Modeling the Potential for Replacing Groundwater with Surface Water for Irrigation by Using On-Farm Storage Reservoirs in the Mississippi Delta

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A groundwater conservation strategy is proposed in this research, the use of surface water in lieu of groundwater for irrigation. Previous research shows the effectiveness of using stream water in lieu of groundwater on fields located within one-quarter mile of a stream, and the effectiveness of capturing rainfall in catfish ponds. This research proposes another form of surface water capture -- that of on-farm storage reservoirs, which may be as simple as large ditches which will serve to capture precipitation and tailwater.

A model was developed for optimizing the size of on-site water retention structures (ditches) to capture rainfall on agricultural fields in the Mississippi Delta. The climatological driver for the model is precipitation minus 0.8 pan evaporation, which is then adjusted by a crop coefficient to produce an irrigation demand value based on the age of the crop. The model uses long-term weather records (50 years of daily data) to estimate daily values of these climatological inputs, which are then summed to weeks through the year. Total field irrigation demand, ditch demand, ditch volume, overflow, and ground water used are outputs of the model, calculated according to specified field size and ditch volume. The percentage of required irrigation demand that is met by rain stored in the ditch is calculated weekly for the entire growing season.

Field acreage, runoff coefficient, ditch acreage, and ditch depth are interactive inputs in the model. Outputs of the model recalculate as inputs are changed. Optimization is achieved when groundwater use is minimized, annual overflow is minimized, and the smallest possible amount of the field is used for the ditch. Previous research assessed the impact of crop type and irrigation system on aquifer volume and showed that the aquifer could be reduced in volume by as much as 1,500,000 A-F over the next 50 years under current practices. This study shows that if only 10% of Delta producers adopted the 95:5 ratio on-farm surface water storage scheme for irrigation, that decline in volume in the aquifer could be reduced to 100,000 A-F over the same time period. If 15% of producers adopted the scheme, the aquifer could become stable in about seven years, and totally sustainable in about 25 years.

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 Mississippi River Valley Shallow Alluvial Aquifer (MRVA) 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 urgent nature of this water problem, it is estimated that about 35,000 new acres are currently being brought into irrigated production each year (Pennington, 2011).

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 such as changing irrigation methods and using precipitation and other surface water sources as substitutes for aquifer withdrawals, thereby reducing 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 augment an existing climatological model to assess the effectiveness of capturing precipitation in on-farm storage structures to use in place of groundwater for irrigation, and thereby conserve groundwater. This is the fourth phase of an on-going project to identify and recommend management strategies to curtail the drawdown in the MRVA and make the resource more sustainable. 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 and a field was within a quarter-mile buffer around a stream. In the 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 (Wax, et al, 2010). 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. As stated above, phase four introduces the potential of using on-farm structures (ditches, reservoirs) built specifically to capture rainfall and irrigation tailwater for use in lieu of groundwater for irrigation.

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, 2007). 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

For phases one, two, and three of the research, climatological data, crop coefficient formulas, crop data, and water use data for the growing season were collected. Growing season was defined as May through August. In this study, all but the evaporation data were collected and analyzed for Sunflower County, MS. 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 (Wax, et al, 2010).

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 1961-2010. 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:

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

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

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

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).

Water Use Data

Field crop water use data were supplied by Yazoo-Mississippi Delta Joint Water Management District (YMD) in acre-feet/acre (A-F/A). For 2002 through 2009, these data were divided into the amount of water used by each specific irrigation method for cotton, corn, soybeans, and rice as well as the total average water use for each of the crops. Locations of the survey wells are shown in Figure 4.

Catfish water use is dependent upon whether the producer uses the maintain-full (MF) or the dropadd (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 1961-2010.

These water use data for row crops, rice, and aquaculture were combined with acreage data to calculate the total amount of water used by each crop in the county in 2006. This evaluation of water use by crop type was the basis for developing an initial model used to establish a benchmark of MRVA volume changes into the future if nothing changed from the 2006 conditions. This benchmark was used as a standard against which all other MRVA volume change scenarios resulting from climatic variability, land use, and management changes were compared. Figure 5 is a conceptual flow chart of the model.

Initial MRVA drawdown model

Calculated irrigation demand (precipitation minus 0.8*pan evaporation) from the past 50 years (1961-2010) was used as a variable in the model to estimate the total water use for each year 50 years into the future (2008-2057). The average of the annual recharge volumes measured in the aquifer between1989-2010 was then used with the modeled water volume declines each year to characterize the cumulative water volume changes each year over the 50-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.

Figure 6 shows the static model drawdown curve 50 years into the future. Figures 7 and 8 show how the static model situation changes into the future with adoption of the best (most conservative) and worst (most consumptive) irrigation methods. Figure 9 shows how the addition of surface water when available from streams within one-eighth of a mile of fields reduces groundwater use for irrigation

Atmospheric and plant water demand

In addition to atmospheric demand (evaporation), plant 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 plant demand to estimate the total daily crop demand for water. Irrigation demand is derived for each day by subtracting the calculated daily total demand for water from daily precipitation. In this manner, water use by all five crops was linked to climatic variability each year. Figure 10 shows an example of calculated irrigation demand for Corn from 1961-2009, and compares the calculated demand against the measured irrigation from 2002-2009. Weekly irrigation demand was compared to weekly precipitation to determine how much of the water demand could be supplied by precipitation if it fell at the right time (effective precipitation).

Figure 11 conveys the concept of effective precipitation. This analysis shows that climate could provide the entire water need of the plants in 70-percent of the years for corn, 65-percent of the years for soybeans and cotton, and even 5-percent 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. This is the impetus for the analyses in Phase IV.

On-farm storage analysis (phase IV)

Storing precipitation in on-farm structures can be an effective way to reduce reliance of Delta producers on groundwater. As pointed out above, the climate delivers a surplus of water to the region in many years. An on-farm water storage management scheme could also capture over-pumped irrigation water (tailwater) for re-use, further maximizing efficiency of irrigation by curtailing waste from runoff of that water.

An added benefit of this management practice would also be the reduction of nutrient runoff from fields. Combined annual mean streamflow for the Mississippi and Atchafalaya Rivers represents about 80-percent of the estimated freshwater discharge to the Gulf, and the Mississippi River combined with the Atchafalaya River contributes over 85% of the total nutrient load to the Gulf of Mexico (Dunn, 1996). The hypoxic zone in the Gulf covered about 8,000 square miles in 2010 (USGS, 2010). That same year the Natural Resources Conservation Service launched the Mississippi River Basin Healthy Watersheds Initiative, and this research fits directly into the mission of that program to reduce nutrient runoff into the Gulf. Therefore, developing a method to optimize on-farm storage of surface water could be beneficial to conservation of both water quantity and water quality.

