Refining effective precipitation estimates for a model simulating conservation of groundwater in the Mississippi Delta Shallow Alluvial Aquifer

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The shallow alluvial aquifer in the Mississippi Delta region is heavily used for irrigation of corn, soybeans, and cotton, as well as for rice flooding and filling aquaculture ponds in the prominent catfish industry. Water volume in the aquifer is subject to seasonal declines and annual fluctuations caused by both climatological and crop water use variations from year-to-year.

Available climate, crop acreage, irrigation water use, and groundwater decline data from the 19 counties in the Delta were used to construct a model that simulates the effects of climatic variability, crop acreage changes, and specific irrigation methods on consequent variations in the water volume in the aquifer. Climatic variability was accounted for by predictive equations that related annual measured plant water use (irrigation) to total growing season precipitation amounts. This derived relationship allowed the application of a long-term climatological record (50 years) to simulate the cumulative impact of climate on groundwater use for irrigation.

The relationship between rainfall and anticipated crop water use was initially estimated by a simple regression between total growing season rainfall and measured irrigation water use for the period 2002-2007, with a resulting R^2 value of 0.93. Adding data from 2008 caused R^2 to drop to 0.63. It was recognized that total growing season rainfall was not representative of the timing, or episodic nature, of rainfall compared to plant water demand day-by-day through the growing season. To account for this timing issue, weekly rainfall amounts were compared to weekly expected crop water demand to produce an effective rainfall estimate. The resulting improvements are shown. This effective rainfall compared to irrigation use is expected to provide a much-improved rainfall-irrigation coefficient for use in the model.

Key words: Climatological processes, Groundwater, Irrigation, Management and Planning, Water Use

Introduction

Agricultural producers in Mississippi are increasingly relying on irrigation to insure that crops receive the right amount of water at the right time to enhance yields. The shallow alluvial aquifer is the most heavily developed source of groundwater in the Mississippi Delta region and the entire state (Figure 1). The aquifer is heavily used for irrigation of corn, soybeans, and cotton, as well as for rice flooding and filling aquaculture ponds in the prominent catfish industry. Demand for the groundwater resource continues to grow at a rapid rate (Figure 2).

Water volume in the aquifer is subject to seasonal declines and annual fluctuations caused by both climatological and crop water use variations from year-to-year. These declines can be dramatic and are most notable during the period April-October of each year, particularly in years when normal crop water demands are accentuated by concurrent abnormally dry climatic conditions. Recharge during the remainder of the year has recently been insufficient to restore water volume, and the aquifer is now being mined at the approximate rate of 300,000 acre-feet per year (Figure

3). To underscore the critical nature of this water problem, the most recently documented water volume decline in the aquifer (October 2005-October 2006) is estimated at 500,000 acre-feet (Pennington, 2006). This may represent a worst-case situation in which severe drought combined with consequent increased demand for irrigation. It is estimated that water use for row crops doubled during this period (Pennington, 2006).

It is of critical importance to understand how climatological variability and cultural uses of the water cause the groundwater volume in the aquifer to vary. It is also critical to discover and implement management strategies to change irrigation methods and to use precipitation and other surface water sources as substitutes for aquifer withdrawals and thereby reduce the use of groundwater in the region. Stopping the consistent drop in water volume in the aquifer will require a curtailment averaging about 300,000 acre-feet of groundwater use each year, and the highest priority of this research project is to find and recommend solutions to this problem. This information is essential to agricultural producers in the region and to planners in the Yazoo Mississippi Delta Joint Water Management District who must design sustainable water use scenarios which will allow continuation of the productivity of the region.

The objective of this research is to develop a model that can be used as a management tool to find ways to meet the needs for water use while conserving groundwater. This is the third phase of the project to meet these objectives. In phase one of the project, the growing season precipitation was used to develop a relationship that estimated irrigation use, and this was the driving mechanism of the model that simulated water use to the year 2056. Phase two added the use of surface water when growing season precipitation was 30% or more above normal. In this third phase, a new climatological input was introduced into the model—irrigation demand. Irrigation demand was calculated using daily precipitation, evaporation, and a crop coefficient to estimate daily water needs by crop type. Daily values were summed to one week segments which were added to derive the total growing season irrigation demand. Weekly summations increased temporal resolution, improving model efficiency in accounting for excess daily rainfall, allowing the model to apply excess rainfall in subsequent days.

Background Information

Agriculture is the major water consumer in the southeast region, and aquaculture specifically has the potential to become disproportionately consumptive. For example, most row crops in the region require 30-40 cm/yr, whereas catfish farming requires up to 100 cm/yr under current practices. In the Delta region of Mississippi where nearly 60% of U.S. farm raised catfish are produced, catfish production accounts for about 28% of all water used (Pennington, 2005).

Research to reduce reliance on groundwater in aquaculture has shown remarkable potential reductions in groundwater through use of management strategies to create storage capacity which can capture rainfall to keep ponds filled. For example, studies show the potential to reduce consumption of groundwater in delta catfish ponds by nearly 70% annually through precipitation capture (Pote and Wax, 1993; Pote, et al, 1988; Cathcart et al., 2006). Extension Services in Alabama and Louisiana include variations of those strategies as industry best management practices for reducing groundwater use in those states (Auburn University, 2002; LCES, 2003). In rice production, straight levee systems and use of multiple inlets have been shown to be specific irrigation methods that significantly reduce water use (Smith et al., 2006). Intermittent (wet-dry) irrigation has been shown to reduce water use and non-point source runoff by up to 50% with no yield losses in Mississippi field trials (Massey et al., 2006). Massey (Personal Communication, 2010) states that conserving one inch of pumped groundwater saves producers 0.7 gallons of diesel per acre or 34 kilowatt hours of electricity per acre.

Methods

In order to assess the change in volume of water in the aquifer, it was necessary to collect climatological data, crop coefficient formulas, crop data, and water use data for the growing season. Growing season was defined as May through August. In this study, all but the evaporation data were collected and analyzed for Sunflower County only. It was assumed that climate and cultural land uses (crops, acreages, irrigation methods) in Sunflower County were representative of the entire Delta region. These data were used in a model that was developed to identify and account for relationships between climatological variability and cultural water use. The model is interactive, allowing the user to change input values and alter the final output, thus allowing for specific scenarios to be simulated. Successive alternative combinations of variables were simulated with the model to determine possible methods and strategies to aid in groundwater conservation and management.

Climatological Data

The precipitation record from Moorhead, MS (located centrally in Sunflower County) and the evaporation record from Stoneville, MS were used in the analysis. The data were arrayed in an Excel spreadsheet, and missing data were identified. Gaps in the data were filled with data from the next-nearest climate station location. The result was a serially complete and homogeneous daily record of precipitation and evaporation from 1961-2009. The evaporation data were used to represent potential evaporation (PE), or the demand of the atmosphere for water. To include consideration for the physiological demand of different crops at different phenological stages, the PE was modified by crop coefficients.

