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# An Integration of GIS and Simulation Models for a Cost Benefit Analysis of Irrigation Development

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## Abstract

This study incorporates spatially explicit geographic information system and simulation models to develop an optimal irrigation system. The purpose of the optimized irrigation system was to save depleted ground water supplies. ArcGIS was used to calculate the area of potential irrigable soils, and EPANET (a hydrological simulation program) was used to calculate energy costs. Crop yield response functions were used to estimate the yield of cotton to the amount of irrigation and the accumulation of soil salinity over a 50-year period. Four irrigation designs (A, B, C, and D) were analyzed with different irrigation schedules.

Design A allowed all producers to irrigate simultaneously at 600 gallons per minute (gpm) or 2,271 liters per minute (lpm) while designs B and C divided the irrigable areas into two parts. Design D divided the areas into four parts to allow producers to irrigate one part at a time at 800 gpm (3,028 lpm). Irrigation scheduling not only lessened the water use and cost, but also amplified the profitability of the irrigation system. In design A, if all producers adopted 600 gpm (2,271 lpm) pivots and operated simultaneously, the cost of the 360,000 gpm (1,363,000 lpm) pipeline would be prohibitive. In contrast, designs B, C, and D increased net benefits and lowered the breakeven price of cotton. The 50-year net present value for designs A, B, C, and D was profitable over 75, 70, 70, and 65 cents of cotton price per pound (454 g), respectively. Thus, this study endorses irrigation scheduling as a tool for efficient irrigation development and management, and increases water conservation.

**Keywords:** geographic information system, simulation model, net present value, irrigation system

## 1. Introduction

In the context of climate change reduced water supplies and increasing energy prices, it is crucial to identify methodologies, tools, and actions that optimize the use of water, energy, and other durable resources for environmental and economic benefits. The increasing dependence on irrigated agriculture requires efficient irrigation planning to conserve water and maximize net revenue. Several studies have used geographic information systems (GIS) for irrigation planning, management (Belmonte, González, Mayorga, & Fernández, 1999; Todorovic & Steduto, 2003; Satti & Jacobs, 2004; and Singh, Jhorar, Van Dam, & Fredde, 2006), and for irrigation scheduling (George, Raghuwanshi, & Singh, 2004; Fortes, Platonov, & Pereira, 2005). Geographically mapped spatially explicit soil data and simulation models can be combined to optimize cost efficient and dynamic management planning for scarce water supplies. However, the combined GIS and simulation models have not been used to select, design, and manage the pressurized irrigation system. This project design is methodologically unique as it integrates spatially specific data mapped in GIS software, hydrological simulation models, and economic optimization models to develop a feasible irrigation system. In addition, this paper also discusses the cost minimization benefits of irrigation system by irrigation scheduling which is an addition to the literature. Irrigation scheduling here refers to the application of irrigation water to different sections of land in different times rather than simultaneously. Thus, the general objective of this study was to develop the irrigation design using GIS, and the hydrological and mathematical simulation models to analyze the profitability of an irrigation system under different scheduling. Further, this study also conducts sensitivity of net returns of irrigation systems under different cotton prices and electrical conductivity (EC) or salinity levels. The specific objectives of this study were: (1) to identify irrigable areas and the length and route of pipelines using GIS, (2) to determine the cost of the pipeline and the net economic returns of irrigation from yield increment using an

EPANET hydrological simulation model and mathematical optimization model, respectively, and (3) to determine the net economic returns of an irrigation system under different irrigation scheduling, cotton prices, and salinity levels within the irrigation district. This study hypothesizes that irrigation scheduling increases the net benefit of the irrigation system or lowers the breakeven price for cotton.

### *1.1 Background and Study Area*

The North Fork of the Red River of southwestern Oklahoma, USA is overburdened with salt from three canyons including Kaiser, Robinson, and Salton. This study area is a part of a chloride control and salinity management project in North Fork of Red River under which there is a potential for construction of the Cable Mountain Reservoir (CMR). The CMR was proposed to augment the water supply of Altus dam which is in the Lugert-Altus Irrigation District, about 29 km north of the city of Altus, OK. The Altus Reservoir has been losing its water storage capacity due to sediment accumulation (Bureau of Reclamation, 2005). Displacement of available reservoir capacity by sediment will diminish the project's capacity to supply water within 30 to 50 years. The CMR is one of the proposed alternatives to increase and augment the water supply of Lake Altus (Bureau of Reclamation, 2005). The estimated holding capacity of the proposed CMR is 12,335 hectare-meter, more volume than is required to replace water lost from Lake Altus. This study proposes the use of additional water to irrigate arable lands at lower elevations of the reservoir in Tillman Terrace Area (TTA), located to the southwest of the state of Oklahoma. Ground water has been extensively used since 1950 in Tillman County for irrigation and municipal uses resulting in depletion of ground water and encroaching salt water from the North Fork River (Osborn, 2002). Thus, irrigation development to TTA reduces the depletion of groundwater and salinity problem in North Fork River.