A farm storage reservoir model was developed to quantify the effectiveness and usefulness of this management strategy and addresses two large obstructions to sustainability of agricultural production in the Delta – declining groundwater volume in the MRVA and nutrient loads added to the Mississippi river and the Gulf of Mexico. Optimization of the management scheme requires quantification of the best ratio between field size and water containment structure size. Containment structures in this research are considered to be man-made features as simple as a ditch at the lowest point in a field or as sophisticated as a reservoir in a totally land-leveled area with underground drainage structures and pumps to collect precipitation and distribute it to the storage structure.

The Natural Resources Conservation Service (NRCS) of the USDA is already supporting the idea of on-farm storage for irrigation use. Several prototype facilities are already constructed in the Delta, but their effectiveness has not yet been proven because they have not been used through a growing season. Figure 12 shows a ditch near the border of Bolivar and Sunflower Counties designed to hold 12 acre-feet of water when full. The water is then in turn pumped into an adjacent reservoir designed to hold 93 acre-feet of water. The ditch is 12 feet wide, six-feet deep and 3,720 feet long. Construction of the ditch alone required excavation of 21,700 yard3 of earth. The reservoir is 10 acres in area and nine-feet deep. It required excavation of 43,000 yard3.

Farm storage reservoir model

The farm storage model is interactive and is set up in an Excel spreadsheet (Figures 13 and 14). The initial data set for the model includes Precipitation minus 0.8*Evaporation. This is adjusted by a crop coefficient to produce an Irrigation Demand value based on the age of the crop. Precipitation - Evaporation and Irrigation Demand are both summed by weeks and used as inputs. The values are in acre-feet. Analyses are conducted for each of the row crops and rice.

Model Specifics

The model begins on day one of week one of the growing season. The six elements accounted for in the model include 1) mass water balance (precipitation and evapotranspiration), 2) field demand (includes crop irrigation demand during growing season and evaporation in other parts of year), 3) ditch demand (includes evaporation the whole year), 4) ditch volume (precipitation-evaporation, runoff and pumping out) 5) overflow from the ditch, and 6) groundwater used.

Model Output

Ground water use, total field irrigation demand, annual overflow, and growing season overflow are summed seasonally in the model. The seasonal values are used to optimize the model to find the most efficient scenario -- one in which the ratio between the size of the ditch and the field provides the best combination of maximum surface water supply and minimal crop acreage reduction.

The interactive part of the model has four inputs: 1) field acreage, 2) runoff coefficient, 3) ditch acreage, and 4) ditch depth. The inputs are referenced to cells within the model calculation sheet which recalculates as inputs are changed (see Figures 13 and 14). This allows the model output to be easily optimized while instantly viewing the results in the form of charts. The model identifies optimal parameters of field and ditch size in which groundwater use is minimized, annual overflow is minimized, and the smallest amount of the field is used for the ditch.

Irrigation Ratios

The model is a tool that can be used to evaluate field to reservoir/ditch ratios in order to optimize production in various crops. Two ratios were examined in this study for corn, cotton, and soybeans. They include the 95:5 and the 97.5:2.5. The first ratio is 95 acres of production to 5 acres of reservoir/ditch. The second is 97.5 acres of production and 2.5 acres of reservoir/ditch.

Results

Analyses show that if 100-percent of producers adopted the 95:5 ratio, the aquifer would rebound by 8,794,259 A-F at the end of the 50-year period as compared to the static model (Table 1). Under the 97.5:2.5 ratio, if 100-percent of the producers used the plan, the aquifer would increase by 7,070,346 A-F at the end of the 50-year period compared to the static model (Table2).

Realizing that 100-percent producer participation is unlikely, various adoption rates were examined to see how the aquifer would respond through time. Figures 15 and 16 show the 95:5 and 97.5 ratios with various adoption rates. In Figure 15, for the 95:5 ratio, it can be seen that if just 15-percent of producers adopted the practice, the aquifer would stabilize and begin showing artesian flow in about 30 years. After experiencing some dry years the water table drops below the top of the aquifer and artesian flow ceases in about 2047 before returning again thereafter. In Figure 16, for the 97.5:2.5 ratio, it is seen that if just 15-percent of producers adopt the management strategy, the aquifer at least stabilizes in a few years. However, if 25-percent of producers adopt the 97.5:2.5 ratio, the aquifer would show artesian flow in about 14 years and continue to stay full thereafter.

Conclusions

The analyses show that climate could provide the entire water need of the plants in 70-percent of the years for corn, 65-percent of the years for soybeans and cotton, and even 5-percent of the years for rice. This shows that precipitation capture could be a viable solution to reducing groundwater use for irrigation. An on-farm water storage management scheme can also capture over-pumped irrigation water (tailwater) for re-use, further maximizing efficiency of irrigation by curtailing waste from runoff of that water.

If producers adopted, at a minimum, the 97.5:2.5 ratio management practice, this minimal management strategy could potentially conserve 48-percent, 35-percent and 42-percent of groundwater for cotton, corn and soybeans, respectively. Even in extreme drought years such as 2007, cotton corn and soybeans produced under the 97.5:2.5 management strategy could conserve 32-percent, 46-percent and 38-percent of groundwater, respectively.

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Table 1. Aquifer volume change over 50 years with various adoption percentages, 95:5 plan (A-F)

Static	100%	25%	15%	10%
-1,150,385	+8,794,259	+1,335,775	+341,311	-155,920

Table 2. Aquifer volume change over 50 years with various adoption percentages, 97.5:2.5 plan (A-F)

