Climatological and cultural influences on annual groundwater decline in the Mississippi Delta shallow alluvial aquifer

Charles L. Wax, Jonathan W. Pote, Tia L. Merrell
Department of Geosciences, Mississippi State University
wax@geosci.msstate.edu

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. The most recently documented water volume decline in the aquifer is estimated at 500,000 acre-feet. This may represent a worst-case situation in which severe drought combined with consequent increased demand for irrigation. Additionally, the region was impacted by historic drought again during the growing season of 2007, and impacts to the aquifer have not yet been quantified.

Available climate, crop acreage, irrigation water use, and groundwater decline data from Sunflower County was used to represent the climate-groundwater interactions in the Mississippi Delta region. This research resulted in 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 growing season precipitation amounts. This derived relationship allowed the application of a long-term climatological record (45 years) to simulate the cumulative impact of climate on groundwater use for irrigation.

Results indicate that under the present use scenario, groundwater will remain stable in wet to normal precipitation years, but will decline during drought periods and not recover fully. Use of the model to simulate changes in irrigation methods and crop acreages from 2008 through 2053 shows potential to stabilize the water volume in the aquifer through implementation of various management strategies. The model appears to be a tool that can be used to assess the impact of climatic variability and changes in the cultural practices on groundwater use in the region—a tool that will be useful in making management decisions that will allow sustainable use of the groundwater resource.

Keywords: 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). Additionally, the region was impacted by historic drought again during the growing season of 2007, and impacts to the aquifer have not yet been quantified.

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.

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).

Methods

In order to assess the change in volume of water in the aquifer, it was necessary to collect climatological data, crop data, and water use data. In this study, these 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 climate record from Moorhead, MS (located centrally in Sunflower County) was used in the analysis. Specifically, daily precipitation data from the U.S. Historical Climatology Network were acquired and inspected for completeness. 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 from 1949-2006. The precipitation data were then organized into growing season totals for each year. Growing season was defined as May through September.

Crop data

Crop data for cotton, rice, soybeans, and catfish were collected from the U.S. Department of Agriculture's National Agricultural Statistics Service (NASS). For the four crops, total acres and total irrigated acres were retrieved for the years 2002-2006 (the only years for which water use data were available). Similar data for corn, which was not reported in NASS, were obtained through personal communication with the county agent for Sunflower County. 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 and 2006, 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 141 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 2005-2006 specific irrigation methods-to-total average water use was formulated to identify relationships between the given average water use and constituent water use amounts associated with each specific irrigation method for the years 2002-2004.

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 1960-2006. Then 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.

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 a prototype evaluation of water use by crop type.

Rainfall-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. Growing season rainfall was regressed against the total average water use for cotton, corn, soybeans, and rice for 2002-2006 to develop a function for estimating the amount of water use by crops based on the amount of rain received. 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 rainfall-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 rainfall-water use relationships developed for each crop, growing season precipitation from the past 45 years (1961-2006) was used as a variable in the model to estimate the total water use for each year 45 years into the future (2008-2053). The average of the annual recharge volumes measured in the aquifer between1989-2006 was then used with the modeled water volume declines each year to characterize the cumulative water volume changes over the 45-year period. Then the model was 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 45 blocks with each block representing one year (Figure 5). 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 45-year model simulation (2008-2053) using Sunflower County 2006 static cultural water uses (Table 1) for each year with rainfall recorded from 1961-2006 are shown in Figure 6. In this scenario, it can be seen that water volume in the aquifer begins at about -300,000 A-F and consistently drops to about -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 -1,000,000 A-F during the period 2041-2053. Subsequent simulations were conducted with alternative scenarios of land uses, irrigation methods, and management strategies employed.

Figure 7 shows the results when water use practices were changed to reflect more conservative water use methods for each crop: 100% pivot irrigation for cotton; 100% multiple inlet for rice; 40% straight, 3% pivot, 55% contour, and 2% zero grade for soybeans; and 25% MF, 75% 6/3 management strategy for catfish. The acreage planted in corn was also doubled for this model simulation. It can be seen that these changes resulted in consistent recovery of water volume beginning in about 2016, ending in 2053 with a positive volume of around 600,000 A-F.

