

Figure 7. These four irrigation efficiency management practices vary in water savings potential per area covered with about 76,000 m^3/km^2 possible per year from using furrow dikes and piping and up to 460,000 m^3/km^2 possible per year from using tailwater recovery. (Source data: [37]).

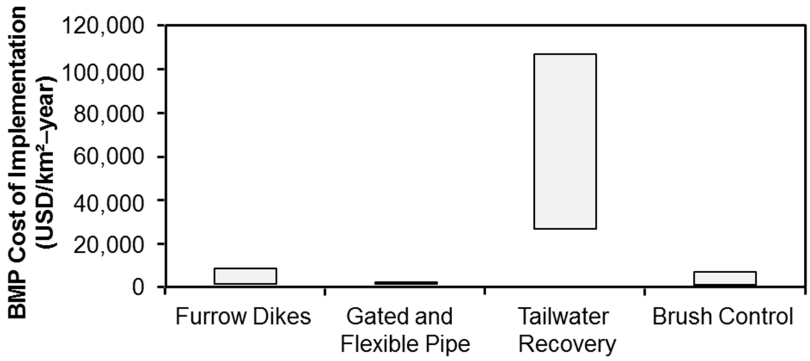

Figure 8. These four irrigation efficiency methods vary in cost of implementation with costs ranging from \$1,500/$km^2 \cdot$ year for gated and flexible pipe to over \$100,000/$km^2 \cdot$ year for the more expensive tailwater recovery systems. (Source data: [37]).

The water savings, V_{ws}, in m^3/year possible from implementation of a water-efficient practice is calculated using Equation (1) where A_{irr} represents the amount of irrigated land in km^2.

$$V_{ws} = \sigma_W \cdot A_{irr} \tag{1}$$

The estimated total cost, C, in one year of the implementation of one of these irrigation efficiency practices over a stretch of irrigated land is calculated using Equation (2), where A_{irr} represents the amount of irrigated land in each county in km^2.

$$C = C_{area} \cdot A_{irr} \tag{2}$$

The estimated cost per volume [m^3/yr] of water savings, C_{vol}, is then determined using Equation (3).

$$C_{vol} = C_{area} / \sigma_W \tag{3}$$

These equations are used to estimate the total water savings that could be made available, the total cost, and the cost per volume of water saved through use of BMPs. The cost is then compared to the market price for water used for hydraulic fracturing. The results of this analysis are shown in Section 3.

3. Results and Discussion

3.1. The Water Market for Hydraulic Fracturing in Texas

With the surge in oil and gas drilling in the nearby Eagle Ford Shale, energy companies have been buying or leasing water rights on the Rio Grande in South Texas [48]. One of the major irrigation districts in the Lower Rio Grande, Hidalgo County Irrigation District No. 2, has added diversion points in the Middle Rio Grande where water can be easily delivered to energy entities [48]. Landowners in other parts of the shale basin have sold water from their wells to oil and gas producers, sometimes requiring the producers desiring access to the land's mineral rights to also drill a water well on the property and purchase that water for fracturing any oil or gas wells. Landowners might sell their water through water marketing firms [48]. One firm reportedly sold more than 220,000 m^3 to oil and gas companies [61].

The Permian Basin resides in drought-prone West Texas where many of the area's reservoirs were less than 3% full in 2014 [5]. The Permian Basin sits under the Ogallala Aquifer in the northern part of the basin and under the Edwards-Trinity Aquifer in the southern part of the basin. Landowners selling fresh water to oil and gas operations supply water from these two aquifers. Figure 9 shows these and other mining water transactions that occurred between 2009 and 2014. The mining water use sector includes water use for oil and gas, as well as for other resource extraction industries like coal and sand mining. The figure does not show transactions in the Barnett Shale because of uncertainty in the locations of these transactions.

As the number of mining transactions has increased, so has the price of water per cubic meter. Figure 10 shows the change in water price for the mining sector. Between 1987 and 2008, prior to the increase in hydraulic fracturing in much of Texas, the median lease price for mining water was approximately \$0.03 per m^3 and the average price was approximately \$0.10 per m^3 [12,24,49–67]. Between 2009 and 2014, the median lease price was approximately \$3.90 per m^3 and the average price was \$4.00 per m^3 [12,24,49–67]. This change in price between the two periods could be due to the spike in water demand for oil and gas drilling as well as the decrease in water supplies caused by the intense, state-wide drought that began in 2011, among other factors.

It is relevant to note that a transfer of a large quantity is often negotiated at a much lower price than the smaller volume, marginal, transactions for oil and gas water sales [12,24,49–67]. Even so, the price for water for oil and gas activity in Texas is magnitudes higher than that for agriculture or even urban use, meaning changes in price in the future will likely still carry a large enough differential that the price of water could influence changes in behavior or technology in the buying (oil and gas) or selling (agriculture) sectors. It is also relevant to note that oil and gas activity is temporary. While water often moves to higher value uses, water would not move to the mining sector permanently. The water movement is often in leases of water volumes rather than sales of water rights—unless the company owns the land and thus owns rights to the groundwater beneath it.