Crop coefficient formulas

The SCS (1970) established consumptive crop use coefficient curves for a variety of crops. Ranjha and Ferguson (1982) matched these values with curves of best fit and derived the following equations to calculate a crop coefficient for three crops, using crop age in days from emergence as input:

CC (Soybeans) = $0.21-(2.97)(DAY)10^{-3}+(4.74)(DAY)^2 10^{-4}-(4.03)(DAY)^3 10^{-6}$

CC (Corn) = $0.12+(0.01)(DAY)+(0.18)(DAY)^2 10^{-3}-(2.05)(DAY)^3 10^{-6}$

CC (Cotton)= $0.11-(0.011)(DAY)+(0.55)(DAY)^2 10^{-3}-(3.49)(DAY)^3 10^{-6}$

Crop Data

Crop data for cotton, rice, soybeans, corn, and catfish were collected from the U.S. Department of Agriculture's National Agricultural Statistics Service (NASS). For the five crops, total acres and total irrigated acres were retrieved for the years 2002-2009 (the only years for which water use data were available). The percentages of each type of irrigation or management method used for each of the five crop types in 2006 are shown in Table 1.

Water Use Data

Water use data were supplied by Yazoo-Mississippi Delta Joint Water Management District (YMD) in acre-feet/acre (A-F/A). For 2005 through 2009, these data were divided into the amount of water used by each specific irrigation method for cotton, corn, soybeans, and rice (as determined by a survey of about 140 sites monitored by YMD shown in Figure 4), as well as the total average water use for each of the crops. For 2002-2004, only the total average water use amount for each of the four crops was provided. Therefore, a ratio based on the 2005-2008 specific irrigation methods-to-total average water use from 2002-2004 was formulated to identify relationships between the given average water use and constituent water use amounts associated with each specific irrigation method for each crop for the years 2002-2004 (Merrell, 2008). As an example, Table 2 shows that furrow irrigation water use for cotton in 2007 was 0.53 A-F/A. The total average water use for irrigation in 2007 was 0.50 A-F/A. Furrow water use was then divided by the total average water use (0.53 A-F/A / 0.50 A-F/A) to get the furrow-to-average water use coefficient of 1.06. The same procedure was used for the pivot irrigation method. The ratio was calculated for the years 2005—2008, and the average of those four years is used as the specific irrigation coefficient for cotton in the model.

Catfish water use is dependent upon whether the producer uses the maintain-full (MF) or the drop-add (6/3) management scheme. Only total average water use by catfish ponds was provided by YMD, also in A-F/A, and only for 2004 and 2006. So, the catfish water use model developed by Pote and Wax (1993) was used with the Moorhead climate data to estimate the amounts of water used by each of the management schemes in Sunflower County for the period 1961-2009. A ratio between the total average water use and the water use associated with the two possible management schemes in catfish ponds was developed, similar to the water use amounts determined for the specific irrigation methods of the row crops and rice. As shown in Table 3, an average of the four years for which measurements were available was calculated to obtain the percentage of water use by each of the management schemes.

These water use data for row crops, rice, and aquaculture were combined with acreage data to calculate the total amount of water used for irrigation for each crop in the county in 2006. This analysis provided an evaluation of water use by crop type which was the basis for developing a static model. The static model was used as a standard against which all other scenarios of climatic variability, land use and management changes were compared.

Irrigation demand-water use relationship

Recognizing that the amount of rainfall during a growing season significantly influences the amount of irrigation needed, a method was developed to account for this climatological variability. Total growing season precipitation was initially used, but problems with timing and distribution of rainfall through the growing season led to a weak relationship in some years. It was therefore decided to increase the resolution of the model and therefore refine effective precipitation estimates by examining moisture deficits and surpluses on a daily basis.

In addition to atmospheric demand (evaporation), crop water demand was introduced into the model by use of a crop coefficient relating crop water use to phenological stage. Evaporation data and the crop coefficient combine the climatic demand and crop demand to estimate the total daily demand for water. Irrigation demand is derived for each day by subtracting the calculated daily total demand for water from daily precipitation.

Daily accounting of water demand resulted in the use of only rainfall needed to satisfy each day's specific irrigation demand, discarding the excess rainfall for that day. In reality, the environment does not "restart" each day; that extra moisture would be saved in the soil and applied to the next few days' water need, reducing the irrigation demand over those few days. In order to more accurately model actual field practices, daily irrigation demand values were summed by weeks through the growing season, capturing the "excess" rainfall on any day and thereby reducing the weekly demand for irrigation. The weekly values were then summed to get a total seasonal irrigation demand. This more realistically calculated irrigation demand was regressed against actual seasonal water use, as measured by YMD, to find the relationship to predict actual water that will be used in any year. Calculated seasonal irrigation demand is now used as the climatological variability input to drive the model.

Table 4 shows how growing season calculated irrigation demand was regressed against measured total average water use for cotton, corn, soybeans, and rice for 2002-2009 to develop the function for estimating the amount of water use by crops based on the amount of irrigation demand. Figure 5 shows a comparison of measured water compared to the water use calculated by this method for the row crops and rice for the period 2002-2009. Figure 6 shows an example of calculated irrigation demand for Corn from1961-2009, and compares the calculated demand against the measured irrigation from 2002-2009. Catfish water use was obtained from model-estimates based on daily rainfall rather than total growing season rainfall. In this manner, water use by all five crops was linked to climatic variability each year.

Model development

The purpose of this research is to determine causes of short-term aquifer declines resulting primarily from cultural water uses and climatological processes. The climate data, crop data, water use data, and irrigation demand - water use relationships were used to develop a model that could assess water volume declines in the aquifer over a growing season. Based on crop average water use relationships in effect in Sunflower County in 2006, the model calculated amounts of water taken from the aquifer by each specific irrigation method and management method for each of the five crops. The model then summed the specific water uses for each year, resulting in a total annual reduction in the volume of water in the aquifer.

Using the 2006 Sunflower County land use and crop water use relationships with irrigation demand-water use relationships developed for each crop, calculated irrigation demand from the past 49 years (1961-2009) was used as a variable in the model to estimate the total water use for each year 49 years into the future (2008-2056). The average of the annual recharge volumes measured in the aquifer between 1989-2009 was then used with the modeled water volume declines each year to characterize the cumulative water volume changes over the 49-year period. The model was subsequently used to simulate different scenarios of water use by changing crop acreages or irrigation methods from the static 2006 data, permitting assessment of changes in water volumes over time under different land use and management conditions. Consequently, the model was used to formulate recommendations for monitoring and managing water volume changes in the aquifer.

Results

The model is an interactive Excel spreadsheet consisting of 49 blocks with each block representing one year (Figure 7). Each block is comprised of 13 rows and 15 columns. It is interactive through column 'G' with columns 'H' through 'O' containing formulas based on the information entered in columns 'A' through 'G.' Single or multiple variables can be changed to alter the overall water use amount given in cell 'O13.'