Figure 8 shows the results when water use practices were changed to reflect the least conservative water use methods for each crop: cotton and corn 100% furrow irrigation; rice 100% contour; soybeans 100% pivot; and catfish 100% maintain full. These changes resulted in consistent water volume declines from the beginning of the 45-year period, ending at about -4,000,000,000 A-F in 2053.

Conclusions

The model is a sensitive tool that is useful for various forms of analysis. Growing season precipitation can be used to simulate interannual climatological variability through time. Crop acreages and irrigation methods 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 methods, and that the aquifer water volume is apparently very strongly related to changes in water use methods associated with climatological variability.

References

Auburn University, 2002. Auburn University and USDA/ Natural Resources Conservation Service, Managing Ponds to reduce Effluent Volume, BMP No. 21. (http://efotg.nrcs.usda.gov.references/public/AL/ G02ReduceEffluent.pdf)

Cathcart, T.P., C.L. Wax, J.W. Pote and Sugeng Triyono, 2007. "A Climatological Basis for Conserving Groundwater and Reducing Overflow in Aquaculture Ponds in the Southeast United States." Aquacultural Engineering, 36(2007)225-232.

LCES, 2003. "Aquacultural Production Best Management Practices (BMPs)", Pub. 2894 4/03 (Online only). Louisiana Cooperative Extension Service, Baton Rouge, LA.(http://www.agctr.lsu.edu/NR/rdonlyres/4005CC33-BF01-4FAB-8EA3-E2D9ABCE038C/2616/pub2894aquaBMP6.pdf)

Massey, J.H., M.C. Smith, A. Johnson, J.Thomas, P.L.Tacker, E.D.Vories, S. Lancaster, A.A.Andrews, and P.Ampim, 2006. Multiple-Inlet plus Intermittent Rice Irrigation Increases Rainfall Capture and Reduces Non-Point Source Runoff. Proceedings, 31st Rice Technical Working Group Meeting. The Woodlands, TX.

Pennington, Dean, 2005. 2005 Annual Report, Yazoo Mississippi Delta Joint Water Management District, Stoneville, MS 38766.

Pennington, Dean, 2006. Executive Director, Yazoo Mississippi Delta Joint Water Management District. Personal communication, October 31, 2006.