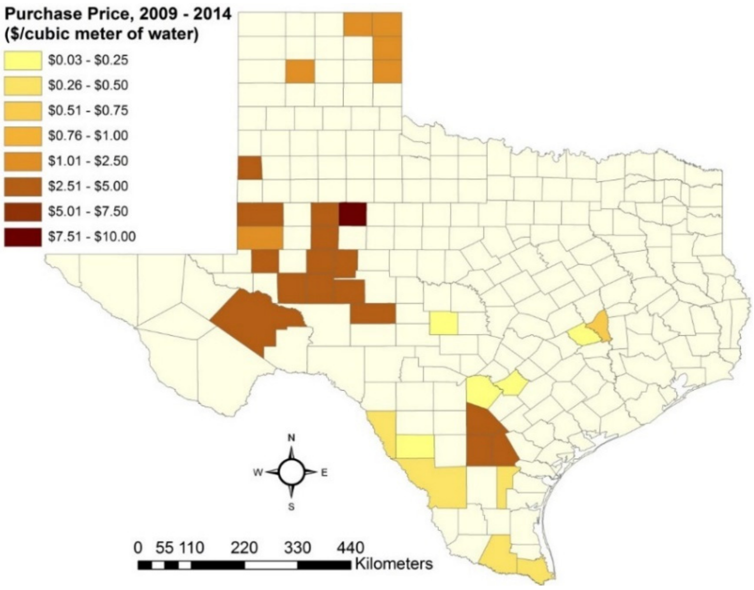

Figure 9. The figure shows the average purchasing price for water in the mining sector between 2009 and 2014, during the shale boom in Texas. The transactions cover mainly oil and gas water use. Water transactions for mining have increased in price and volume in much of the state. Depending on the area, water might originate as groundwater or surface water. Alternative water sources including brackish, effluent, and recycled produced water are becoming more common. (Data were acquired from various sources including private operators and [12,22,24,49–67].)

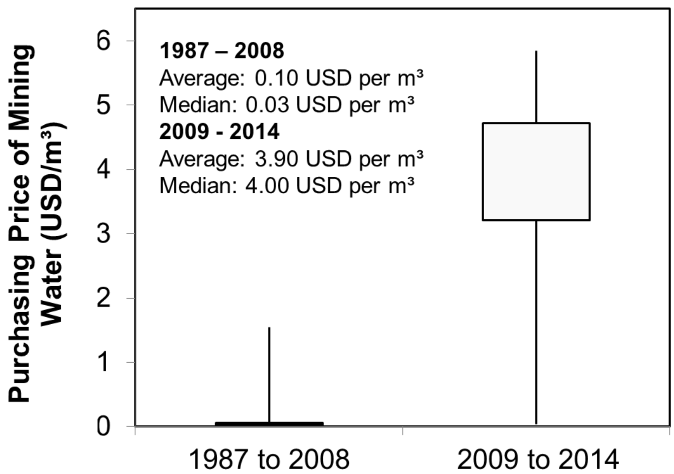

Figure 10. In the areas that encompass the Eagle Ford Shale and the Permian Basin, water prices in the mining sector increased dramatically since 2009. The box plots show the 1st and 3rd quartiles within the boxes and the data beyond those quartiles as whiskers. (Data were acquired from various sources including private operators and [12,23,49–67]. The dataset includes approximately 30 transactions prior to 2009 and over 1200 transactions after 2009).

3.2. Transaction Costs

In examining Texas' water market, it is important to keep transaction costs in mind as they might create a significant barrier to market allocation of water resources and might cause implementation to lag [69]. Transaction costs are the resources used to define, establish, maintain, and transfer property rights [70]. These costs might include administrative costs or costs of exchanging ownership titles [70]. They are incurred by a subset of the actors [69].

A detailed analysis of transaction costs in water markets across Texas is beyond the scope of this paper. However, transaction costs are likely to vary across the state of Texas. Policies vary at the state level between groundwater and surface water management and availability and at the regional level between groundwater conservation districts, river basin authorities, and other districts. Garrick and Aylward found that, for environmental flows, even in the same river basin, transaction costs vary within and between states [69].

Additional questions remain over whether to include costs of basic research and costs to raise visibility of the market, as well as potential strategies to optimize water availability. The agriculture sector is more sensitive to transaction costs than the industrial sector [71], so oil and gas operators might be more likely to instigate a trade involving improvements in water efficiency before irrigators.

Regional water markets, as opposed to state- or basin-wide markets, often create pockets of favorable market conditions—water rights are defined clearly with low transaction costs [69]. Because of the existing vibrant water market in the Lower Rio Grande, the water market and its transaction costs are examined at this level rather than as part of the state-wide system. The watermaster keeps current water balances for each water right holder [72]. The watermaster acts as a broker of water, and individuals interested in purchasing or leasing water can get information on available water from the watermaster relatively inexpensively over the phone [72]. Water price is determined by negotiation between buyers and sellers, allowing price to fluctuate based on supply and demand [72]. Water rights are protected via monitoring by TCEQ.

Transaction costs incurred in the water market in the Lower Rio Grande Valley in Texas are captured by the watermaster department at the TCEQ [73]. Water rights holders in the Lower Rio Grande river basin, the Concho river basin, and river basins in South Texas pay TCEQ for permits, licenses, and fees [11]. These funds are then allocated toward administrative costs of the watermaster offices [74]. While water rights in the Rio Grande Watermaster area account for the majority of water market activity in watermaster service areas, they account for 40% of diversions by volume. Assuming water rights fees are proportional to the amount of diversion, water rights holders on the Rio Grande pay their watermaster \$627,000, or \$0.01 per m^3 of water in 2013–2014 [75]. Water transactions in the basin draw \$2,350,000 in sales and leases over the same period, meaning transaction costs account for 21% of total water costs [75]. A transaction cost of \$0.01 per m^3 is approximately 30% the cost of the average purchase price of agriculture water between 2009 and 2014. However, it is approximately 0.23% of the average purchase price of mining water over the same period. There are additional transaction costs in increased irrigation analysis and water monitoring. Texas A & M Agrilife Extension, a large agriculture research entity in Texas posts funding support of \$151,000 for irrigation research in years past [76]. Including this cost of research does not change the cost per volume, \$0.01 per m^3, but yields a result of 25% transaction costs as a percent of total water costs. This cost fits within ranges found in previous work in which water market transaction costs range from 8%–34% [70,77–81].