Static	100%	25%	15%	10%
-1,150,385	+7,070,346	+904,797	+82,724	-328,311

Figure 1. Distribution of permitted wells in Mississippi, 2005

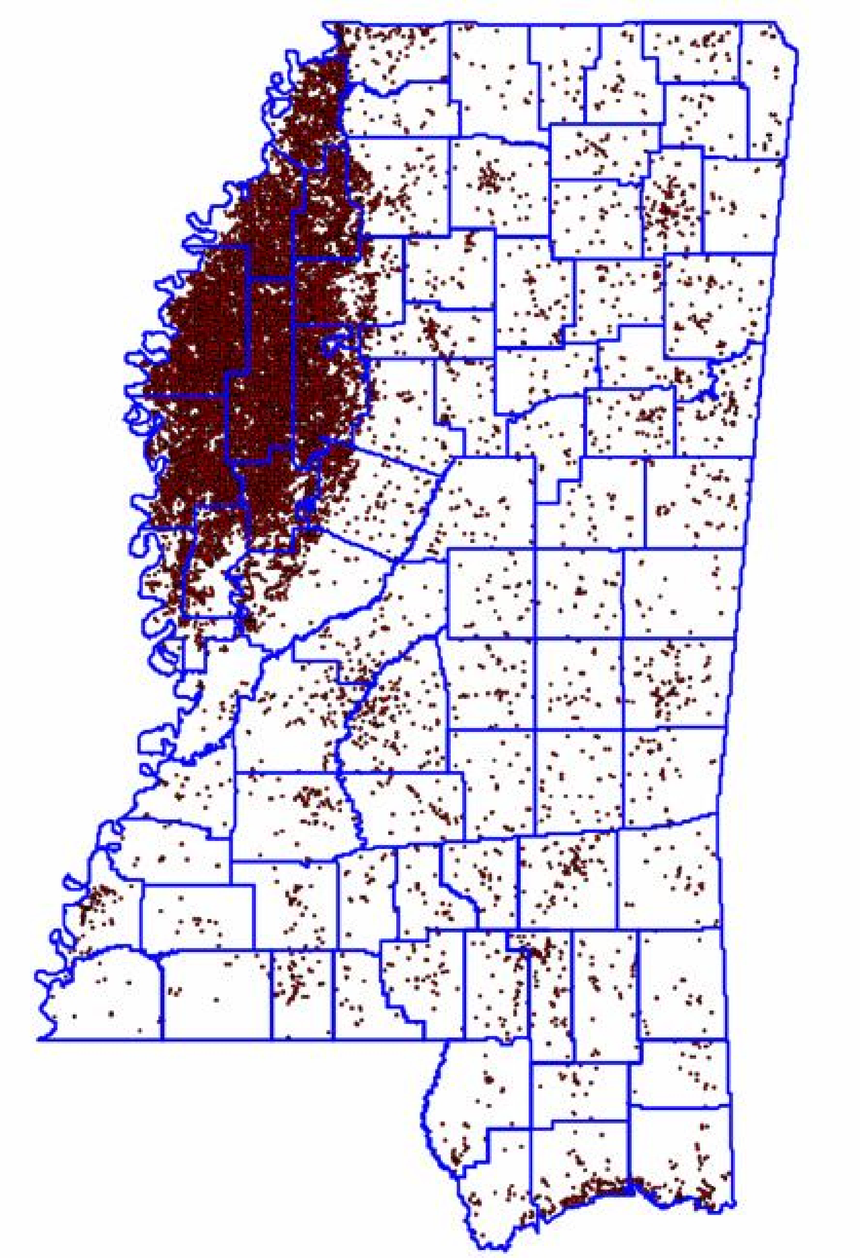


Figure 2: New Permit Requests, 2006

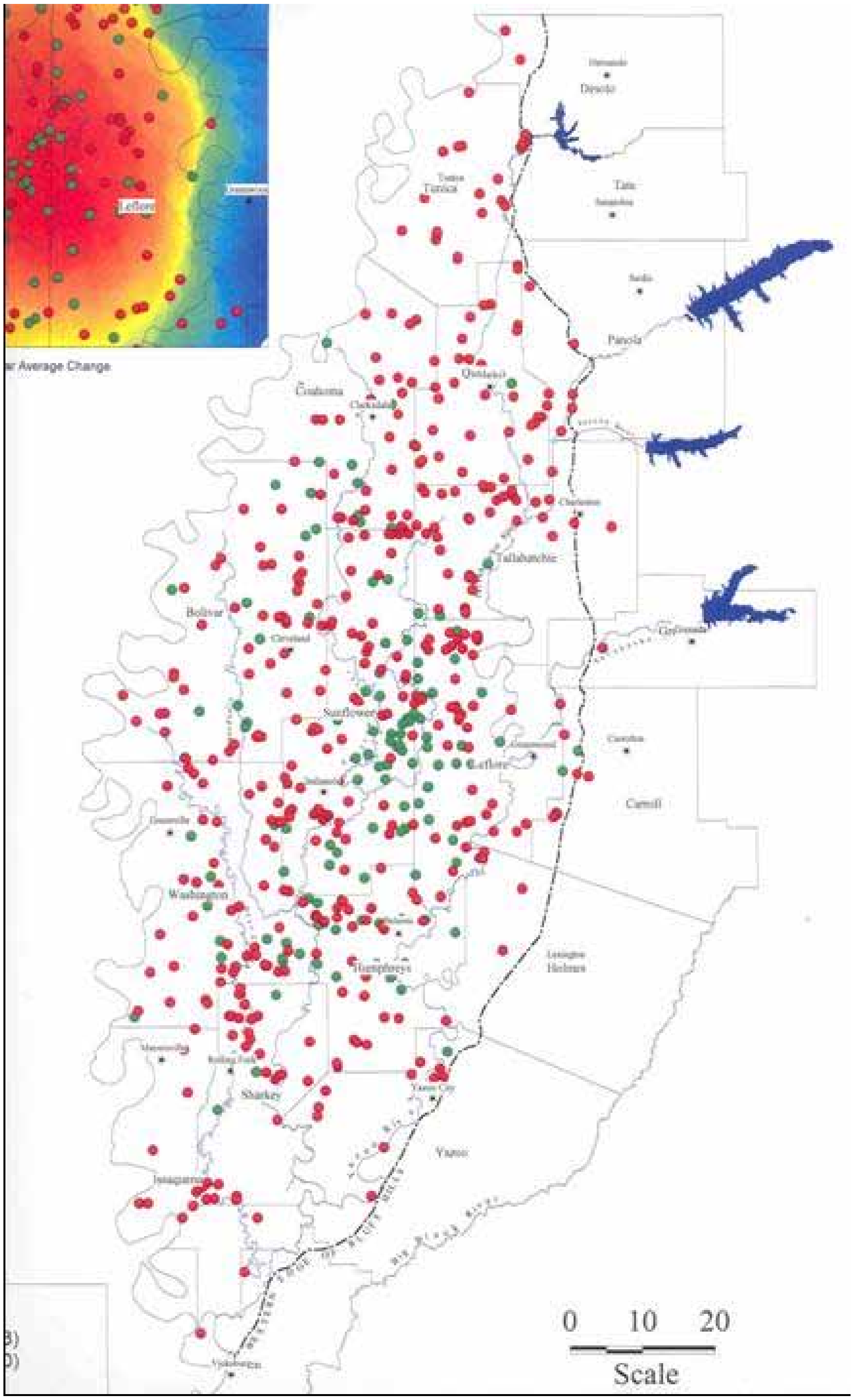