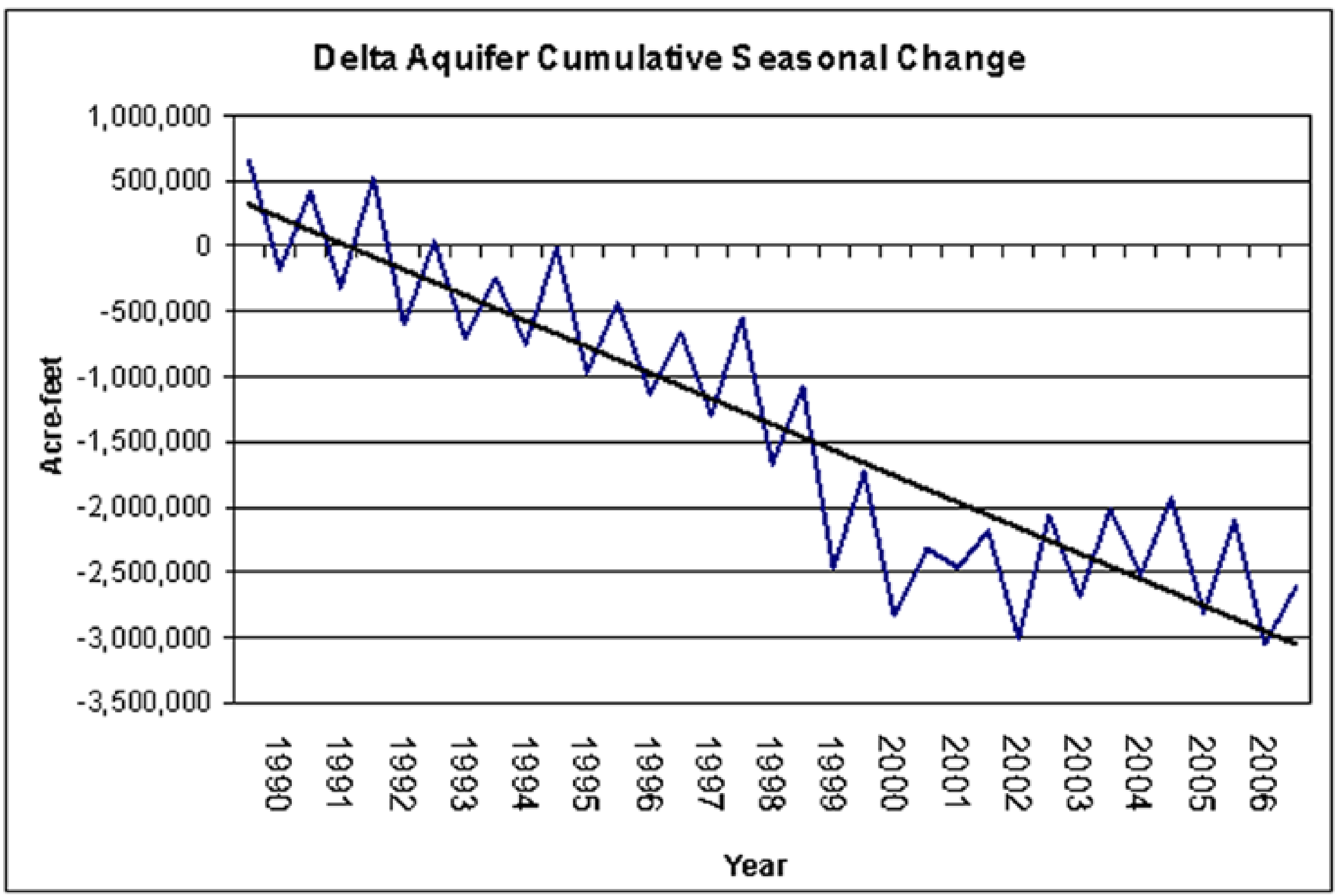
Pote, J.W., C.L. Wax and C.S. Tucker, 1988. Water in Catfish Production: Sources, Uses, and Conservations. Special Bulletin 88-3, November 1988, Mississippi Agricultural and Forestry Experiment Station, Mississippi State, MS.