In addition to the policy costs associated with managing a watermaster area in Texas, there are additional non-policy costs related to the voluntary transaction between oil and gas operators and irrigation districts to increase irrigation efficiency. If this operation were to be promoted via policy measures in the future, there would be additional transition costs for the policy change and transaction costs between water users. Changes in institutional costs mean changes to the environmental or legal system, development of market enabling institutions, like additional water markets, and market transactions [70]. For example, TCEQ allocated 1.3×10^6 U.S. dollars between 2014 and 2015 towards creation of a new watermaster on the Brazos River in Texas [74]. Water right holders see an additional transaction cost via an annual fee of 50 U.S. dollars plus a use fee based on authorized amount of water and type of use [82]. In other basins, there might be institutional lock-in costs, costs imposed by current institutional choices on future efforts to reverse or alter water use patterns and infrastructure [79]. Attempts to regulate the water market through defining ground and surface water property rights could face opposition and high transition costs.

However, there is also a cost in keeping the Texas legal system in its current status as an unregulated market, potentially resulting in depleted aquifers and impacts on estuaries [70,83]. Prior appropriation yields third party effects on junior water rights holders, especially if trade moves water downstream of junior water right holders [83]. There is less of an effect when all users share in losses or gains in supply due to drought or precipitation, as with the correlative right system in the Lower Rio Grande Valley [83]. Water markets are more economically efficient and provide private and social benefits compared to policies encouraging irrigation efficiency through subsidies [40]. A step change in policy may be necessary due to Texas' path dependency [79]. Iterative reforms, including informal trading, diversion limits, water rights reform, and adaptation, took hold over three decades in the Murray-Darling Basin in Australia [79]. This gradual policy development could be used as an example in Texas. Policies should be directed at water trade while minimizing concerns over where the water goes or how it is used [83]. Effective institutional investment in transition costs yields stable transaction costs [69]. Policy design should foster technical change [84].

3.3. Opportunities for Collaboration: Irrigation and Hydraulic Fracturing

Figure 11 shows the estimated cost of BMP implementation per cubic meter of potential water savings upon installation. These implementation costs are minor compared to the current purchasing price for water in the mining sector in Texas, indicating the potential for an energy-agriculture partnership in which the energy sector pays for the improved irrigation efficiency measures and receives the water made available in return. Given that buying water in water markets is more cost effective than other policies intended to encourage improved irrigation efficiency through subsidies, there is potential for irrigation efficiency improvements through market mechanisms [40]. In the past, water trading involving improvements in irrigation management strategies has improved water efficiency beyond the volume purchased, making water available to the ecosystem and improving environmental flows in the process [85]. In one past example, in 2007, the City of Roma in Starr County was awarded $2.8 million from the Economically Distressed Area Program to purchase water rights. Rather than buying more water from the markets, the city engineers decided to make a trade for water rights with irrigation districts in Cameron County [85]. The city funded improvements to irrigation canal conveyance efficiency within Irrigation District No. 2 and received the excess water rights in return. The City of Roma received the needed water supply, while the irrigation districts still received the water they needed and even had about 1×10^5 m^3 (800 ac-ft) of additional savings per year. This example illustrates some of the potential for cross-sectorial water benefits from efficiency investments made by the marginal user.

As shown in Figure 12, the water savings for each BMP varies and both Hidalgo and Cameron Counties have a large potential for water savings. While each management practice cannot be applied on every irrigated acre, these numbers serve as a measure of the maximum potential water savings and implementation costs in these two Texas counties.

The high potential water savings opens up the opportunity for a water market in the Lower Rio Grande Valley. Typically, hydraulic fracturing in the Eagle Ford Shale uses approximately 16,100 m^3 of water per well [86]; therefore, with the implementation of BMPs to every irrigated acre in Hidalgo and Cameron Counties, more than 26,000 hydraulic fracturing operations could benefit from newly available water rights.

However, oil and gas wells are only active for a limited amount of time. A company could feasibly drill multiple wells in series on the same water right, profiting even more from the single purchase of conservation measures. Furthermore, irrigation districts and farms could profit from the sale by either keeping some of the conserved water or creating and charging a leased or market price for water rights reasonably above the actual cost of conservation. There are several contractual options for transferring saved water, but those are beyond the scope of this paper, which is only to quantify the potential agricultural water savings.

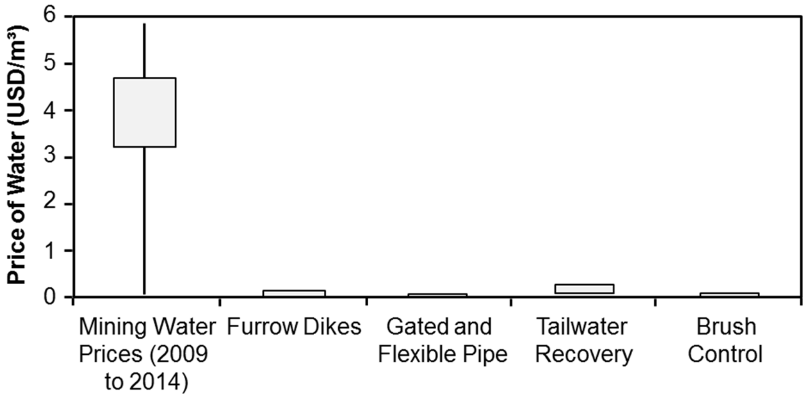

Figure 11. The price of water varies per Best Management Practice (BMP), but all water conservation measures cost less than the wholesale price of water for hydraulic fracturing in Texas. The box plot of water price shows the 1st and 3rd quartiles within the boxes. The lines extending beyond the box, or whiskers, show the data outside of those quartiles. The price paid for mining water does not include transaction costs which vary regionally. (Figure created by the authors based on analysis and data from private operators and [12,24,49–67].)