Results of the first 48-year model simulation (2008-2055) using Sunflower County 2006 static cultural water uses for each year (Table 1) with rainfall recorded from 1961-2008 are shown in Figure 8. In this scenario, it can be seen that water volume in the aquifer begins at a little more than negative 200,000 A-F and consistently drops to about negative 600,000 A-F in the first eight years. The drawdown stabilizes and water volume even rises between about 2015-2040, then water volume again drops consistently to about negative 1,600,000 A-F during the period 2041-2055. Subsequent simulations were conducted with alternative scenarios of land uses, irrigation methods, and management strategies employed.

Figure 9 shows the results for that 48-year period when water use practices were changed to reflect the most conservative water use method for each crop: 100% pivot irrigation for cotton; 100% zero grade for rice; 100% pivot for corn; 100% zero grade for soybeans; and 100% 6/3 management strategy for catfish. It can be seen that these changes resulted in consistent recovery of water volume beginning after the first year of these practices, ending in 2055 with a positive volume of around 2,900,000 A-F.

Figure 10 shows the results for that 48-year period when water use practices were changed to reflect the most consumptive water use methods for each crop: for cotton,100% furrow irrigation; corn 100% straight levee; rice 100% contour levee; soybeans 100% pivot; and catfish 100% maintain full. These changes resulted in consistent water volume declines from the beginning of the 48-year period, ending at about negative 4,200,000 A-F in 2055.

Figure 11 shows results of using surface water in lieu of groundwater in combination with the use of the new irrigation demand as the climatological driver for the model for the 49-year period 2008-2056 (and incorporating the wet year 2009). Using surface water for 25% of irrigation demand when growing season rainfall was 30% or more above average resulted in consistent declines in water volume from the beginning of the period until about 2017. During this 10-year period there were no years in which growing season precipitation met the 30% above normal threshold. From about 2017 to 2044 water volumes in the aquifer increased or stayed level, well above what the volume would have been each year if no surface water had been used. Beginning in 2044 another group of years occurred when the precipitation did not meet the 30% threshold and water volumes declined accordingly until the end of the period, but still ended about positive 1,000,000 A-F above the static scenario.

Conclusions

The model is a sensitive tool that is useful for various forms of analysis. Growing season irrigation demand, in place of total growing season rainfall, can be used to more effectively simulate inter-annual climatological variability through time. Crop acreages and irrigation methods, including use of surface water when available, can be used to account for cultural influences on water use through time. This combination of climatological and cultural drivers of groundwater demand can be used in the model to determine best and worst case scenarios in overall groundwater use in the aquifer. Results indicate that the aquifer responds to small changes in water use associated with crop type, irrigation methods, and use of surface water when available. Results also show that the aquifer water volume is apparently very strongly related to changes in water use methods associated with climatological variability.

Figure 12 shows how often precipitation could supply crop water needs for each of the row crops and rice through the 49-year period by comparing calculated irrigation demand and total growing season precipitation. The bars above the mid-line represent years when the climate delivers "extra" water, more than the crops can use. These are years when the extra, or surplus, water could be stored. The bars below the mid-line represent years when rainfall is not sufficient to meet the needs of the crops. In these years, 100% of the water delivered by the climate is used and the crop needs must be supplemented with groundwater irrigation.

The analysis concludes that climate could provide the entire water need of the plants in 70% of the years for corn, 65% of the years for soybeans and cotton, and even 5% of the years for rice. Even though the distribution of the extra water through the growing season may rule out total dependence of producers on this source of water, this analysis does demonstrate that extra water delivered by the climate could be a source of water that could be used often in place of pumped groundwater. Instituting this practice could save energy, save producers money, and enhance the sustainability of the aquifer.

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Table 1: Irrigated acres and type of irrigation or management method used for each crop type in Sunflower County, 2006

Crop	Acres irrigated	% furrow	% straight	% pivot	% contour	% zero grade	% multiple inlet	% MF	% 6/3
cotton	60,300	81		19					
rice	27,600		56		20	12	12		
corn	8,910	100							
soybeans	86,350	49	50	3	6	2			
catfish	24,300							34	66

Table 2. Development of specific irrigation coefficients: cotton example

	Total Avg (A-F/A)	Furrow (A-F/A)	Pivot (A-F/A)	Furrow to Avg	Pivot to Avg
2008	0.60	0.60		1.00	
2007	0.50	0.53	0.40	1.06	0.80
2006	0.84	0.89	0.62	1.06	0.74
2005	0.51	0.55	0.42	1.08	0.82
				1.05	0.79

Table 3. Explanation of catfish management scheme water use

Equation: MFx + 6/3 (1-x) = Total Water Use (A-F/A)

	MF	6/3	Total	X	1-X
2004	3.16	0.53	1.45	0.35	0.65
2006	3.52	1.56	2.4	0.43	0.57
2007	3.65	1.03	1.9	0.33	0.67
2008	3.35	0.79	1.4	0.24	0.76
			Average	0.34	0.66