## **2. Materials and Methods**

### *2.1 Potential Irrigable Areas*

Irrigable areas were identified for allocation of irrigation water and for determination of the optimal quantity of irrigation water for the area. A GIS was used to determine irrigable areas from the Natural Resources Conservation Services (NRCS) -SSURGO database (NRCS, 2010) map of soil types and their classifications in the Tillman and Kiowa counties. The land classification capability categorizes land based on the suitability of soil quality for potential agricultural output. These land categories class are types I-VIII which represent progressively greater limitations and narrower choices for agriculture. There are land capability subclasses, denoted by codes e, w, s, and c, which are respectively related to problems with erosion, wetness, root zones, and climate. Irrigable soil types were defined as I, Iie, and IIw (National Soil Survey Handbook, USDA). The section shape files of Tillman and Kiowa counties were intersected with the SSURGO database to determine soil type in each township and sections of the counties.

Irrigable areas were further identified by slope, elevation, and plot size to form a set of potential sites for irrigation. The fields with 10 m slopes less than three percent were selected. The land area was filtered to the areas with elevation less than 436 meter above sea level (masl) since elevation of CMR is 436 masl. The fields with less than 4 ha of irrigable field soils were removed on an assumption that it would be uneconomical to irrigate those small areas.

### *2.2 Pipeline Network Design of the Irrigation System*

A feasible irrigation pipeline network was designed given the area and shape of field sites using ArcMap 9.3. The elevation of irrigable areas was used to calculate the head pressure and the required power to deliver the water into the field. Global Mapper was used to create elevation of every pivot node of the pipeline (Global Mapper, 2011).

Settlement areas, railway tracks, and gullies that exemplified physical obstacles for an irrigation system were excluded. The editor in ArcGIS was used to draw the pipeline network to provide irrigation for each pivot circle. The pipeline route was designated to follow the maximum elevation level from the CMR to TTA to minimize the pumping cost of the irrigation system.

### *2.3 Cost of Earthwork*

As the cost of earthwork depends on pipe size, the linear cost per foot of earthwork for different sizes of pipes, small and large was determined. Trenches of five feet or deeper have to be excavated with certain slopes for the safety of the workers and the durability of the trench (Occupational Safety and Health Administration (OSHA), 2011). The costs of trenching for larger and smaller pipelines were different because larger wall slopes are required for larger trenches (> 1.5 m deep) and smaller trenches require smaller wall slopes (<1.5 m deep) (OSHA, 2011). The cost of trenching was estimated with a regression model where the dependent variable was

cost of trenching and the independent variables were trench width, trench depth, and square of the trench depth. Total earthwork cost was calculated as a sum of trenching, backfilling, and packing costs. Finally, pipe cost and total earthwork were summed as total piping cost. The total costs were then annualized for equal payments over a 50-year period at a discount rate of four, five, six, and eight percent. A spreadsheet was used to develop the cost for purchase and installation cost of alternative sizes of pipe from 6 to 120 inches (0.15 to 3 m), using data on the cost of pipe, excavation, and backfilling using estimates from RS Means (Mossman and Plotner, 2009).

#### 2.4 Pipeline Design and Cost Estimation

The most economically beneficial design of a pipeline system to serve an irrigation district from a reservoir depends not only on the quantity and quality of the water, but also on the distance and elevation changes between the reservoir and irrigation district. As the diameter of pipe increases, the total cost of the pipe increases, but the energy required for pumping water (pumping cost or energy cost) through the pipe decreases. Pipe size can be optimized to contribute to decrease in the cost of pipeline to some extent. The optimal size of pipeline was determined using EPANET software (EPA, 2011).

The EPANET models water flow and pressure loss in distribution systems to help size the pipeline and determine the pump location, to minimize energy cost (EPA, 2011). The GIS provided the estimate of pipe lengths. The pipeline size was varied to minimize the annual cost of pipeline construction and pumping cost. The minimum annual cost involves a tradeoff between pipe size and energy cost. In EPANET software, the pipeline diameters were iteratively increased or decreased until the minimum size of pipeline was determined that gave the pressure required at different points. The pumps were added to low pressure points to meet the minimum pressure of 35 PSI (0.01 kg m<sup>-2</sup>) for each pivot system operation. A standard capital recovery factor was used to annualize the pipe cost. The annual capital cost for the pipeline and the annual pumping costs were added to get the size of pipeline for minimal annual cost.