Figure 3: Seasonal Cumulative Aquifer Volume Decline, 1990-2006

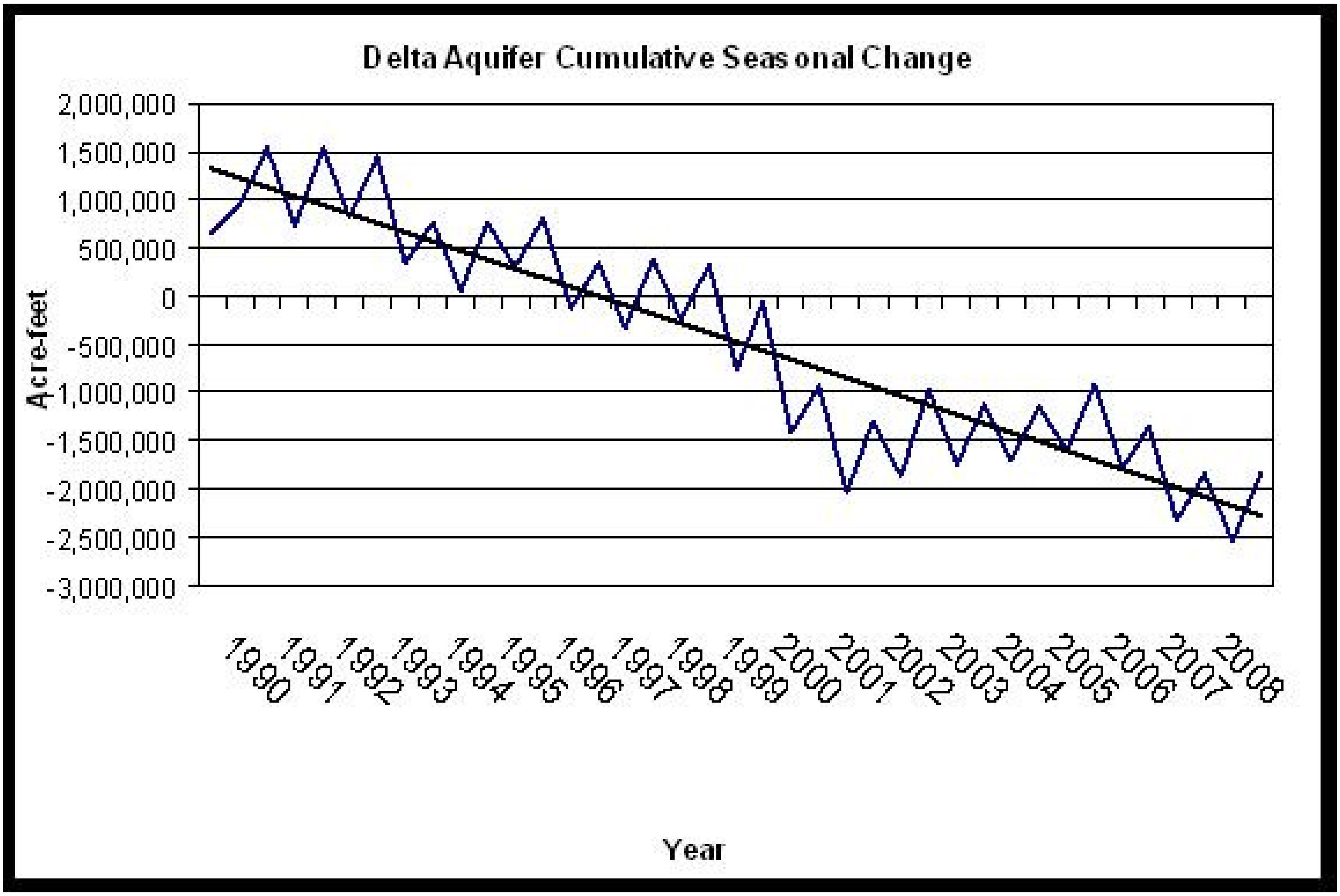


Figure 4: Locations of Water Use Survey Wells, 2006

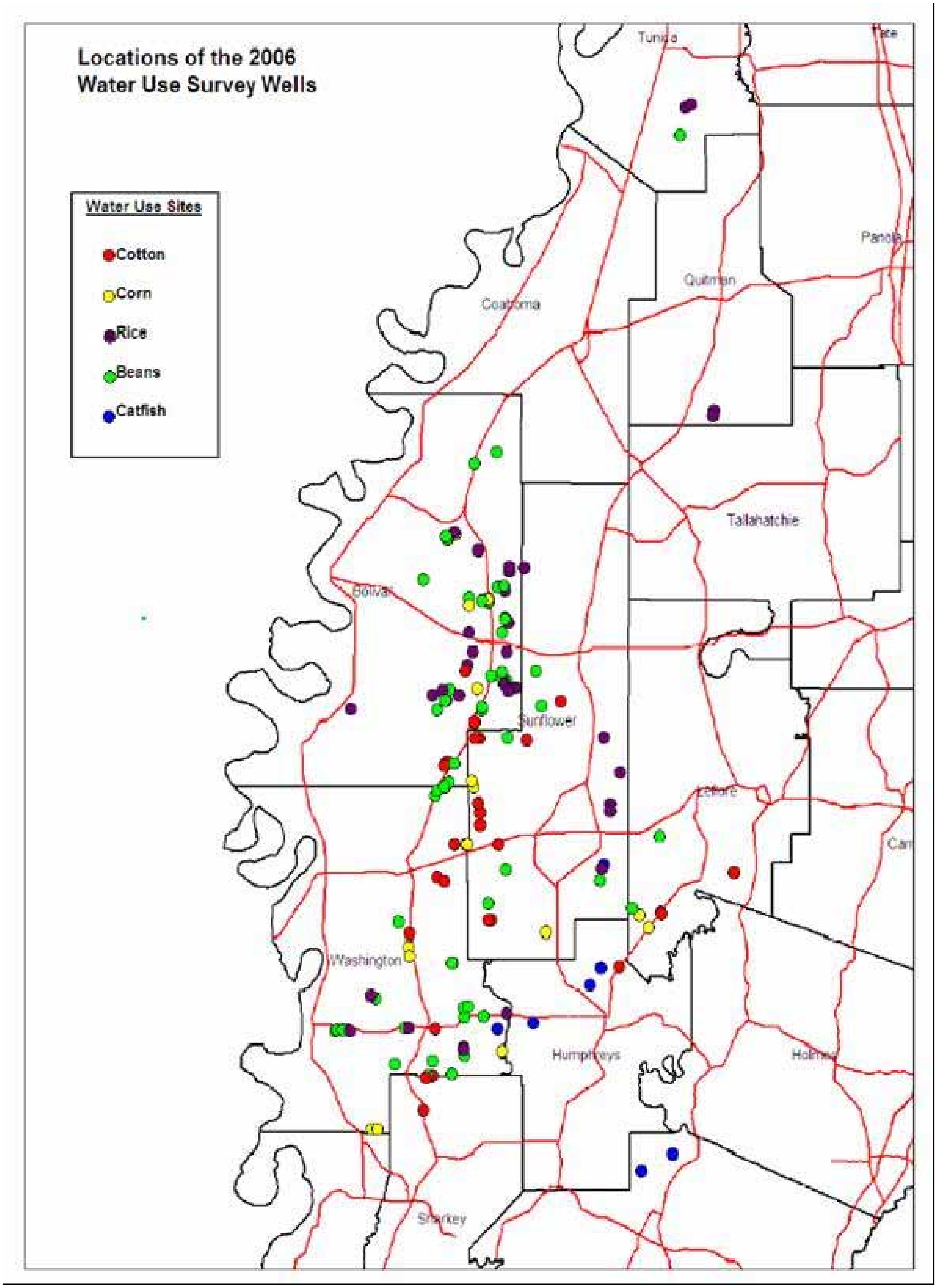


Figure 5: Conceptual flow chart of the original model

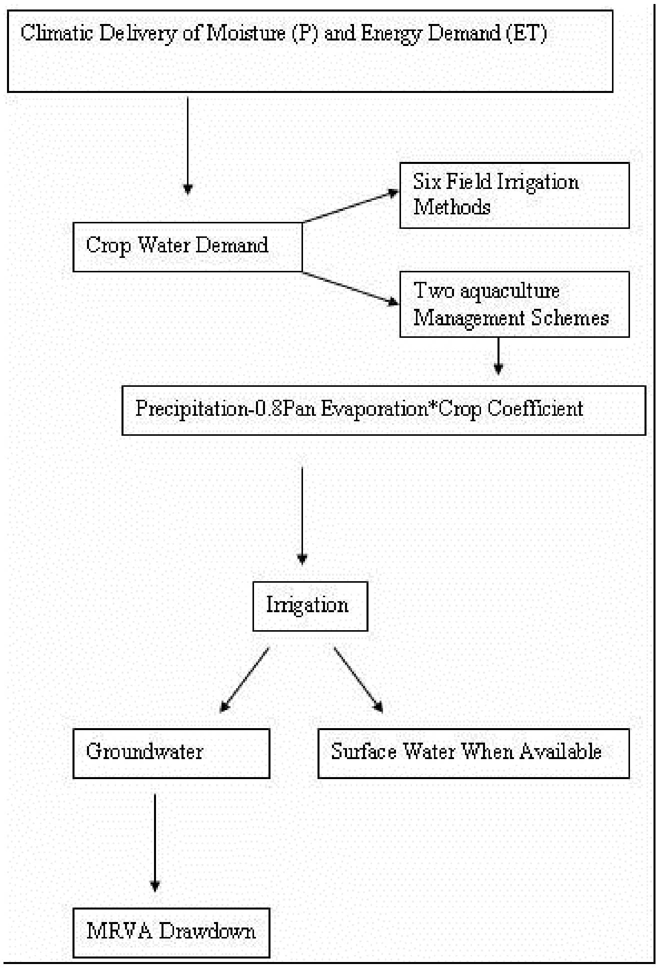