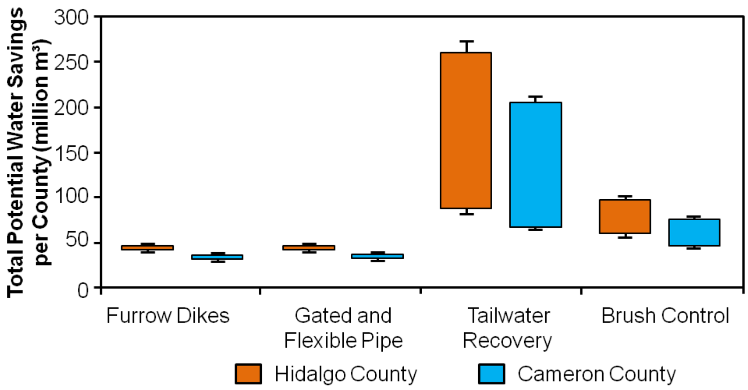

Figure 12. In addition to the variation for each BMP, the water savings varies in each county. With the high irrigation water use in both Cameron and Hidalgo counties, each county has a great potential for water savings through improved irrigation efficiency. Equation 3 was employed to determine these estimated savings.

We find that for up to $154 million, including transaction costs, a maximum of 800 million m^3 (650,000 ac-ft) of water use could be avoided by implementing four best management practices for irrigation efficiency across Hidalgo and Cameron counties in South Texas. By incorporating irrigation BMPs, irrigation districts in Hidalgo and Cameron County would likely be able to save water, maintain their crops, and profit from the sale. Simultaneously, shale oil and gas companies would have access to freshwater for hydraulic fracturing while reducing their risk of exposure to municipal restrictions and water shortages. Thus, this makeshift water market could solve water needs for multiple sectors. Also, Texas possesses many other major rivers which are, like the Rio Grande, reaching full allocation. While oil and gas operators can pay for water now, that purchase often offsets other water uses, for example, reducing the amount of irrigated agriculture activity or increasing stress on water supplies. A water market promoting irrigation efficiency measures might encourage better resource allocation and increase the amount of water available for economic activity (e.g., hydraulic fracturing as analyzed in this paper) and/or ecosystems as Texas considers instream flow requirements into its bays and estuaries.

The markets already exist, some in better form than others. Efficient and effective water management requires collaboration among stakeholders to achieve common goals in allocating limited water resources [87]. There is a potential for the market to move toward integrated partnerships that benefit irrigators or irrigation districts and oil and gas operators rather than existing adaptive strategies to combat water stress. This energy-agriculture partnership could work in areas where water allocations are nearing their maximum capacity. When water is inexpensive, it is not cost-effective to save it or make investments to reduce consumption. However, when water is expensive, or if there is a buyer who will pay a lot for it, there is an economic incentive to reduce usage either to reduce costs or to gain revenues in the sale of water.

A trade instigated by the irrigator or the oil and gas company would be possible in a market. A proposal by either party during negotiations for water exchange brought on by oil and gas operators in need of water could instigate a trade. Similarly, irrigators or irrigation districts seeking capital for efficiency investment could post volumes available for lease. The latter would be less likely as there are not many existing portals through which to advertise such a sale. However, by investing in efficiency measures, an irrigator or irrigation district could sell more water without reaching a limit (if there is one) or otherwise overdrawing their resources (if there is not a limit). The cross-sectoral investment could be proposed by the irrigators or irrigation districts, possibly in an effort to reap extended benefits from the surge in capital or for other reasons or by the oil and gas company, possibly for increased public approval or other social benefit. For example, Southwestern Energy mitigates the impacts of its hydraulic fracturing operations on the environment by rehabilitating lost wetlands or creating a new habitat in Arkansas [88].

Some irrigation districts might be reluctant to transfer water outside of their district. However, in a lease of water, the irrigation district or irrigator would still retain the underlying right to water [9]. One of the major irrigation districts in the Lower Rio Grande, Hidalgo County Irrigation District No. 2, has added diversion points in the Middle Rio Grande where water can be easily delivered to energy entities [48]. The management practices mentioned in this manuscript would require adding an extra step in this negotiation to pay for irrigation efficiency measures rather than leasing existing excess water from the irrigation district.

Specifying a contract that entitles an energy company to water saved through efficiency enhancements could include high transaction costs. Energy companies already negotiate with many landowners in the areas they serve [12]. This system would likely not increase or decrease the amount of landowners with which energy companies negotiate. However, it would probably increase the time spent in negotiation and management systems needed for the water.

In the Rio Grande Valley, irrigation districts provide larger systems of water users with whom the energy companies can negotiate. Moreover, the watermaster in the region provides information on available water such that a company would be able to narrow their search. In other areas of the state, where water markets are unregulated, transaction costs are higher and willingness to participate in trades to reduce current demand through efficiency measures rather than buying additional water becomes a barrier.

It is important that negotiations for water trading include a baseline for water availability. Because a contract would be based on money paid for an amount of water provided, the negotiating point for both parties should be based on a drought year. A farmer interested in selling water and still producing crops would likely want to ensure they will have enough water to do so after a trade as would the operator interested in fracturing wells with the saved water.

4. Conclusions

The Texas water market has historically been dominated by transactions within the agriculture sector and transactions between the agriculture and municipal sectors in local markets around the state. However, between 2009 and 2015, the market experienced an increase in demand for water by the energy industry. Between 1987 and 2008, prior to the increase in hydraulic fracturing in much of Texas, the median lease price for mining water was approximately $0.03 per cubic meters ($m^3$) and the average price was approximately $0.10 per m^3 [12,24,49–67]. In this analysis, we found that between 2009 and 2014, the median lease price for water in the mining sector was approximately $3.90 per m^3 and the average price was $4.00 per thousand m^3, an increase of two orders of magnitude [12,24,49–67]. These prices and market trends open up the possibility for innovation and investments in management practices for water use efficiency in various sectors.