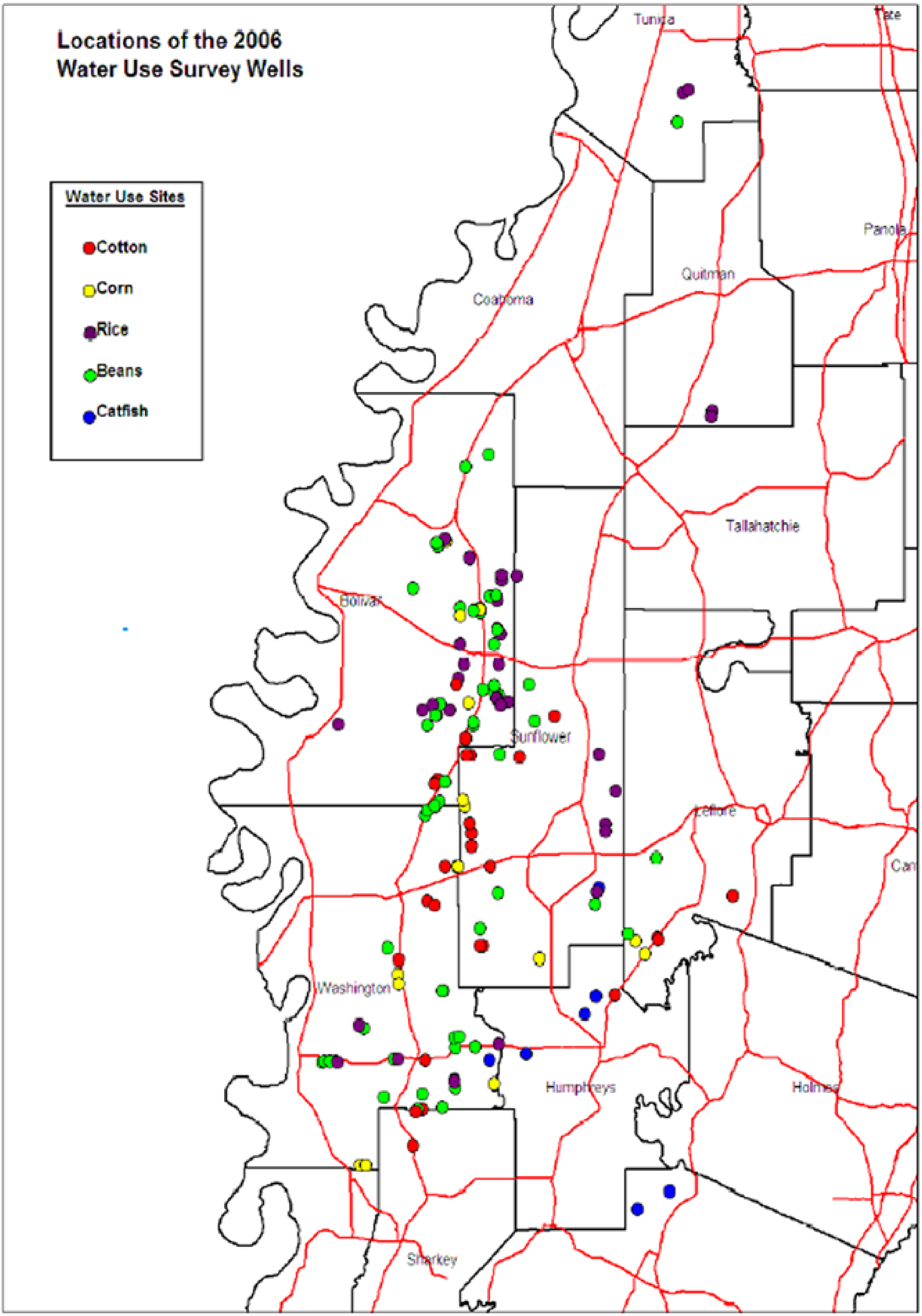
Pote, J.W. and C.L. Wax, 1993. "Modeling the Climatological Potential for Water Conservation in Aquaculture." Transactions of the American Society of Agricultural Engineers, Volume 36 (5), 1343-1348.