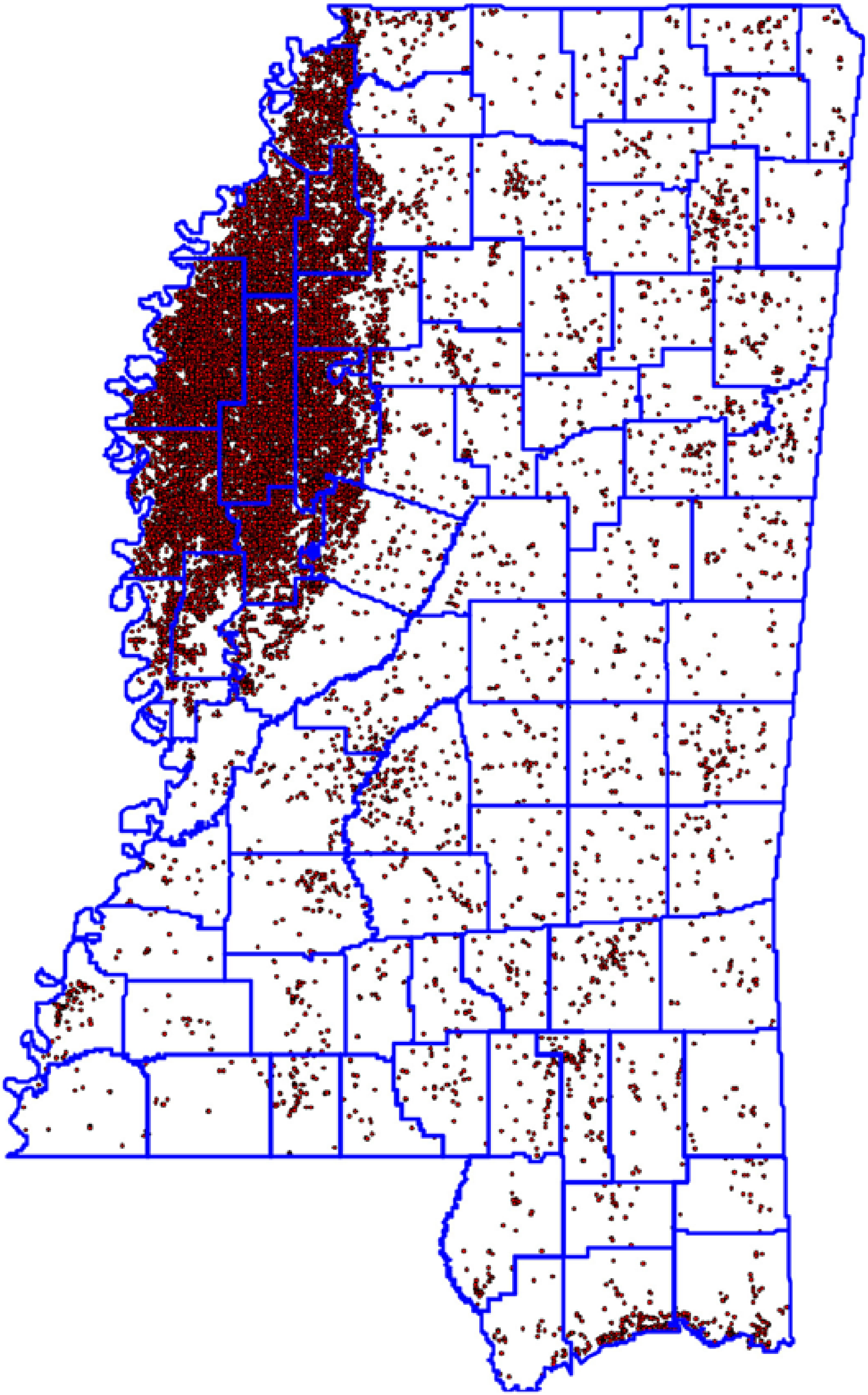

Figure 1. Distribution of permitted wells in Mississippi, 2005.

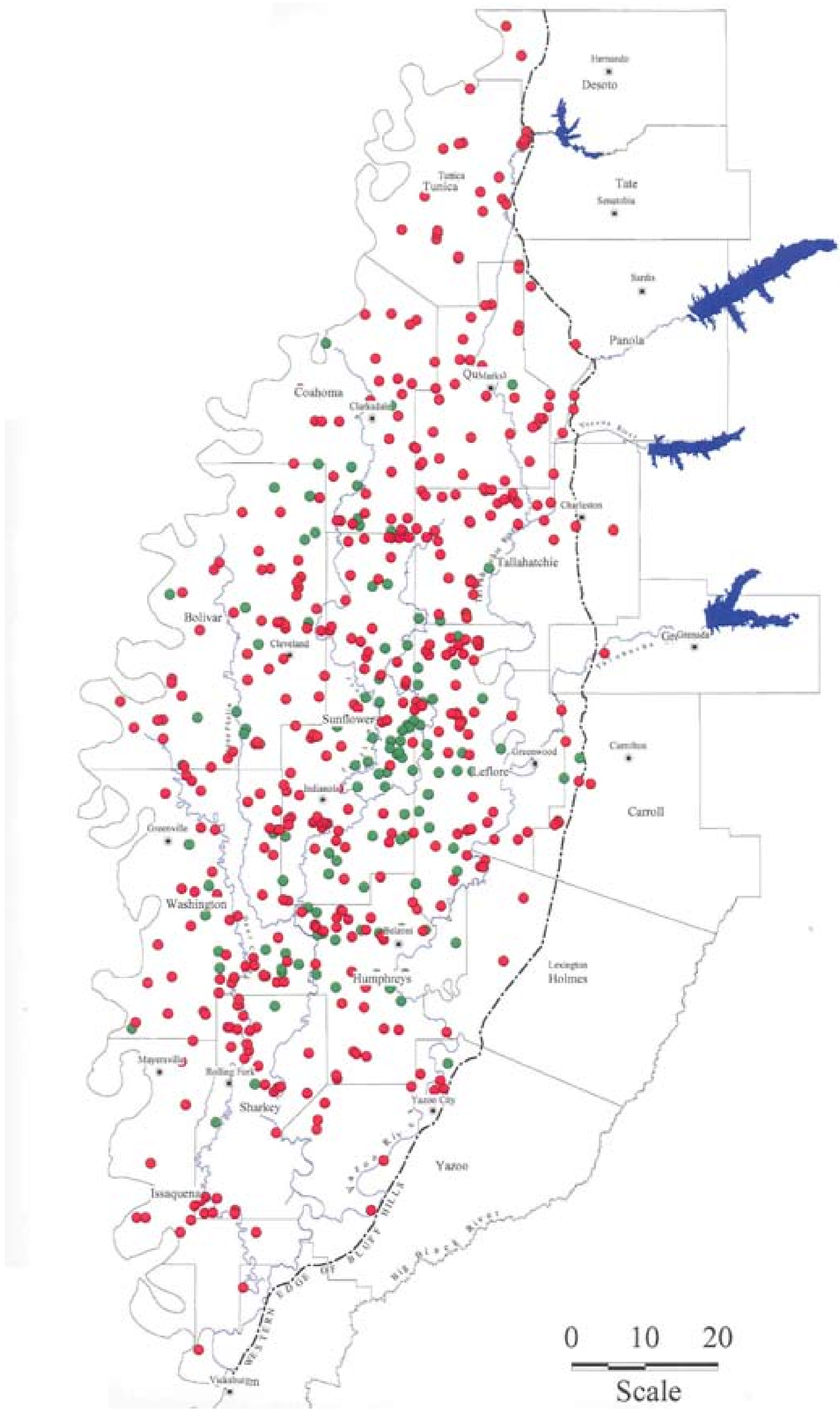

Figure 2: New Permit Requests, 2006.