However, there are limitations to this market. Interbasin transfer of surface water is allowed but restricted. Groundwater Conservation Districts can also limit a market by requiring permits or levy fees for water exported out of the district [16–18]. While statewide water trades are made more difficult, these rules do not inhibit market activity on the regional level within a district. Transaction costs might also create a significant barrier to market allocation of water resources and cause implementation to lag [69]. Transaction costs vary across the state of Texas. Policies vary at the state level between groundwater and surface water management and availability and at the regional level between groundwater conservation districts, river basin authorities, and other districts. Transaction costs associated with administrative fees account for approximately 21% of total water costs in the Rio Grande Valley. This cost fits within ranges found in previous research in which transaction costs range from 8% to 34% [70,77–81].

By implementing a combination of improved efficiency mechanisms, agricultural producers and their economic partners, which might include shale liquid and gas companies or not, can optimize their water conservation and achieve more water availability for themselves and/or the environment. In the energy-agriculture partnership, this increased water availability would augment the ability to hydraulically fracture more wells in the Rio Grande Valley or elsewhere and maintain the same amount of agricultural activity and possibly increase environmental flows. This makeshift water market could solve water needs for the hydraulic fracturing and agricultural industries in this case, or many other partners in similar examples, and create a more water resource-friendly environment in the process. However, the assumption that all measures for water efficiency reduce water has been challenged by past research. Improved management practices are preferred to improved technologies [35].

In this study we find that for up to $154 million, including transaction costs, a maximum of 800 million m^3 (650,000 ac-ft) of water use could be avoided by implementing four best management practices for irrigation efficiency across Hidalgo and Cameron counties in South Texas. While it might not be possible to apply these practices to every acre of irrigated land in these counties, this value provides a measure of the maximum amount of water available through implementation of water-efficient techniques. There is also room for increased efficiency through use of other irrigation management methods not covered in this analysis.

While BMPs might save water, irrigators or irrigation districts might be unwilling to implement them. Many factors affect adoption of water efficiency mechanisms, particularly water price and farm finances, education, policy, and water availability. The partnership with oil and gas companies could eliminate the financial hurdle. However, it is important to ensure farmers are educated, policies are favorable, and water availability concerns are managed.

The estimated amount of water that could be made available through adoption of the irrigation management practices analyzed in this manuscript is much greater than the amount of water used for hydraulic fracturing in the area. Thus, freshwater demand for hydraulic fracturing in the Lower Rio Grande Valley could feasibly be covered through trades for irrigation efficiency measures.

If the agriculture-energy partnership were to be promoted via policy measures in the future, there would be additional transition costs for the policy change and transaction costs between water users.

Changes in institutional costs mean changes to the environmental or legal system, development of market enabling institutions, like additional water markets, and market transactions [70]. For example, TCEQ allocated 1.3×10^6 U.S. dollars between 2014 and 2015 towards creation of a new watermaster on the Brazos River in Texas [74]. Attempts to regulate the water market through defining ground and surface water property rights could face opposition and high transition costs. However, there is also a cost in keeping the Texas legal system in its current status as an unregulated market, potentially resulting in depleted aquifers and impacts on estuaries [70,83].

Water markets are more economically efficient and provide private and social benefits compared to policies encouraging irrigation efficiency through subsidies [41]. Iterative reforms, including informal trading, diversion limits, water rights reform, and adaptation, took hold over three decades in the Murray-Darling Basin in Australia [79]. This gradual policy development could be used as an example in Texas. Policies directed at water trade while minimizing concerns over where the water goes or how it is used could liberate the possibility for these investments [83]. Effective institutional investment in transition costs yields stable transaction costs [70].

Acknowledgments: This work was funded by the U.S. Department of Energy, the Cynthia and George Mitchell Foundation, and the National Science Foundation's Integrative Graduate Education and Research Traineeship. The authors would like to acknowledge Ashlynn Stillwell, Carey King, Sheila Olmstead, Cal Cooper, and Matt Muniz for their intellectual contributions to this work.

Author Contributions: The lead author, Margaret Cook, conducted the bulk of the research and writing of this manuscript, including the literature and financial document review, personal interviews, and developing the methodology. Michael Webber developed the original research question, advised the research direction for the work, and contributed to the writing and editing.

Conflicts of Interest: The lead author, Margaret Cook, interned at Apache Corporation during the writing of this manuscript.

References

1. Vorosmarty, C.J.; McIntyre, P.B.; Gessner, M.O.; Dudgeon, D.; Prusevich, A.; Green, P.; Glidden, S.; Bunn, S.E.; Sullivan, C.A.; Reidy Liermann, C.; *et al*. Global threats to human water security and river biodiversity. *Nature* **2010**, *467*, 555–561. [CrossRef] [PubMed]
2. U.S. Census Bureau. The 2012 Statistical Abstract. 2012. Available online: http://www.census.gov/compendia/statab/cats/population.html (accessed on 3 June 2014).
3. National Drought Mitigation Center. Current U.S. Drought Monitor. 2013. Available online: http://droughtmonitor.unl.edu/ (accessed on 3 June 2014).
4. USGS. Groundwater Depletion. 2014. Available online: http://water.usgs.gov/edu/gwdepletion.html (accessed on 12 December 2014).
5. Water Data for Texas. 2015. Available online: http://www.waterdatafortexas.org/reservoirs/statewide (accessed on 13 November 2015).
6. Getches, D. *Water Law in a Nutshell*; West Publishing Company: St. Paul, MN, USA, 2009.
7. Texas Water Code. Sec. 11.085. Available online: http://www.statutes.legis.state.tx.us/Docs/WA/htm/WA.11. htm (accessed on 31 December 2015).
8. Griffin, R.; Characklis, G. Issues and Trends in Texas Water Marketing. *Water Resour.* **2002**, 29–33.
9. Texas Water Development Board (TWDB). A Texan's Guide to Water and Water Rights Marketing. 2003. Available online: http://www.twdb.texas.gov/publications/reports/infosheets/doc/WaterRightsMarketingBrochure.pdf (accessed on 27 December 2015).
10. Loomis, J.B.; Quattlebaum, K.; Brown, T.C.; Alexander, S.J. Expanding Institutional Arrangements for Acquiring Water for Environmental Purposes: Transactions Evidence for the Western United States. *Int. J. Water Resour. Dev.* **2003**, *19*, 21–28. [CrossRef]
11. Texas Commission on Environmental Quality (TCEQ). Rio Grande Watermaster Program. 2015. Available online: https://www.tceq.texas.gov/permitting/water_rights/wmaster/rgwr/riogrande.html (accessed on 13 November 2015).