#### 2.5 Water Demand and Energy Cost

The water demand at each pivot and number of pivots determines the diameter and cost of pipelines. Energy cost in this study is the cost of energy for pumping water to the fields. The pressure of at least 35 PSI (0.01 kg m<sup>-2</sup>) in an individual pivot is obtained by adjusting the pumps in the required areas of the irrigation system. The energy cost for pumping was estimated with the use of the volume of water and pressure head required as indicated by the brake horse power methods as described in Keller and Bliesner (1990).

$$Bhp = \frac{GPM * Head (ft)}{3960 * Peff * Meff} \quad (1)$$

where gpm is gallons per minute, *Peff* is pumping efficiency, *Meff* is motor efficiency, and Head (ft) is the pressure. The head loss was calculated using Hazen William's formula (Jensen, 1983) as shown below:

$$Head\ loss = \frac{10.46 \left( \frac{GPM}{C} \right)^{1.85} * length}{D^{4.87}} + ELC + DelH \quad (2)$$

where *C* is the retardation constant, which is 120 for steel or aluminum, 140 for Cement Asbestos, and 150 for plastic, *D* is diameter of pipe (inches), *ELC* is elevation change, and *DelH* is delivery head.

Energy costs (EGC) were calculated using the following formula (Keller and Bliesner, 1990):

$$EGC = \frac{(GPM * Hd) * kwBhp * hpy * pelec}{3690 * Peff * Meff} \quad (3)$$

where *Hd* is head loss in feet, *kwBhp* is kilowatt per brake horse power, *hpy* is hours per year, and *pelec* is electricity cost per kwh. Thus, the pumps were chosen according to the pressure requirement to deliver water in each pivot according to output of EPANET. The pumping cost for the irrigation system was calculated using equation (3).

#### 2.6 Crop Yield Response Function

The crop yield response function of a crop to irrigation supply and soil salinity is a crucial factor in an optimization model for irrigation systems with water salinity (Feinerman, 1993). Several studies have estimated response functions (Dinar & Knapp, 1986; Dinar, V. Sharma, & D. Sharma, 1991; Datta, 1998; Kiani & Abbasi, 2009). Because cotton is the major irrigated crop in the study region and also very resistant to salinity (up to 7.7 mmhos cm<sup>-1</sup> EC), the responses of cotton yields for 50 years to different levels of irrigation and water quality for

major irrigable soil types were simulated using Environmental Policy Integrated Climate (EPIC) model (Choi, 2011). The quadratic yield function for each individual soil types is:

$$Y_{st} = a_{s0} + a_{s1}W_{st} + a_{s2}S_{st} + a_{s3}NR_{st} + a_{s4}W_{st}^2 + a_{s5}S_{st}^2 + a_{s6}\frac{S_{st}}{W_{st}} \quad (4)$$

where  $W_{st}$  is the total water (i.e. sum of irrigation and rainfall) applied (ac-feet),  $S_{st}$  is the quantity of salt in irrigation water (tons/ac-ft), plus the salt in the soil profile,  $\frac{S_{st}}{W_{st}}$  is the amount of total salt (soil +irrigation salt) divided by the total amount of water (irrigation plus rain fall) per acre, and  $NR_t$  is the precipitation in the non-growing season (ft).

### 2.7 Net Present Value Estimation

The net present value for a 50-year period was calculated for each individual pivot circle which contains one or more soil types. It was not possible to develop a single integrated optimization program. The net present value (NPV) is calculated using the following formula:

$$\max_I NPV = \sum_{t=1}^T \frac{1}{(1+r)^t} A_s \{P \cdot Y_t - C_{irr} \cdot I - C_o\} \quad (5)$$

Subject to,

$$Y_{st} = a_{s0} + a_{s1}W_{st} + a_{s2}Sh_{st} + a_{s3}NR_{st} + a_{s4}W_{st}^2 + a_{s5}Sh_{st}^2 + a_{s6}\frac{Sh_{st}}{W_{st}} \quad (6)$$

$$Sh_t = b_{s0} + b_{s1}I_{st} + b_{s2}Is_t + b_{s3}Sp_{st} + b_{s4}Rg_t * W_t \quad (7)$$

$$W_{st} = (Rg_t + Is_t) \quad (8)$$

$$Sh_{st} = (S_{st} + SI_{st}) \quad (9)$$

$$Sp_{st} = c_{s0} + c_{s1}Sh_{st-1} + c_{s2}R_{wt-1} \quad (10)$$

where  $Y_{st}$  is yield (lbs/acre) in soil  $s$ , year  $t$ ,  $A_s$  is the acreage of a soil type  $s$  in the individual irrigation circles (number of soils types differ for each pivot circle),  $P$  is the price of cotton lint (\$/lb) (price was assumed same over the year but a sensitivity of change in price (\$0.50, \$0.65, \$0.70, and \$0.9) was calculated),  $W_{st}$  is the total water applied (i.e., sum of the growing season rainfall ( $Rg_t$ ) and irrigation water ( $Is_{st}$ )),  $Sh_{st}$  is the total salt for soil  $s$  and year  $t$  (i.e., sum of salt in soil ( $S_{st}$ ) and salt in irrigation water ( $SI_{st}$ )),  $Sp_{st}$  is the soil salt at planting,  $Sh_{st-1}$  is soil salt at previous harvest,  $R_{wt-1}$  is non-season (winter) rainfall,  $C_{irr}$  is the irrigation cost (\$/acre-feet),  $C_o$  is the operation cost, and  $r$  is discount rate.