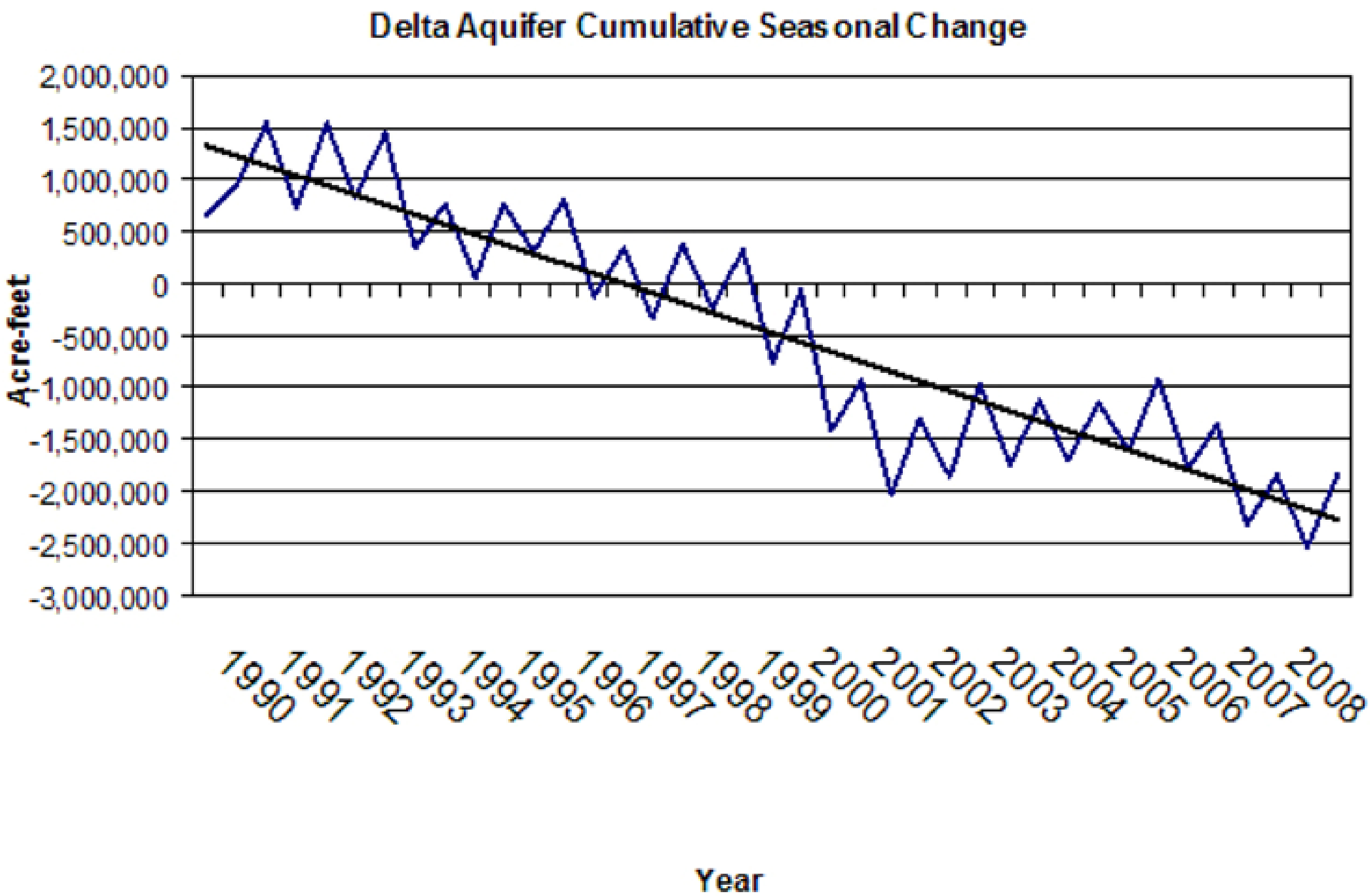

Figure 3: Seasonal Cumulative Aquifer Volume Decline, 1990-2006.

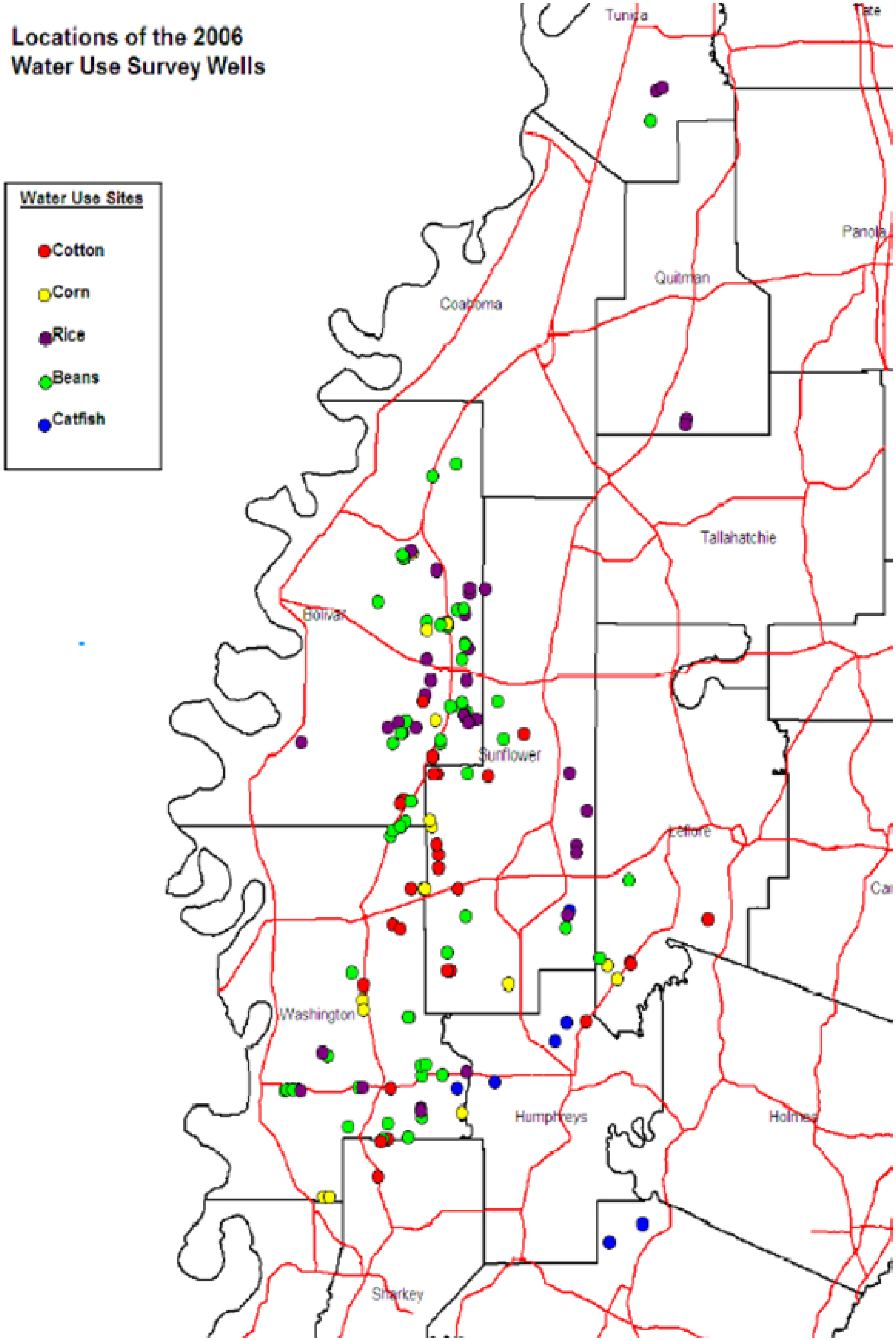

Figure 4: Locations of Water Use Survey Wells, 2006.