Figure 6: Static model with cultural and climatic variability the same

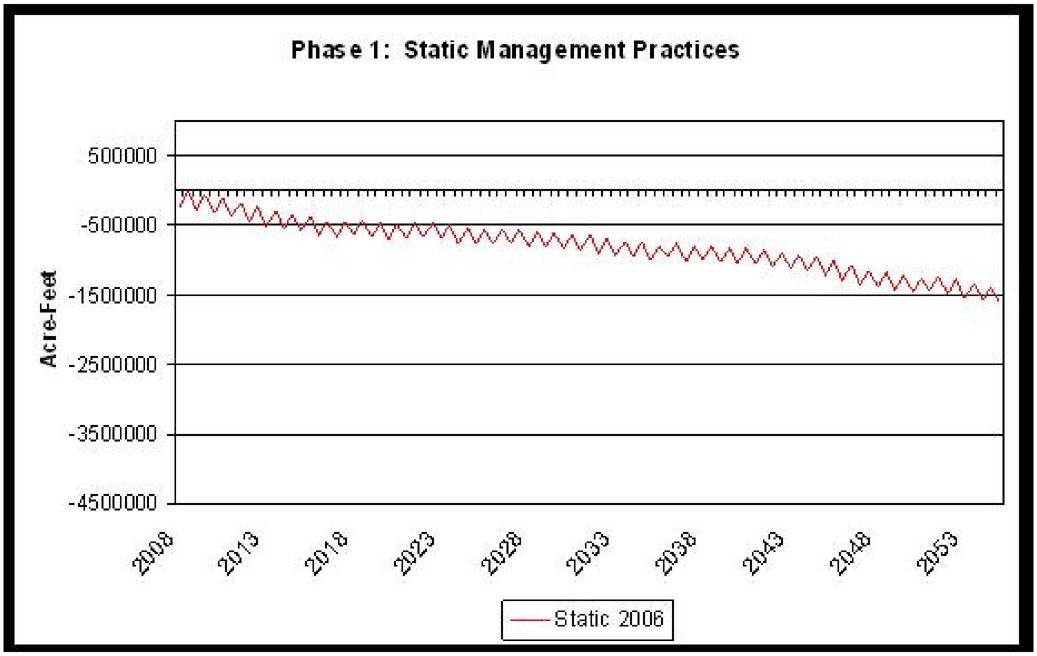


Figure 7: Static model versus most conservative methods

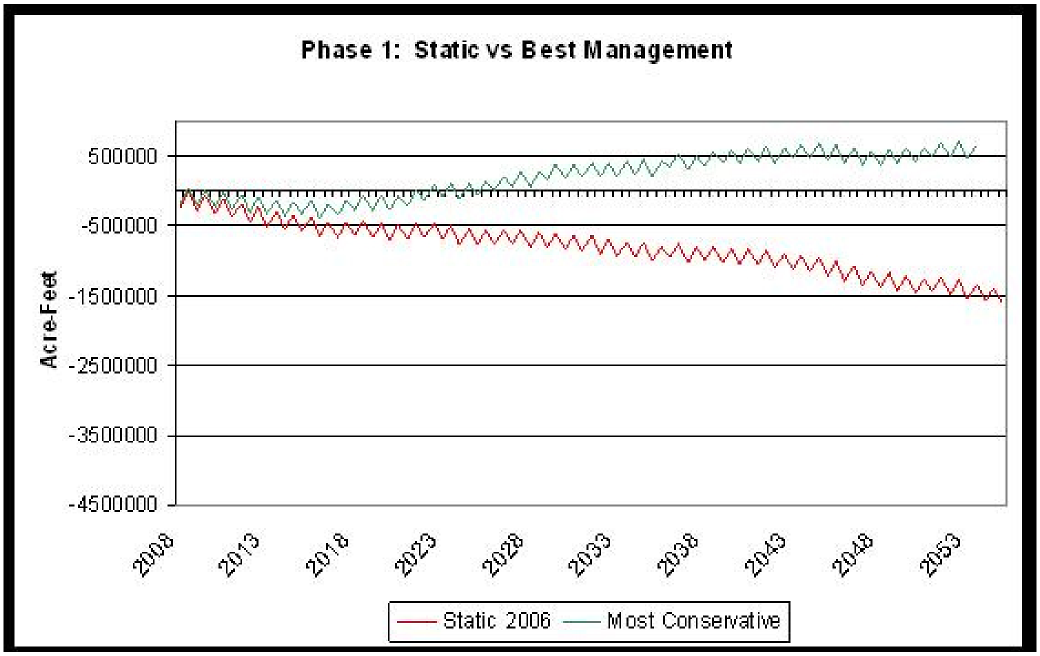


Figure 8: Static model versus most consumptive methods