## 3. Results and Discussions

### 3.1 Irrigable Soil Types and Areas

Potential irrigable areas in Tillman and Kiowa counties are shown in Figure 1.

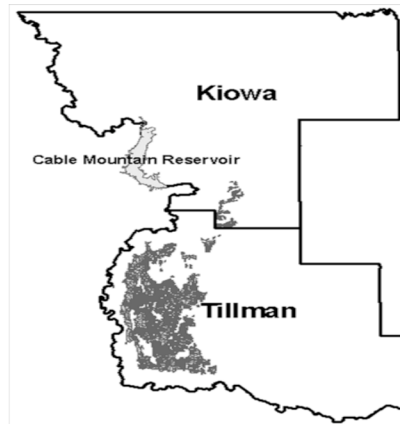


Figure 1. Potential irrigable areas in Tillman and Kiowa counties.

The area of potential irrigable soils totaled 67,868 acres (27,465 ha). Tipton Sandy Loam and Tipton Loam are the dominant soil types within the area. There were 5,196 acres (2,102 ha) which were not designated as irrigable

but which producers were currently irrigating. These contributed approximately 45 more pivot circles. As people would likely continue irrigation in those areas, these areas were included in potential irrigable areas for the region. Most of the irrigable areas were covered by 543 pivot circles. There can be up to four pivot circles, each with an area of 125.6 acres (50.8 ha), in each section of land. Total irrigable areas, including identified irrigable soils, and non-irrigable soils that are currently under irrigation, were 73,064 acres (29,568 ha). Of this area, a total of 64,433 acres (26,075 ha) were covered by 513 full pivot circles and 2,764 acres (1,119 ha) were covered by 30 partial pivot circles.

### 3.2 Irrigation Network

Irrigation water flows through the main pipeline (North to South) from the reservoir to the lateral pipelines (East to West). Each lateral pipeline was connected with final pipelines which deliver water to the individual pivot in the fields. The entire pipeline outline is provided in Figure 2.

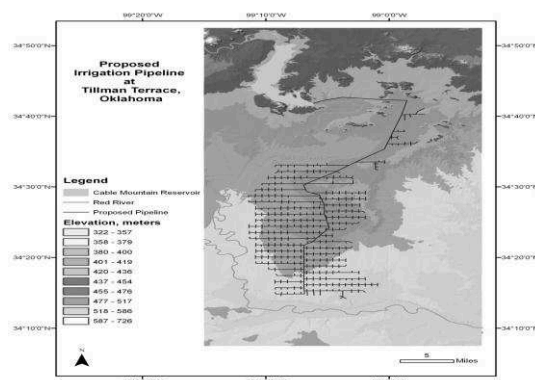


Figure 2. Outline of pipeline from the reservoir to Tillman Terrace with main, lateral, and final pipelines. North-South line is main pipeline and East-West lines are lateral pipelines overlaid on the elevation file.

The length of main, lateral, and final pipelines were 66 miles (106 km), 214 miles (344 km), and 243 miles (391 km), respectively. The size of main pipeline ranged from 48 to 120 inches (1.22 to 3 m), lateral pipelines ranged from 12 to 36 inches (0.3 to 0.9 m), and final pipes were 8 to 10 inches (0.2 to 0.25 m).