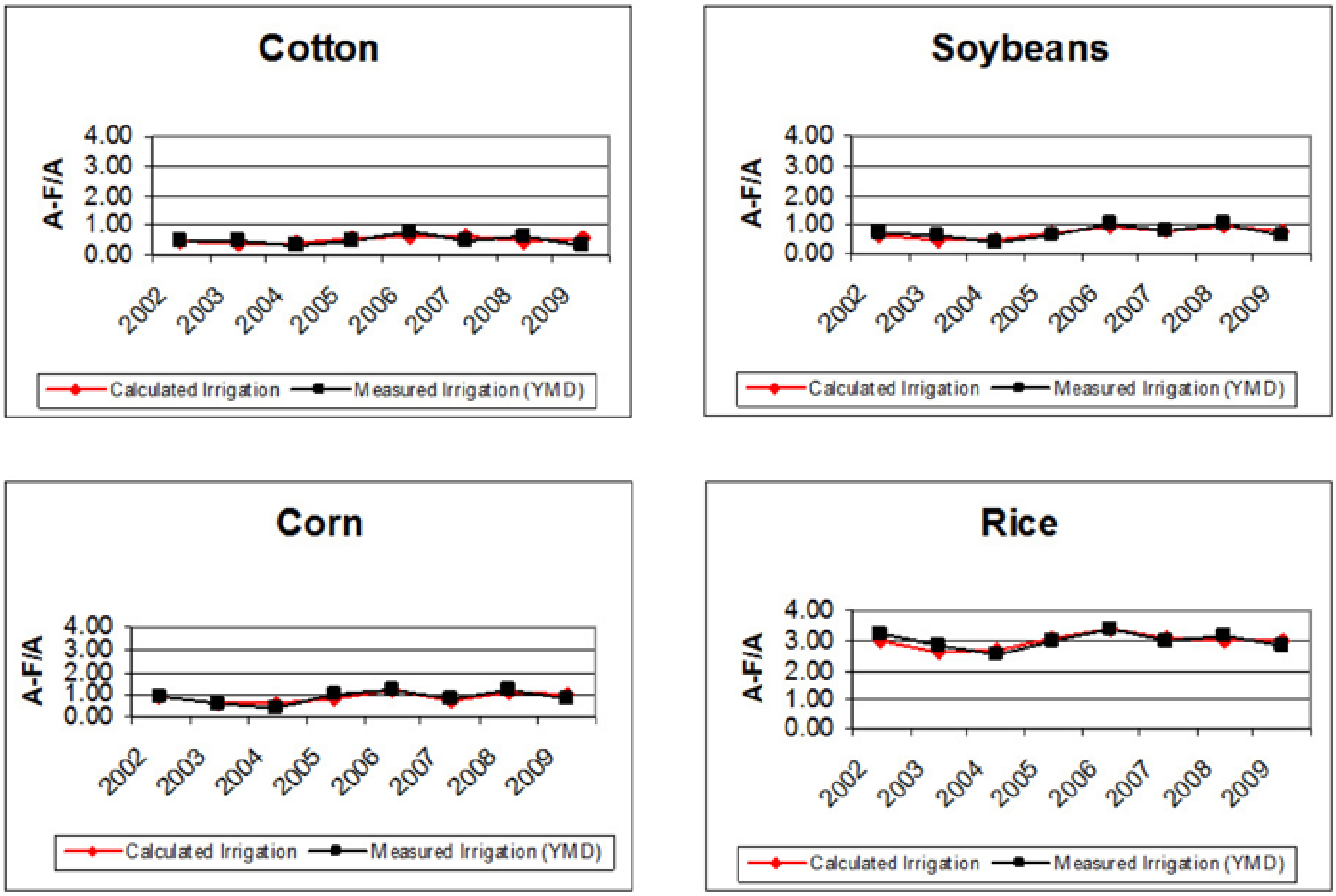

Figure 5. Comparison of calculated and measured water use.

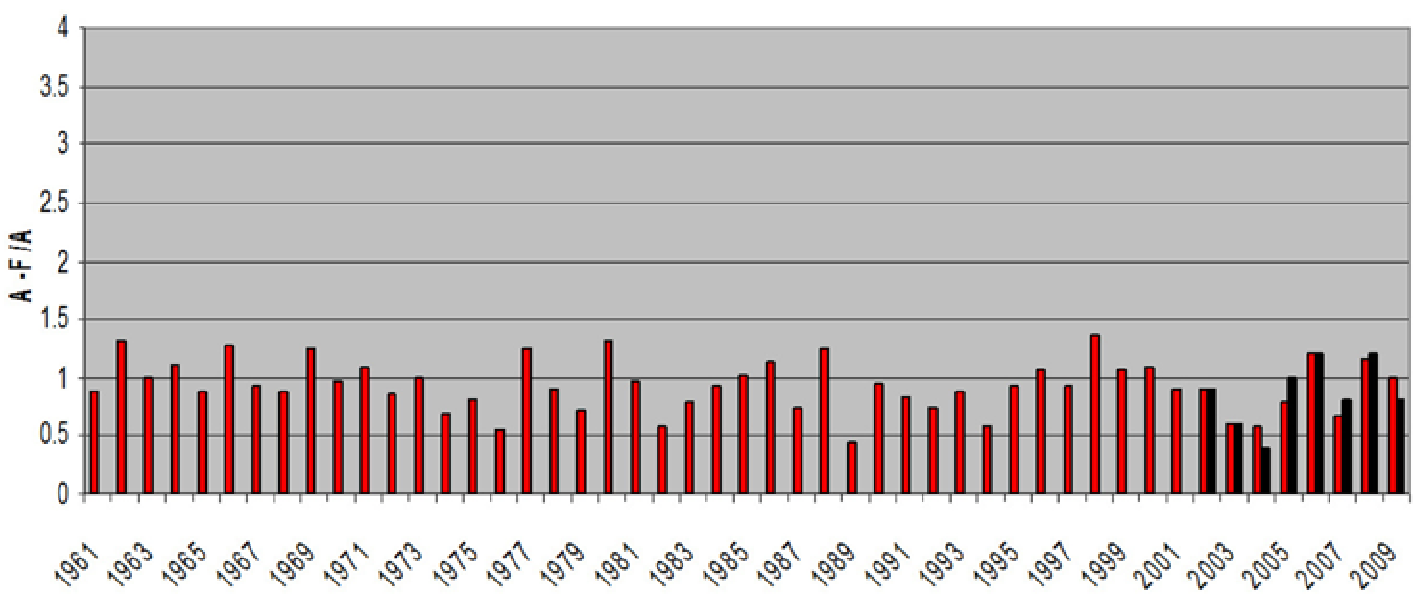

Figure 6: Calculated (1961-2009) vs. Measured (2002-2009) Corn Irrigation (Y=1.180774(x) + 0.001839; R^2=0.77)