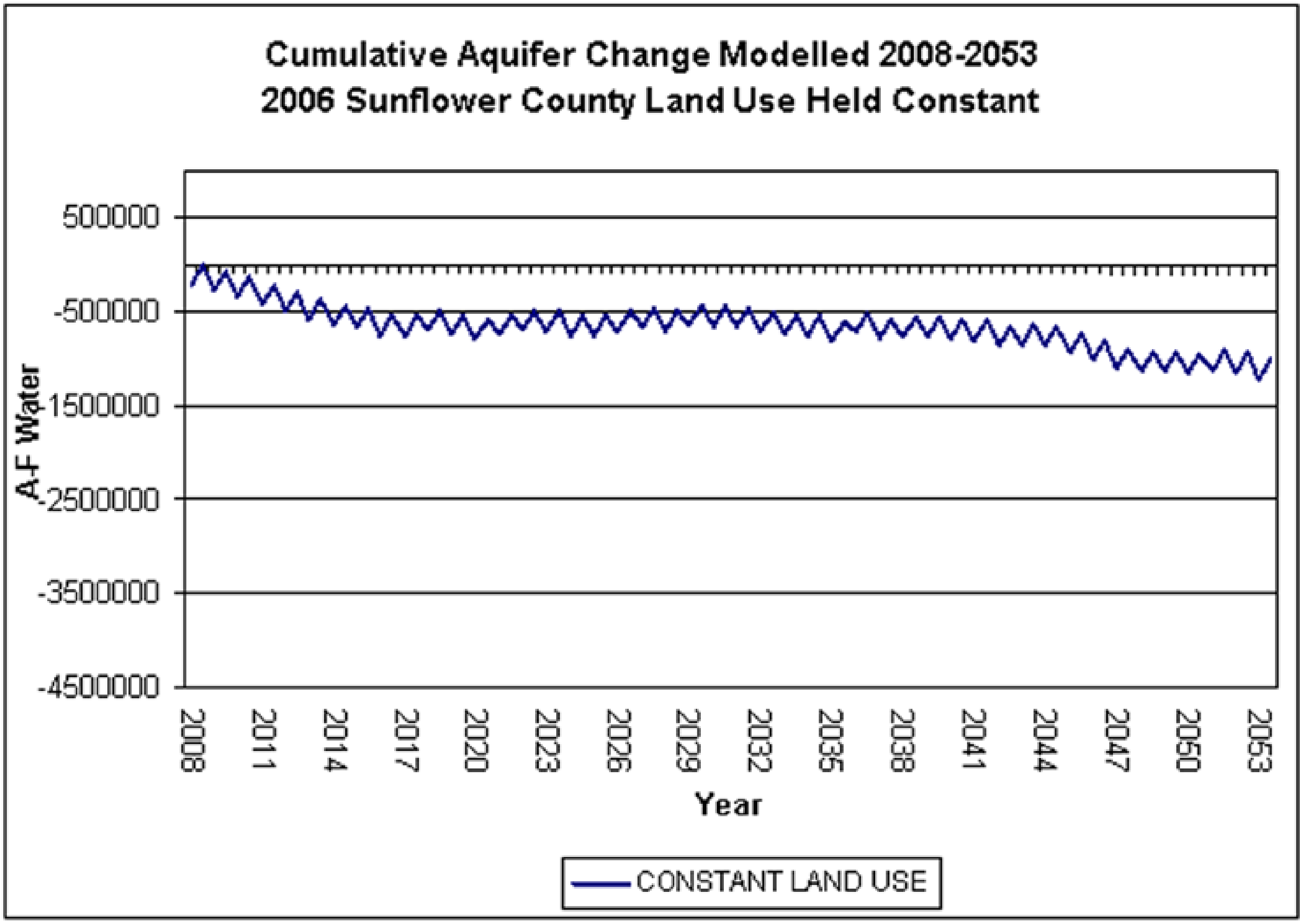
Smith, M.C., J. H. Massey, P. Tacker, E. Vories, D. Pennington, J. Epting, and C.Wilson, 2006. Water use estimates for various rice production systems in Mississippi and Arkansas. Irrigation Science (DOI 10.1007/s00271-006-0041-0; pgs. 1-7).