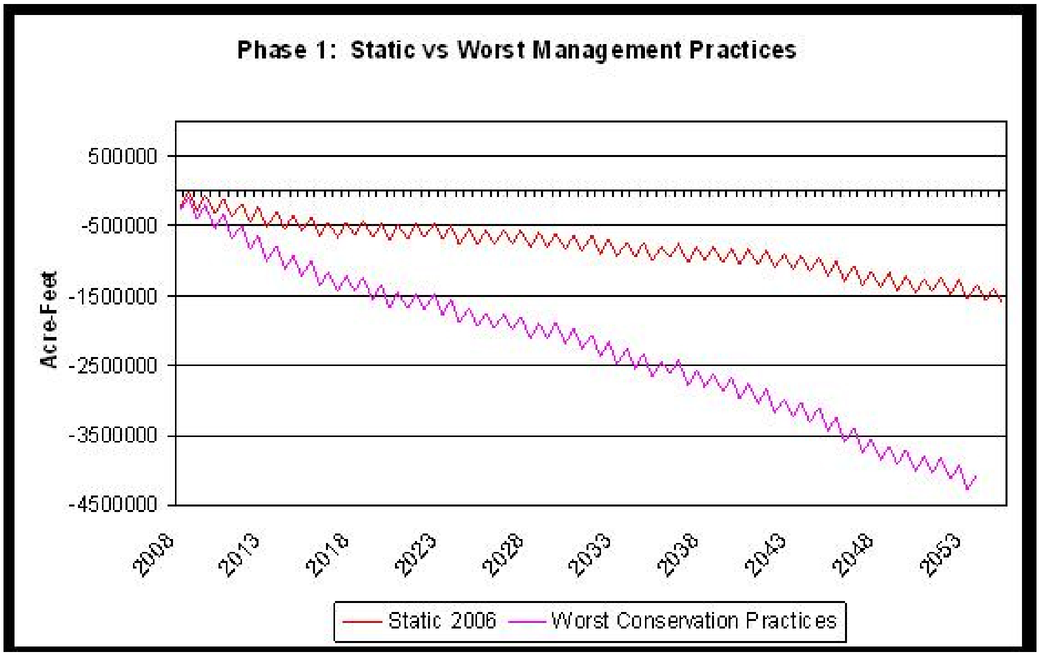


Figure 9: Static versus use of surface water when available from streams

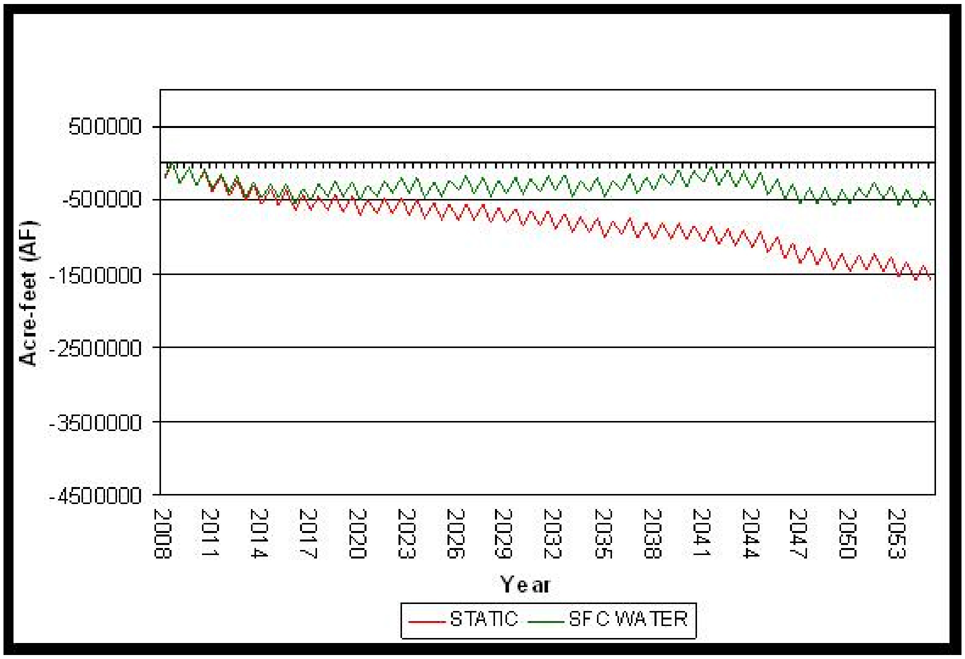


Figure 10: Calculated (1961-2009) vs. Measured (2002-2009) Corn Irrigation (Y=1.180774(x) + 0.001839; R^2=0.77)