### 3.3 Trenching and Pipeline Cost

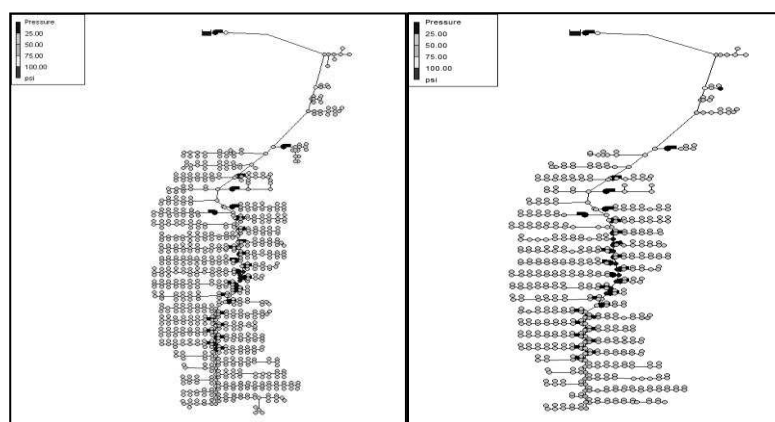
Total pipe costs, trenching costs, and total annualized pipeline costs for 50 years at four percent discount rate increased as the size of pipeline increased. Total pipe costs per linear foot (0.3 m) ranged from \$151 for 0.6 m diameter pipe to \$1,925 for 3 m diameter pipe. Total earthwork cost increased with increasing pipe size, ranging from \$70 per linear foot (0.3 m) for 0.6 m diameter pipe to \$271 for 3 m diameter pipe. Total cost was calculated as a sum of total pipe cost and total earthwork cost, which ranged from \$221 to \$2,196 per linear foot (0.3 m). The 50-year annualized cost at four percent discount rate was \$10 per linear foot (0.3 m) for 0.6 m diameter pipe and reached up to \$102 for 3 m diameter pipe. Diameter of smaller pipes ranged from 6 to 18 inches (0.15 to 0.45 m) while total pipe costs ranged from \$8 (0.15 m) to \$55 (0.45 m). Total earthwork cost increased with increasing pipe size ranged from \$8 to \$16. Total cost (pipe cost + earthwork cost) ranged from \$16 to \$71. The 50-year annualized cost at four percent discount rate ranged from \$0.7 (0.15 m pipe) to \$3.3 (0.45 m pipe).

### 3.4 Irrigation Systems

Four different irrigation system (A-D) designs that would deliver the water to every pivot were identified. Outline of all four designs are provided in Figure 3. Design A (Figure 3a) allowed all producers to irrigate simultaneously at 600 gpm (2,271 lpm) while designs B (Figure 3b) and C (Figure 3c) divided the irrigable areas into two parts. Design D (Figure 3d) divided the area into four parts to allow producers to irrigate one part at a time with 800 gpm (3,028 lpm) of individual pivot demand. The four designs were evaluated in terms of the annual fixed and variable costs.

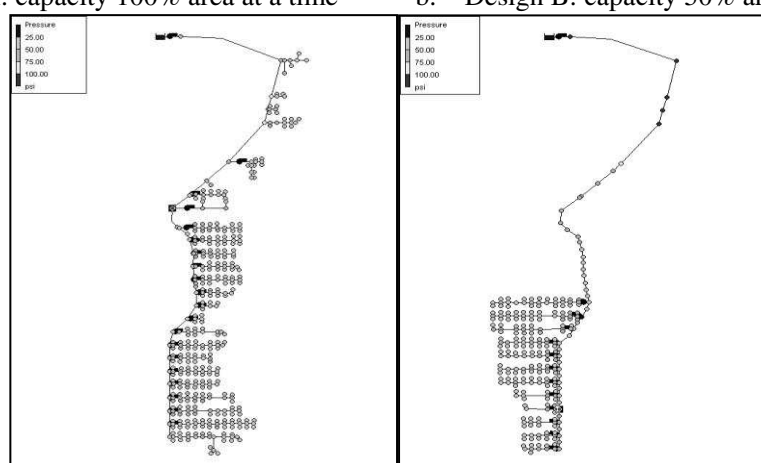
### 3.5 Variable Costs

The variable costs of the irrigation systems included the costs of cotton production, cost of the pivot irrigation system, irrigation labor cost, and other related costs. Total non-irrigation variable cost was estimated to be approximately \$500 per acre (\$1,235 per ha) (Enterprise Budgets (Oklahoma State University), 2011). The annual pumping cost per acre foot was approximately \$50 per acre (\$124 per ha) for all four designs.



a. Design A: capacity 100% area at a time

b. Design B: capacity 50% area at a time



c. Design C: capacity 50% area at a time

d. Design D: capacity 25% area at a time

Figure 3. Illustration of Irrigation Designs; a. Design A: Capacity 100% area at a time, b. Design B: Capacity 50% area at a time, c. Design C: Capacity 50% area at a time, and d. Design D: Capacity 25% area at a time.

### 3.6 Fixed Costs

#### 3.6.1 Design A: Capacity 100% Area at a Time

This design was for the unrestricted irrigation system with demand of 600 gpm (2,271 lpm) for each pivot circle (Figure 3a). This design used main pipelines of 48 to 120 inches (1.22 to 3 m), lateral pipelines of 12 to 36 inch (0.3 to 0.9 m), and final pipelines of 8 and 10 inches (0.2 to 0.25 m). The total water demand was 326,800 gpm (1237,000 lpm) and annual fixed cost was \$986 per ha at a four percent discount rate and a 1.5 mmhos  $\text{cm}^{-1}$  EC level (Table 1). Table 1 shows that the total annualized fixed cost per ha increased by 17%, from \$986 to \$1,153, when the discount rate was increased from four to five percent. It increased by 35% when the discount rate was increased from four to six percent, and increased by 74% when the discount rate was raised from 4% to 8%.