12. Potter, I.H. History and Evolution of the Rule of Capture. Report 361. In Proceedings of the 100 Years of Rule of Capture: From East to Groundwater Management Conference, Austin, TX, USA, 15 June 2004; William, F., Mullican, S., III, Suzanne, S., Eds.; Texas Water Development Board (TWDB): Austin, TX, USA, 2004; pp. 1–9.
13. Cook, M.; Huber, K.; Webber, M. Who Regulates It? Water Policy and Hydraulic Fracturing in Texas. *Texas Water J.* **2015**, *6*, 45–63.
14. Mittal, A.; Gaffigan, M. *Energy-Water Nexus: Improvements to Federal Water Use Data Would Increase Understanding of Trends in Power Plant Water Use*; United States Government Accountability Office (U.S. GAO): Washington, DC, USA, 2009.
15. Holland, S.; Moore, M. Cadillac Desert revisited: Property rights, public policy and water-resource depletion. *J. Environ. Econ. Manag.* **2003**, *46*, 131–155. [CrossRef]
16. Avioli, L.F. A New Phase in Water Resource Allocation: The Case for Groundwater Markets in Texas. Master's Thesis, The University of Texas at Austin, Austin, TX, USA, 2013. Available online: https://repositories.lib.utexas.edu/bitstream/handle/2152/22451/AVIOLI-MASTERSREPORT-2013.pdf?sequence=1 (accessed on 3 June 2014).
17. Texas Water Code. Sec. 36.064. Available online: http://www.statutes.legis.state.tx.us/Docs/WA/htm/WA.11.htm (accessed on 31 December 2015).
18. Texas Water Code. Sec. 36.122. Available online: http://www.statutes.legis.state.tx.us/Docs/WA/htm/WA.11.htm (accessed on 31 December 2015).
19. Edwards Aquifer Authority. Edwards Aquifer Authority Rules. 2015; San Antonio, TX, USA. Available online: http://www.edwardsaquifer.org/files/download/d3027b2ff81b5c5 (accessed on 31 December 2015).
20. Energy Information Administration (U.S. EIA). Review of Emerging Resources: U.S. Shale Gas and Shale Oil Plays. 2011. Available online: http://www.eia.gov/analysis/studies/usshalegas (accessed on 5 December 2012).
21. U.S. EIA. Maps: Exploration, Resources, Reserves, and Production. 2012. Available online: ftp://www.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm (accessed on 5 December 2012).
22. Texas Natural Resources Information Services (TNRIS) of the Texas Water Development Board (TWDB). Maps & Data. 2012. Available online: http://www.tnris.org/get-data (accessed on 18 April 2012).
23. RRC. Texas Monthly Oil & Gas Production. 2015. Available online: http://www.rrc.state.tx.us/oil-gas/research-and-statistics/production-data/texas-monthly-oil-gas-production/ (accessed on 13 November 2015).
24. Lee, M. Parched Texans Impose Water-Use Limits for Fracking Gas Wells. Businessweek 2011. Available online: http://www.businessweek.com/news/2011-10-06/parched-texans-impose-water-use-limits-for-fracking-gas-wells.html (accessed on 18 April 2012).
25. Dropkin, A.; Henry, T. How the Denton Fracking Ban Could Work. NPR State Impact 2014. Available online: http://stateimpact.npr.org/texas/tag/denton/ (accessed on 12 December 2014).
26. Hennessy-Fiske, M. Denton, Texas, voters approve "unprecedented" fracking ban. Los Angeles Times 2014. Available online: http://www.latimes.com/nation/la-na-texas-fracking-20141108-story.html (accessed on 12 December 2014).
27. Unger, T. Denton votes to reject fracking. WFAA News 8 2014. Available online: http://www.wfaa.com/story/news/local/denton-county/2014/11/04/denton-voters-consider-ban-on-fracking/18484893/ (accessed on 12 December 2014).
28. Cooper, C.; Apache, Corp., Houston, TX, USA; Barnes, C.; Apache, Corp., Houston, TX, USA; Foreman, S.; Apache, Corp., Houston, TX, USA. Personal communication, 8 August 2014.
29. Nicot, J.P.; Scanlon, B.R.; Reedy, R.C.; Costley, R.A. Source and fate of hydraulic fracturing water in the Barnett Shale: A historical perspective. *Environ. Sci. Technol.* **2014**, *48*, 2464–2471. [CrossRef] [PubMed]
30. Wagner, K. Status and Trends of Irrigated Agriculture in Texas. 2013; Texas Water Resources Institute. Available online: http://twri.tamu.edu/docs/education/2012/em115.pdf (accessed on 12 December 2014).
31. Texas Department of Agriculture (TDA). Texas Ag Stats. 2012. Available online: https://www.texasagriculture.gov/About/TexasAgStats.aspx (accessed on 3 June 2014).
32. Vaughan, E.G.; Crutcher, J.M.; Labatt III, T.W.; McMahan, L.H.; Bradford, B.R.; Cluck, M. Water for Texas 2012 State Water Plan Texas Water Development Board. 2012. Available online: http://www.twdb.state.tx.us/publications/state_water_plan/2012/2012_SWP.pdf (accessed on 5 December 2012).