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

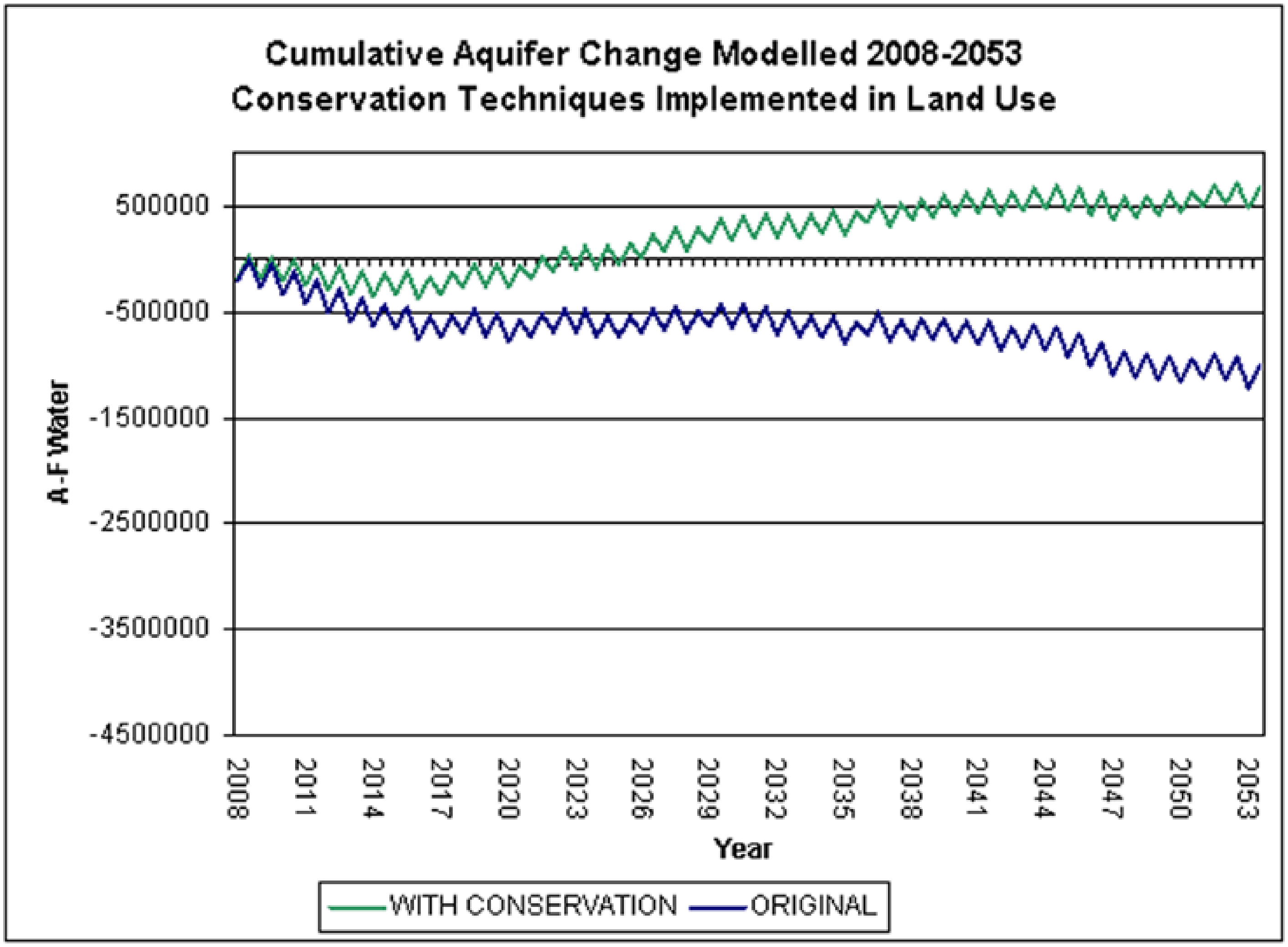
Crop	Acres irrigated	% furrow	% straight	% pivot	% contour	% zero grade	% multiple inlet	% MF	% 6/3
cotton	60,300	81		19					
rice	27,600		56		20	12	12		
corn	8,910	100							
soybeans	86,350	49	50	3	6	2			
catfish	24,300							42	58