Table 1. Annual Fixed Costs of Design A Irrigation System at Different Discount Rates.

| Cost                                 | Cost/ha (4%) | Cost/ha (5%) | Cost/ha (6%) | Cost/ha (8%) |
|--------------------------------------|--------------|--------------|--------------|--------------|
| Pipe costs                           | \$847        | \$990        | \$1,146      | \$1,472      |
| Cost of centrifugal pumps and motors | \$15         | \$17         | \$20         | \$25         |
| Cost of pivot irrigation system      | \$124        | \$146        | \$168        | \$217        |
| Total                                | \$986        | \$1,153      | \$1,334      | \$1,714      |

With an annualized fixed cost of \$986 per ha and total annual variable cost of \$1,359 per ha of the irrigation system, the cotton lint price must be 75 cents or more per pound (454 g) to make this irrigation design economically feasible. A cotton price less than 75 cents per pound (454 g) resulted in a negative NPV for the

project. The aggregate NPV for the non-scheduled irrigation system for cotton lint prices of 75 and 90 cents was \$1,102 and \$8,128 per ha, respectively for EC value of 1.5 mmhos  $\text{cm}^{-1}$  (Table 2). At this level of EC, the total NPV for 67,197 acres (27,193 ha) of land at cotton price of 75 and 90 cents was approximately \$31 million and \$225 million (Table 2), respectively. The average NPV for a 50.8 ha system for EC value of 1.5 was approximately \$413,367 for 90 cents and \$55,970 for 75 cents per pound (454 g) cotton price. The sensitivity of the fluctuation in the NPV of the system to EC was also analyzed. The result showed that an increase in EC would decrease the NPV and decrease the optimal amount of irrigation water to maximize NPV. For design one, a decrease in EC from 1.5 to 0.9 mmhos  $\text{cm}^{-1}$  increased NPV by 12 and 30% for cotton lint prices of 90 and 75 cents per pound (454 g), respectively. The average optimum quantity of irrigation water increased by 35 and 60% for 90 and 75 cents of cotton prices, respectively.

Table 2. Aggregate Net Present Value (NPV) of Irrigated Cotton for Design A at Cotton Price of \$0.75 and \$0.90 Per Pound (454 g) at Different Electrical Conductivity (EC) Levels.

| Cotton price \$0.75                |               |               |               |               |
|------------------------------------|---------------|---------------|---------------|---------------|
| EC level (mmhos $\text{cm}^{-1}$ ) | 0.9           | 1.5           | 2.2           | 3             |
| Total NPV                          | \$38,905,339  | \$30,391,486  | \$24,553,297  | \$21,585,240  |
| Average NPV/50.8 ha                | \$71,649      | \$55,970      | \$45,218      | \$39,752      |
| Average irrigation water (m/ha)    | 0.05          | 0.03          | 0.02          | 0.01          |
| NPV/ha                             | \$1,428       | \$1,102       | \$899         | \$790         |
| Cotton price \$0.90                |               |               |               |               |
| EC Level (mmhos $\text{cm}^{-1}$ ) | 0.9           | 1.5           | 2.2           | 3             |
| Total NPV                          | \$252,422,563 | \$224,458,253 | \$199,760,168 | \$183,232,769 |
| Average NPV/50.8 ha                | \$464,867     | \$413,367     | \$367,882     | \$337,445     |
| Average irrigation water (m/ha)    | 0.10          | 0.08          | 0.05          | 0.03          |
| NPV/ha                             | \$9,141       | \$8,128       | \$7,336       | \$6,728       |

An increase in EC value to 3.0 decreased the NPV by 17 and 28% for 90 and 75 cents of cotton prices, respectively. It also decreased the average optimum irrigation water by 65% for cotton prices of 90 cents and by 78% for cotton prices of 75 cents per pound (454 g).

### 3.6.2 Design B: Capacity 50% Area at a Time

This design was for the restricted irrigation system for instantaneous irrigation water supply (Figure 3b). The design A was modified for scheduling irrigation in design B to the north of each lateral at one time and the south the other time. The total water demand at a time was 217,600 gpm (823,700 lpm). Main pipelines from 36 to 108 inches (0.91 to 2.74 m), lateral pipelines from 12 to 30 inches (0.3 to 0.76 m), and final pipelines from 6 to 10 inches (0.15 to 0.25 m) were used in this design. The annual fixed cost for 50 years for design B decreased to \$691 (Table 3) from \$986 per ha for design A at four percent discount rate. The sensitivity of cost to discount rates to the cost of this system showed that increasing discount rate from four to five, six, and eight percent increased the cost by 18%, 36%, and 76%, respectively.