33. Farm Service Agency, U.S. Department of Agriculture. Crop Acreage Data. 2014. Available online: http://www.fsa.usda.gov/FSA/webapp?area=newsroom&subject=landing&topic=foi-er-fri-cad (accessed on 14 December 2014).
34. USGS. Irrigation Techniques. 2014. Available online: http://water.usgs.gov/edu/irmethods.html (accessed on 12 December 2014).
35. Bjornlund, H.; Nicol, L.; Klein, K. The adoption of improved irrigation technology and management practices–A study of two irrigation districts in Alberta, Canada. *Agric. Water Manag.* **2009**, *96*, 121–131. [CrossRef]
36. Huffaker, R.; Whittlesey, N. A theoretical analysis of economic incentive policies encouraging agricultural water conservation. *Water Resour. Dev.* **2003**, *19*, 37–53. [CrossRef]
37. TWDB Conservation Division. *BMP Guide*; TWDB Conservation Division: Austin, TX, USA, 2004.
38. Skaggs, R.K. Predicting drip irrigation use and adoption in a desert region. *Agric. Water Manag.* **2001**, *51*, 125–142. [CrossRef]
39. Alcon, F.; de Miguel, M.D.; Burton, M. Duration analysis of adoption of drip irrigation technology in southeastern Spain. *Technol. Forecast. Soc. Chang.* **2011**, *78*, 991–1001. [CrossRef]
40. Qureshi, M.E.; Grafton, R.Q.; Kirby, M.; Hanjra, M.A. Understanding irrigation water use efficiency at different scales for better policy reform: A case study of the Murray-Darling Basin, Australia. *Water Policy* **2010**, *13*, 1. [CrossRef]
41. Peterson, J.M.; Ding, Y. Economic adjustments to groundwater depletion in the high plains: Do water-saving irrigation systems save water? *Am. J. Agric. Econ.* **2005**, *87*, 147–159. [CrossRef]
42. Bjornlund, H.; Nicol, L.; and Klein, K. Challenges in implementing economic instruments to manage irrigation water on farms in southern Alberta. *Agric. Water Manag.* **2007**, *92*, 131–141. [CrossRef]
43. Uysal, O.K.; AtÄss´, E. Assessing the performance of participatory irrigation management over time: A case study from Turkey. *Agric. Water Manag.* **2010**, *97*, 1017–1025. [CrossRef]
44. Senthilkumar, K.; Bindraban, P.S.; de Boer, W.; De Ridder, N.; Thiyagarajan, T.M.; Giller, K.E. Characterising rice-based farming systems to identify opportunities for adopting water efficient cultivation methods in Tamil Nadu, India. *Agric. Water Manag.* **2009**, *96*, 1851–1860. [CrossRef]
45. Khalkheili, T.A.; Zamani, G.H. Farmer participation in irrigation management: The case of Doroodzan Dam Irrigation Network, Iran. *Agric. Water Manag.* **2009**, *96*, 859–865.
46. Friedlander, L.; Talb, A.; Lazarovitch, N. Technical considerations affecting adoption of drip irrigation in sub-Saharan Africa. *Agric. Water Manag.* **2013**, *126*, 125–132. [CrossRef]
47. Brewer, J.; Glennon, R.; Ker, A.; Libecap, G. Water markets in the West: Prices, trading and contractual forms. *Econ. Inq.* **2008**, *46*, 91–112. [CrossRef]
48. Doherty, T.; Smith, R. Water Transfers in the West 2012: Projects, Trends, and Leading Practices in Voluntary Water Trading. Western Governors' Association: Denver, CO, 2012. Available online: http://www.westgov.org/component/docman/doc_download/1654-water-transfers-in-the-west?Itemid= (accessed on 3 June 2012).
49. Amarillo City Council Minutes. Available online: http://www.amarillo.gov/departments/citymgr/2013/minutes/minutes_12_03_2013.pdf (accessed on 3 June 2014).
50. Caputo, A. Exelon Still Holding Onto Guadalupe Water. San Antonio Express-News 2009. Available online: http://thearansasproject.org/basin-management/exelon-still-holding-onto-guadalupe-water/ (accessed on 3 June 2014).
51. Comprehensive Annual Financial Report. Canadian River Municipal Water Authority. 2012. Available online: http://crmwa.com/wp-content/uploads/2013/02/FY-11-12-Audited-Financial-Statements-CAFR.pdf (accessed on 3 June 2014).
52. Donohew, Z.; Libecap, G. California Water Transfer Records. 2009. Available online: http://www.bren.ucsb.edu/news/Water_Transfer_Data_Feb_10.xls (accessed on 3 June 2014).
53. Edwards Aquifer Authority. Comprehensive Annual Financial Report. San Antonio, TX, USA, 2010. Available online: http://data.edwardsaquifer.org/files/FY2010%20Comprehensive%20Annual%20Financial%20Report.pdf (accessed on 3 June 2014).
54. Edwards Aquifer Authority. Comprehensive Annual Financial Report. San Antonio, TX, USA, 2011. Available online: http://www.edwardsaquifer.org/files/download/3fdf1888cb38bda (accessed on 3 June 2014).