	A	B	C	D	E	F	G	H
1	2008/2055							
2	Total Acres							
3	COTTON	% furrow	% pivot				GS Precip	Seasonal ID
4	60300	0.81	0.19				18.69	0.46804775
5	RICE	% contour	% straight	% MI	% ZG			
6	27600	0.2	0.56	0.12	0.12		18.69	2.9971192
7	CORN	% furrow	% pivot	% Str	% ZG			
8	8910	1	0	0	0		18.69	1.16513959
9	SOYBEANS	%furrow	% straight	% pivot	% contour	% ZG		
10	86350	0.49	0.4	0.03	0.06	0.02	18.69	0.92303002
11	CATFISH	% MF	% 6/3					
12	24300	0.34	0.66					

I	J	K	L	M	N	O
Furrow Use	Pivot Use				Water Used	
0.491450139	0.369757724				**28240.21337**	
Con Use	St Use	MI Use	ZG Use			
3.62651423	3.17694635	2.667436086	1.678386751		**83514.60657**	
Furrow Use	Pivot Use	Str Use	ZG Use			
1.24669936	0.582569794	1.38651611	0.827249108		**11108.0913**	
Furrow Use	St Use	Pivot Use	Con Use	ZG Use		
1.043023924	0.803036119	0.904569421	0.83995732	0.526127112	**79472.50179**	
MF Use	6/3 Use					
3.3525	0.785833333				**40301.55**	**242637**

Figure 7: Model illustration using 2008 climatological data to estimate water use in the year 2055.

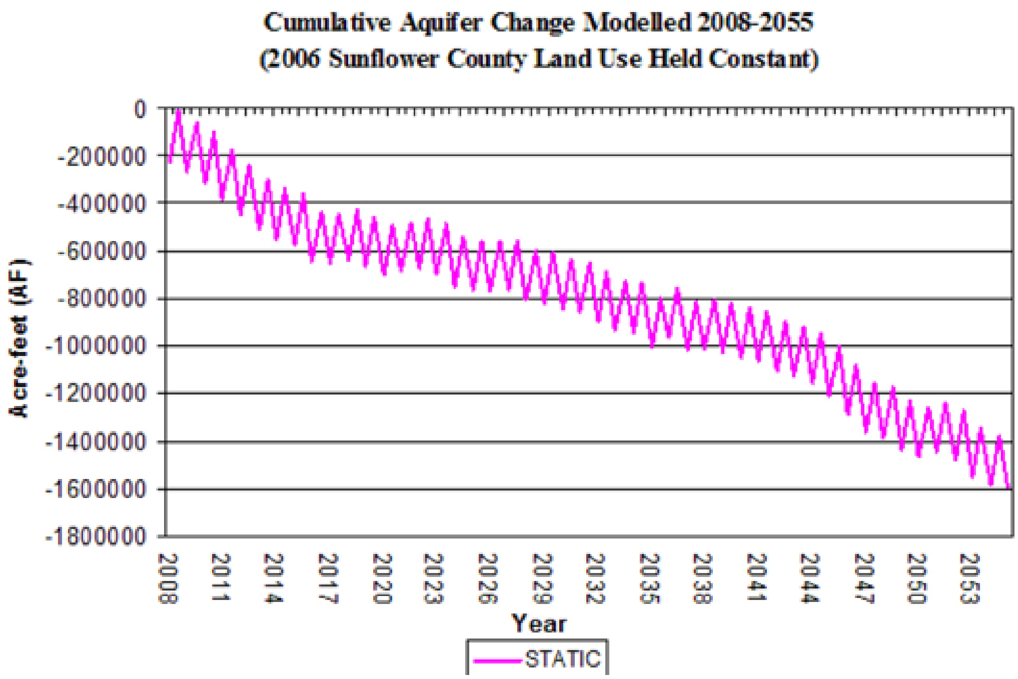

Figure 8: Model Result when land use and irrigation methods are held constant as observed in 2006 in Sunflower County for the 48-year period

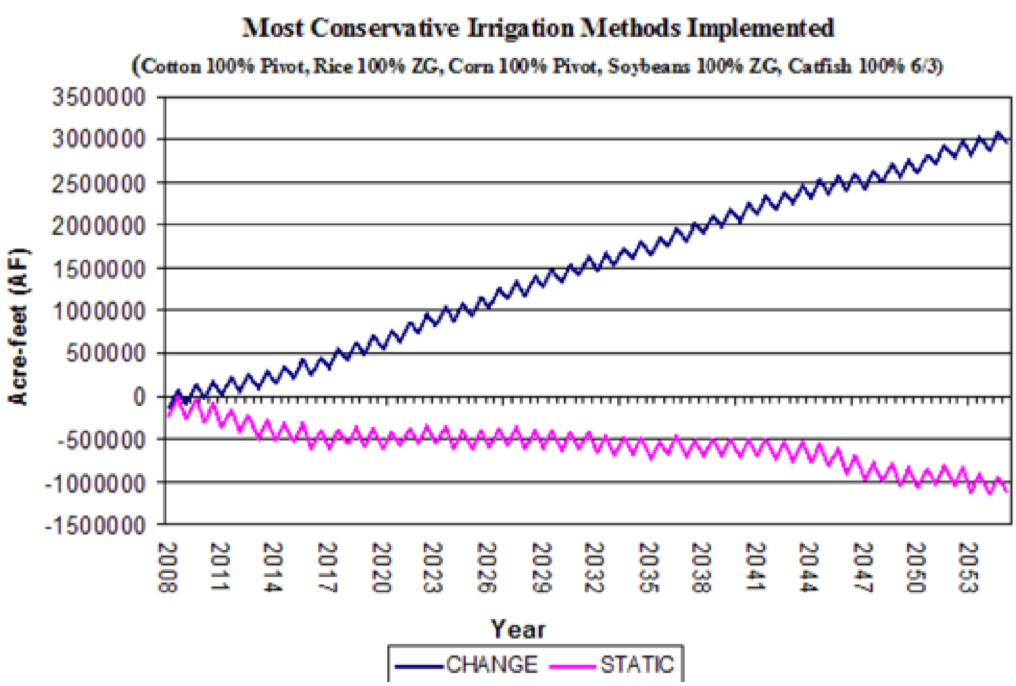

Figure 9: Model results when land use and irrigation methods are changed to reflect adoption of the most conservative irrigation method