Table 3. Annual Cost per Acre of Design B Irrigation System at Different Discount Rates.

| Costs                                | Cost/ha<br>4% | Cost/ha<br>5% | Cost/ha<br>6% | Cost/ha<br>8% |
|--------------------------------------|---------------|---------------|---------------|---------------|
| Cost of pipe and earthwork           | \$553         | \$650         | \$753         | \$971         |
| Cost of pivots                       | \$124         | \$143         | \$168         | \$217         |
| Cost of centrifugal pumps and motors | \$7           | \$7           | \$10          | \$12          |
| Cost of valves                       | \$7           | \$10          | \$10          | \$12          |
| Total                                | \$691         | \$810         | \$941         | \$1,212       |

With an annualized fixed cost of \$691 per ha and total annual variable cost of \$1,359 per ha, design B irrigation system was economically feasible for cotton prices above 70 cents per pound (454 g). At 70 cents per pound (454 g) cotton price this design was feasible for EC level less than and equal to 2.2 mmhos  $\text{cm}^{-1}$ . The NPV increased with increasing cotton price and decreased with increasing EC level linearly.



The aggregate NPVs per ha for the design B irrigation system for cotton lint prices of 70, 75, and 90 cents per pound (454 g) were \$1,665, \$4,434, and \$13,254 (Table 4), respectively for an EC value of 1.5 mmhos  $\text{cm}^{-1}$ . At this level of EC, the total NPVs for 67,197 acres (27,194 ha) of land at cotton price of 70, 75 and 90 cents were approximately \$47 million, \$124 million, and \$368 million (Table 4), respectively. The sensitivity of the NPV to the EC in the irrigation water was also analyzed. The result showed that an increase in EC would decrease the NPV per acreage and decrease the optimal average quantity of irrigation water to maximize NPV.

For design B, an increase in EC from 0.9 to 1.5 mmhos  $\text{cm}^{-1}$  decreased NPV by 40, 24, and 12% for cotton lint prices of 70, 75 and 90 cents per pound (454 g), respectively. An increase in cotton price also increased the total water, and increase in EC levels decreased the total water for the system. With an increase in EC level from 0.9 to 1.5 mmhos  $\text{cm}^{-1}$ , the average optimum quantity of irrigation water decreased by 23%, 22%, and 17% for cotton prices of 70, 75, and 90 cents per pound (454 g), respectively. An increase in EC value from 1.5 to 2.2 decreased the NPV by 64%, 32%, and 19% for 70, 75, and 90 cents of cotton prices, respectively.

Table 4. Aggregate NPV of Irrigated Cotton for Design B at Cotton Price Of \$0.70, \$ 0.75, and \$0.90 per Pound (454 G) a Different Electrical Conductivity (EC) Levels.

| Cotton price \$0.70                |               |               |               |               |
|------------------------------------|---------------|---------------|---------------|---------------|
| EC level (mmhos $\text{cm}^{-1}$ ) | 0.9           | 1.5           | 2.2           | 3             |
| Total NPV                          | \$77,467,321  | \$46,978,340  | \$18,121,976  | -\$2,502,726  |
| Average NPV/50.8 ha                | \$142,665     | \$86,516      | \$33,374      | -\$4,609      |
| Average irrigation water (m/ha)    | 0.14          | 0.10          | 0.06          | 0.04          |
| NPV/ha                             | \$2,786       | \$1,665       | \$603         | -\$153        |
| Cotton price \$0.75                |               |               |               |               |
| EC level (mmhos $\text{cm}^{-1}$ ) | 0.9           | 1.5           | 2.2           | 3             |
| Total NPV                          | \$162,560,744 | \$123,708,374 | \$85,685,646  | \$57,696,768  |
| Average NPV/50.8 ha                | \$299,375     | \$227,824     | \$157,800     | \$106,256     |
| Average irrigation water (m/ha)    | 0.15          | 0.11          | 0.07          | 0.05          |
| NPV/ha                             | \$5,861       | \$4,434       | \$3,036       | \$2,008       |
| Cotton price \$0.90                |               |               |               |               |
| EC level (mmhos $\text{cm}^{-1}$ ) | 0.9           | 1.5           | 2.2           | 3.0           |
| Total NPV                          | \$414,591,644 | \$367,712,681 | \$299,118,775 | \$245,904,800 |
| Average NPV/50.8 ha                | \$763,521     | \$677,187     | \$550,863     | \$452,863     |
| Average irrigation water (m/ha)    | 0.17          | 0.15          | 0.10          | 0.06          |
| NPV/ha                             | \$14,978      | \$13,254      | \$10,734      | \$8,778       |