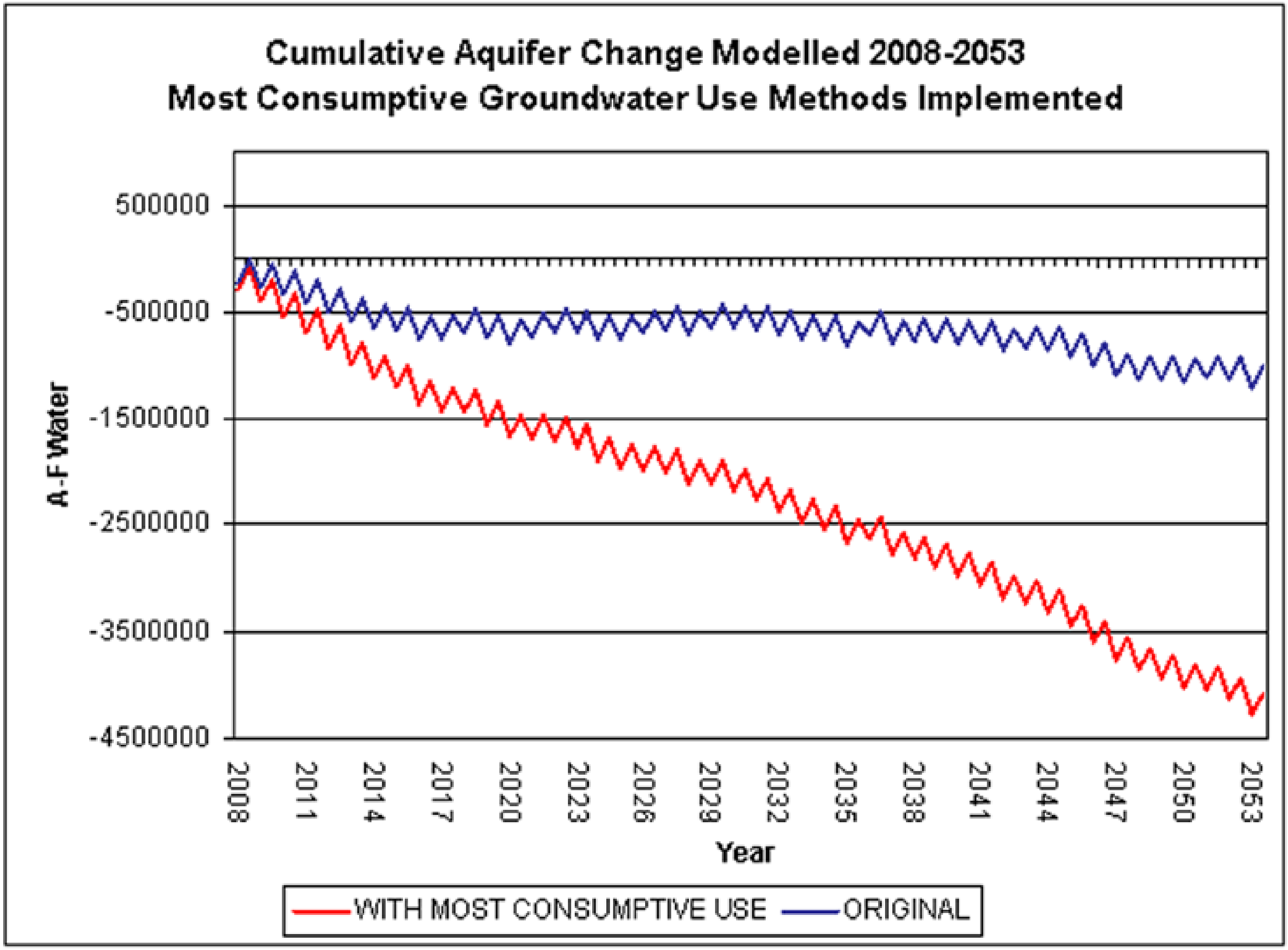



Locations of the 2006
Water Use Survey Wells
Water Use Sites
Cotton
Corn
Rice
Beans
Catfish
Tunica
Panola
Quitman
Coahoma
Tallahatchie
Bolivar
Sunflower
Leflore
Washington
Humphreys
Holmes
Sharkey



Cumulative Aquifer Change Modelled 2008-2053
2006 Sunflower County Land Use Held Constant
500000
-500000
-1500000
-2500000
-3500000
-4500000
A-F Water
2008
2011
2014
2017
2020
2023
2026
2029
2032
2035
2038
2041
2044
2047
2050
2053
Year
CONSTANT LAND USE


Cumulative Aquifer Change Modelled 2008-2053
Conservation Techniques Implemented in Land Use
A-F Water
500000
-500000
-1500000
-2500000
-3500000
-4500000
2008
2011
2014
2017
2020
2023
2026
2029
2032
2035
2038
2041
2044
2047
2050
2053
Year
WITH CONSERVATION
ORIGINAL


Cumulative Aquifer Change Modelled 2008-2053
Most Consumptive Groundwater Use Methods Implemented
A.-F Water
500000
-500000
-1500000
-2500000
-3500000
-4500000
2008
2011
2014
2017
2020
2023
2026
2029
2032
2035
2038
2041
2044
2047
2050
2053
Year
WITH MOST CONSUMPTIVE USE
ORIGINAL