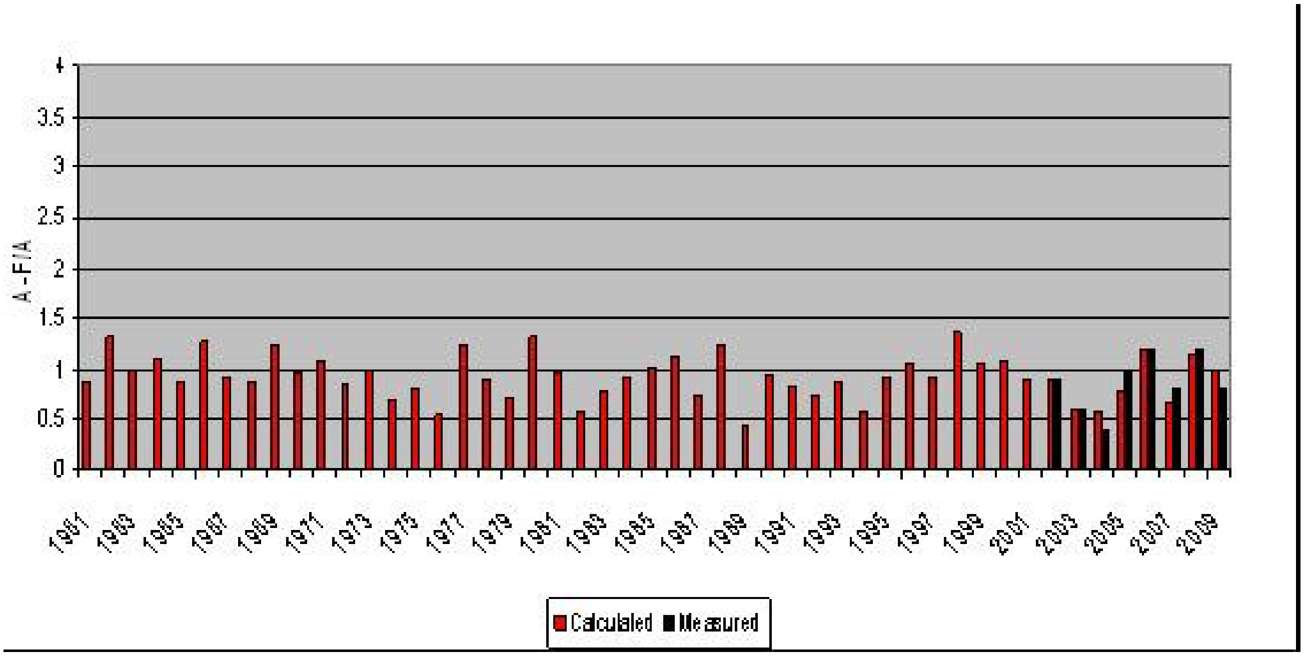


Figure 11: Effective precipitation—years in which climate delivers a surplus or a deficit of precipitation to meet crop water needs.

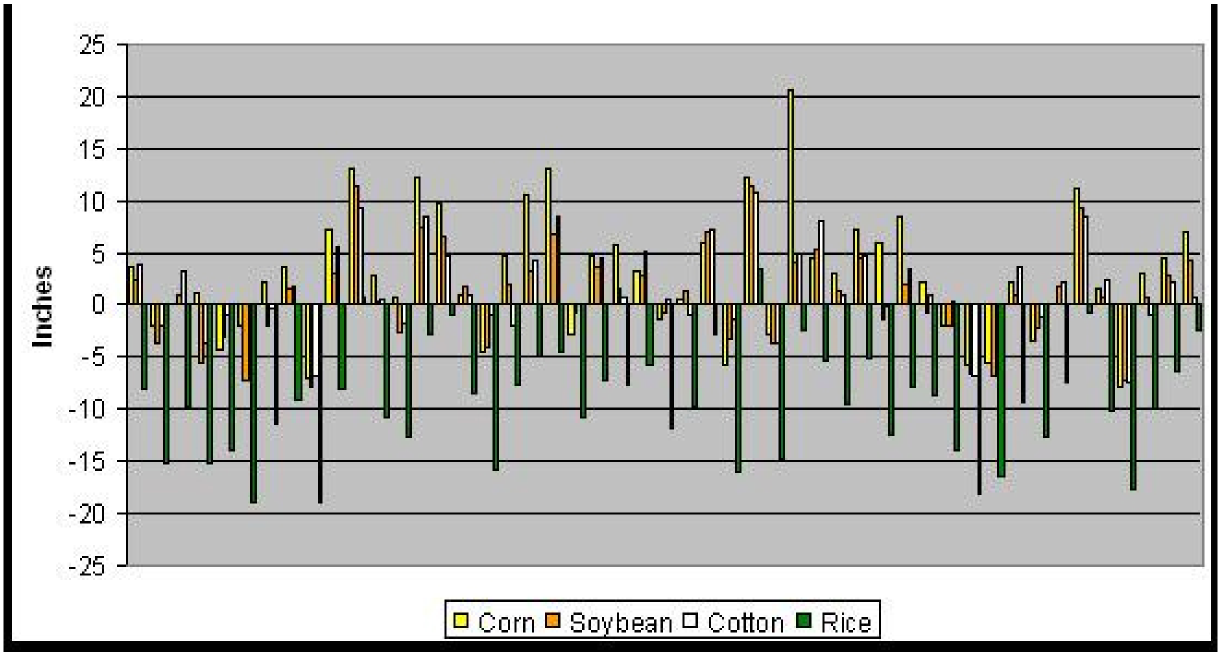
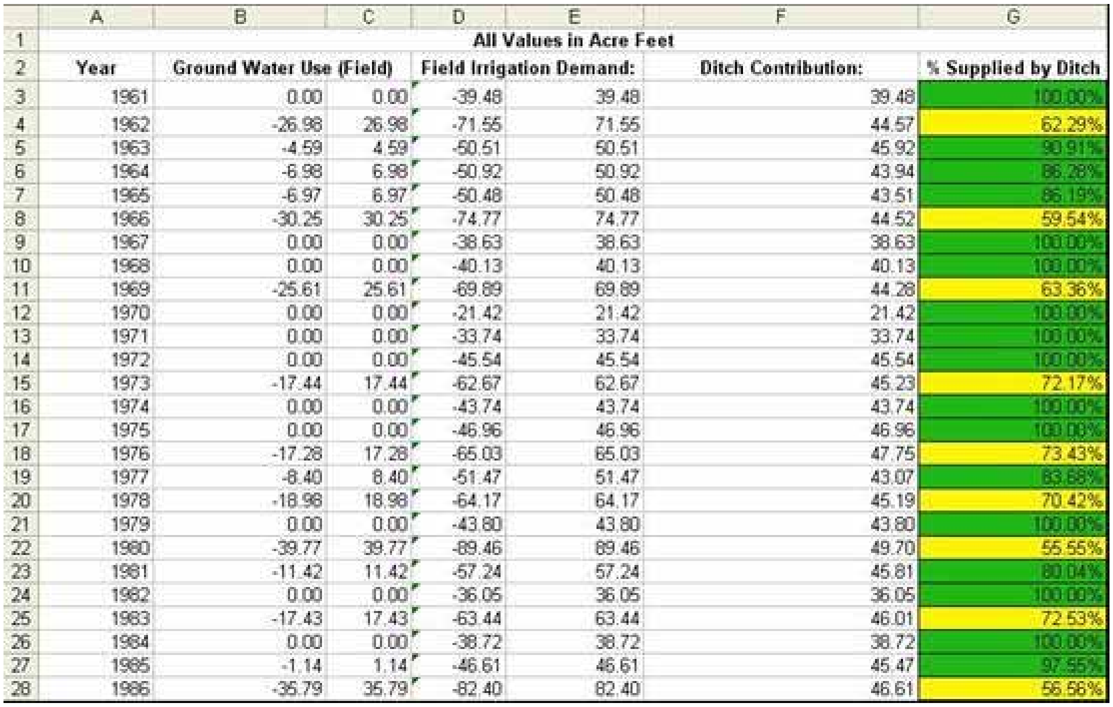