55. Edwards Aquifer Authority. Comprehensive Annual Financial Report. San Antonio, TX, USA, 2012. Available online: http://www.edwardsaquifer.org/files/2012_Comprehensive_Financial_Annual_Report.pdf (accessed on 3 June 2014).
56. Edwards Aquifer Authority. 2013 Operating Budget. San Antonio, TX, USA, 2013. Available online: http://www.eaadevelopment.com/operating-budget/financial-overview (accessed on 3 June 2014).
57. Edwards Aquifer Authority. Groundwater. San Antonio, TX, USA, 2014. Available online: http://data.edwardsaquifer.org/display_permit_portal_m.php?pg=permit_faqs/ (accessed on 3 June 2014).
58. Guadalupe-Blanco River Authority. Minutes of the Board of Directors. 2011. Available online: http://www.gbra.org/documents/board/minutes/110518.pdf (accessed on 3 June 2014).
59. Miller, N. Organization Looking to Sell Water to Oil Companies. Odessa American 2014. Available online: http://www.oaoa.com/news/business/article_b00c22ce-99dd-11e3-8f85-001a4bcf6878.html (accessed on 12 December 2014).
60. Muniz, M.; DJM Water Supply, Three Rivers, TX, USA. Personal communication, 25 June 2012.
61. Muniz, M.; DJM Water Supply, Three Rivers, TX, USA. Personal communication, 9 January 2014.
62. Patoski, J. Boone Pickens Wants to Sell You His Water. Texas Monthly 2001. Available online: http://www.texasmonthly.com/story/boone-pickens-wants-sell-you-his-water (accessed on 3 June 2014).
63. San Antonio River Authority Public Services Regional Planning. 2014. Available online: http://www.sara-tx.org/public_services/water_planning/ (accessed on 3 June 2014).
64. Tarrant Regional Water District. Tarrant Regional Water District Overview. 2014. Available online: http://www.trwd.com/AboutUs (accessed on 3 June 2014).
65. Texas Commission on Environmental Quality. Public Information Request Number (PIR number) 14-14509. Austin, TX, USA, 2013.
66. Welch, K. City Might Sell Last of Hartley County Water Rights. 2013. Available online: http://amarillo.com/news/local-news/2013-12-02/city-might-sell-holdings (accessed on 3 June 2014).
67. Welch, K. Water Authority May Sell Lipscomb County Rights. Amarillo Globe-News 2013. Available online: http://amarillo.com/news/local-news/2013-07-10/water-authority-may-sell-lipscomb-county-rights (accessed on 3 June 2014).
68. Truman, C.C.; Nuti, R.C. Improved water capture and erosion reduction through furrow diking. *Agric. Water Manag.* **2009**, *96*, 1071–1077. [CrossRef]
69. Garrick, D.; Aylward, B. Transaction Costs and Institutional Performance in Market-Based Environmental Water Allocation. *Land Econ.* **2012**, *88*, 536–560. [CrossRef]
70. McCann, L. Transaction costs and environmental policy design. *Ecol. Econ.* **2013**, *88*, 253–262. [CrossRef]
71. Wang, Y. A simulation of water markets with transaction costs. *Agric. Water Manag.* **2012**, *103*, 54–61. [CrossRef]
72. Yoskowitz, D.W. Spot market for water along the Texas Rio Grande: Opportunities for water management. *Natural Resour. J.* **1999**, *39*, 345.
73. Chang, C.; Griffin, R. Water Marketing as a Reallocative Institution in Texas. *Water Resour. Res.* **1992**, *28*, 879–890. [CrossRef]
74. Texas Commission on Environmental Quality. Annual Financial Report. 2014. Available online: http://www.tceq.state.tx.us/assets/public/comm_exec/pubs/sfr/045-14.pdf (accessed on 15 December 2015).
75. Texas Commission on Environmental Quality. *Public Information Request Number (PIR number) 16-24040*; Texas Commission on Environmental Quality: Austin, TX, USA, 2015.
76. Texas A & M Agrilife Extension. Irrigation Technology Program. 2015. Available online: http://itc.tamu.edu/funding.php (accessed on 15 December 2015).
77. Colby, B.G. Transactions costs and efficiency in Western water allocation. *Am. J. Agric. Econ.* **1990**, *72*, 1184–1192. [CrossRef]
78. Garrick, D.; Whitten, S.M.; Coggan, A. Understanding the evolution and performance of water markets and allocation policy: A transaction costs analysis framework. *Ecol. Econ.* **2013**, *88*, 195–205.
79. Hearne, R.R.; Easter, K.W. Water Allocation and Water Markets: An Analysis of Gains-From-Trade in Chile. In *World Bank Technical Paper Number 315*; World Bank: Washington, DC, USA, 1995.
80. Howitt, R.E. Empirical analysis of water market institutions: The 1991 California water market. *Resouce Energy Econ.* **1994**, *16*, 357–371. [CrossRef]

81. Howitt, R.E. Effects of Water Marketing on the Farm Economy. In *Sharing Scarcity: Gainers and Losers in Water Marketing 1994*; Carter, H.O., Vaux, H.J., Jr., Scheuring, A.F., Eds.; Agricultural Issues Center: Davis, CA, USA, 1994; pp. 97–132.
82. Texas Commission on Environmental Quality. Brazos Watermaster. 2015. Available online: https://www.tceq.texas.gov/permitting/water_rights/wmaster/brazos-river-watermaster/ (accessed on 15 December 2015).
83. Grafton, R.Q.; Libecap, G.D.; Edwards, E.C.; O'Brien, R.J.; Landry, C. Comparative assessment of water markets: Insights from the Murray-Darling Basin of Australia and the Western USA. *Water Policy* **2011**, *14*, 175. [CrossRef]
84. McCann, L.; Colby, B.; Easter, K.W.; Kasterine, A.; Kuperan, K.V. Transaction cost measurement for evaluating environmental policies. *Ecol. Econ.* **2005**, *52*, 527–542.
85. Gerston, J.; MacLeod, M.; Jones, C.A. *Efficient Water Use for Texas: Policies, Tools, and Management Strategies*; Texas Water Resources Institute: College Station, TX, USA, 2002.
86. Nicot, J.P.; Scanlon, B.R. Water Use for Shale-Gas Production in Texas, U.S. *Environ. Sci. Tech.* **2012**, *46*, 3580–3586. [CrossRef] [PubMed]
87. Sandoval-Solis, S.; Teasley, R.L.; McKinney, D.C.; Thomas, G.A.; Patino-Gomez, C. Collaborative modeling to evaluate water management scenarios in the Rio Grande Basin. *J. Am. Water Resour. Assoc.* **2013**, *49*, 639–653. Available online: http: //onlinelibrary.wiley.com.ezproxy.lib.utexas.edu/doi/10.1111/jawr.12070/abstract (accessed on 8 June 2015). [CrossRef]
88. Southwestern Energy. Water Use. 2015. Available online: https://www.swn.com/responsibility/documents/water_fact_sheet.pdf (accessed on 31 December 2015).