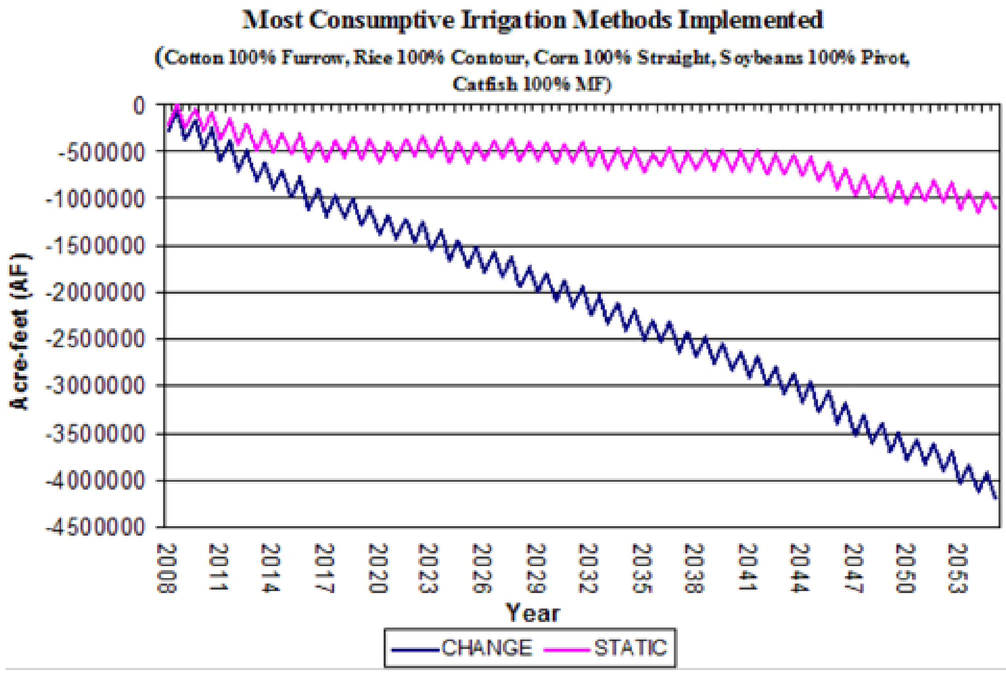

Figure 10: Model results when the most consumptive irrigation methods and management strategies are used.

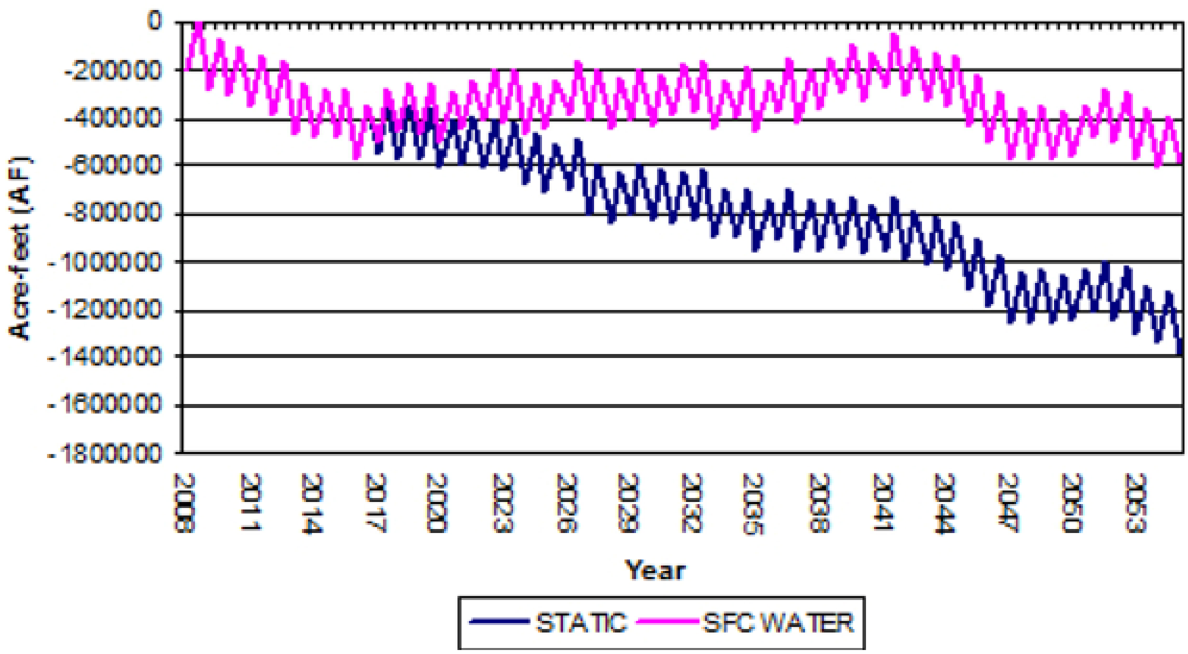

Figure 11: Model results 2008-2056 when surface water irrigation is implemented and irrigation demand is used as the climatological driver.

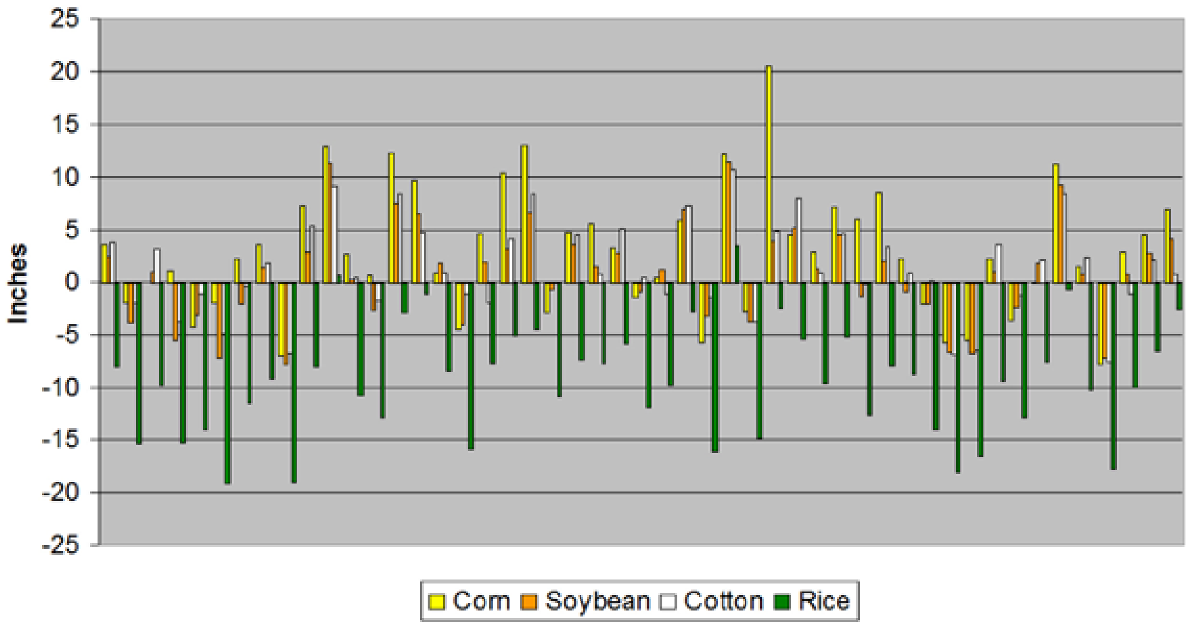

Figure 12: Effective precipitation—years in which climate delivers a surplus or a deficit of precipitation to meet crop water needs.