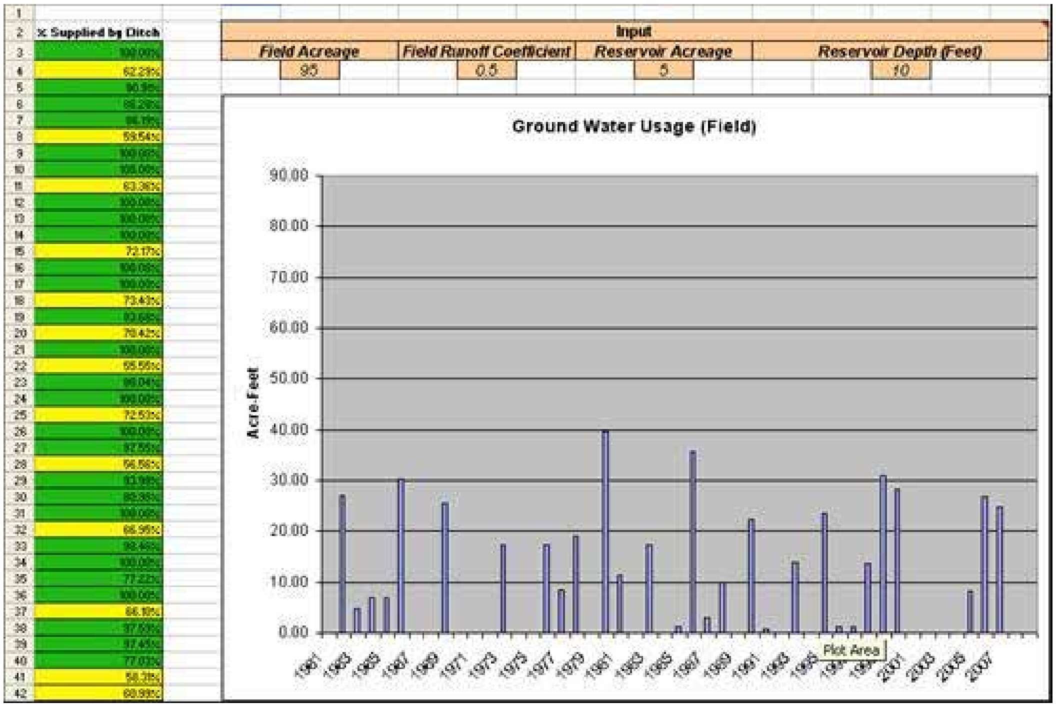
Figure 12: North to south view of a catchment ditch with reservoir on the left and leveled field on the right (Photo: R. Thornton)

Figure 13: Partial view of farm storage reservoir model



	A	B	C	D	E	F	G
1	All Values in Acre Feet						
2	Year	Ground Water Use (Field)		Field Irrigation Demand:		Ditch Contribution:	% Supplied by Ditch
3	1961	0.00	0.00	-39.48	39.48	39.48	100.00%
4	1962	-26.98	26.98	-71.55	71.55	44.57	62.29%
5	1963	-4.59	4.59	-50.51	50.51	45.92	90.91%
6	1964	-6.98	6.98	-50.92	50.92	43.94	86.28%
7	1965	-6.97	6.97	-50.48	50.48	43.51	86.19%
8	1966	-30.25	30.25	-74.77	74.77	44.52	59.54%
9	1967	0.00	0.00	-38.63	38.63	38.63	100.00%
10	1968	0.00	0.00	-40.13	40.13	40.13	100.00%
11	1969	-25.61	25.61	-69.89	69.89	44.28	63.36%
12	1970	0.00	0.00	-21.42	21.42	21.42	100.00%
13	1971	0.00	0.00	-33.74	33.74	33.74	100.00%
14	1972	0.00	0.00	-45.54	45.54	45.54	100.00%
15	1973	-17.44	17.44	-62.67	62.67	45.23	72.17%
16	1974	0.00	0.00	-43.74	43.74	43.74	100.00%
17	1975	0.00	0.00	-46.96	46.96	46.96	100.00%
18	1976	-17.28	17.28	-65.03	65.03	47.75	73.43%
19	1977	-8.40	8.40	-51.47	51.47	43.07	83.68%
20	1978	-18.98	18.98	-64.17	64.17	45.19	70.42%
21	1979	0.00	0.00	-43.80	43.80	43.80	100.00%
22	1980	-39.77	39.77	-89.46	89.46	49.70	55.55%
23	1981	-11.42	11.42	-57.24	57.24	45.81	80.04%
24	1982	0.00	0.00	-36.05	36.05	36.05	100.00%
25	1983	-17.43	17.43	-63.44	63.44	46.01	72.53%
26	1984	0.00	0.00	-38.72	38.72	38.72	100.00%
27	1985	-1.14	1.14	-46.61	46.61	45.47	97.55%
28	1986	-35.79	35.79	-82.40	82.40	46.61	56.56%

Figure 14: Partial view of farm storage reservoir model, continued



Input			
Field Acreage	Field Runoff Coefficient	Reservoir Acreage	Reservoir Depth (Feet)
95	0.5	5	10