### 3.6.3 Design C: Capacity 50% Area at a Time

This design was also for the restricted instantaneous irrigation supply by scheduling irrigation (Figure 3c). The irrigation system was divided into two sections, and irrigation was scheduled for one section at a time. The diameter of the largest pipe for this system was 108 inches (2.74 m). Main pipelines of 36 to 108 inches (0.9 to 2.74 m), lateral pipelines of 12 to 30 inches (0.3 to 0.76 m), and final pipelines of 6 to 10 inches (0.15 to 0.25 m) were used in this design. Water demand for each pivot was increased from 600 to 800 gpm (2271 to 3028 lpm) so that it would take less time to irrigate each section and the other section can be irrigated sooner. This design required 189,000 gpm (715,000 lpm) for a section. This scheduling has an annual fixed cost of \$672 per ha at four percent discount rate (Table 5), which is approximately 32% less than that of design A. A one percent increase in discount rate increased the annual cost of the irrigation system per ha approximately by 17%. Increasing the discount rate from four to six percent and from four to eight percent increased the cost by 36% and 75%, respectively.

Table 5. Annual Fixed Costs of Design C Irrigation System at Different Discount Rates.

| Cost                                 | Cost/ha (4%) | Cost/ha (5%) | Cost/ha (6%) | Cost/ha (8%) |
|--------------------------------------|--------------|--------------|--------------|--------------|
| Pipe cost                            | \$531        | \$625        | \$726        | \$934        |
| Cost of centrifugal pumps and motors | \$10         | \$12         | \$15         | \$17         |
| Cost of pivot                        | \$124        | \$146        | \$168        | \$217        |
| Cost of valves                       | \$7          | \$10         | \$10         | \$12         |
| Total                                | \$672        | \$793        | \$919        | \$1,180      |

At an annualized fixed cost of \$672 per ha and total variable cost of \$1,359 per ha, the irrigation system was only feasible for the cotton lint price of 70 cents or more per pound (454 g). Aggregate NPV per ha at different EC levels for design C at cotton prices of 70, 75, and 90 cents are presented in Table 6. The average NPVs per ha at EC level of 1.5 mmhos  $\text{cm}^{-1}$  for this scheduled irrigation system were \$1,924, \$4,770, and \$13,797 at cotton prices of 70, 75, and 90 cents, respectively. The average optimal annual quantity of irrigation water used at EC level of 1.5 mmhos  $\text{cm}^{-1}$  was 0.10, 0.12, and 0.15 m  $\text{ha}^{-1}$  at cotton prices of 70, 75, and 90 cents, respectively. The NPV and optimal average irrigation water use were reduced when EC level was increased. A decrease in the EC level from 1.5 to 0.9 mmhos  $\text{cm}^{-1}$  increased NPV by 20%, and the average optimum irrigation water increased by 27% at cotton price of 90 cents. It increased the NPV by 24% and average optimum irrigation water increased by 15% at cotton price of 75 cents. Similarly, the NPV increased by 61% and the average optimum irrigation water increased by 38% at cotton prices of 70 cents. An increase in EC level from 1.5 to 2.2 and 3 decreased both the NPV and the optimum quantity of irrigation water. Increasing the EC level to 3 from 1.5 mmhos  $\text{cm}^{-1}$  decreased NPV by 35% (for 90-cent cotton), 53% (for 75-cent cotton), and 101% (for 70-cent cotton). In the same way, the average optimum quantity of irrigation water decreased by approximately 55% for both 90 and 75 cents of cotton prices.

Table 6. Aggregate NPV of Irrigated Cotton for Design C at Cotton Price Of \$0.7, \$ 0.75, and \$ 0.90 per Pound (454 g) at Different Electrical Conductivity (EC) Levels.

| Cotton price \$0.70                |               |               |               |               |
|------------------------------------|---------------|---------------|---------------|---------------|
| EC level (mmhos $\text{cm}^{-1}$ ) | 0.9           | 1.5           | 2.2           | 3             |
| Total                              | 84,426,767    | \$52,429,273  | \$21,858,011  | (\$178,039)   |
| Average NPV/50.8 ha                | \$155,482     | \$96,555      | \$40,254      | (\$328)       |
| Average irrigation water (m/ha)    | 0.14          | 0.10          | 0.07          | 0.04          |
| NPV/ha                             | \$3,100       | \$1,924       | \$800         | \$10          |
| Cotton price \$0.75                |               |               |               |               |
| EC level (mmhos $\text{cm}^{-1}$ ) | 0.9           | 1.5           | 2.2           | 3             |
| Total                              | \$163,589,347 | \$129,892,665 | \$89,989,453  | \$60,422,953  |
| Average NPV/50.8 ha                | \$301,270     | \$239,213     | \$165,726     | \$111,276     |
| Average irrigation water (m/ha)    | 0.13          | 0.12          | 0.08          | 0.05          |
| NPV/ha                             | \$5,926       | \$4,770       | \$3,302       | \$2,218       |
| Cotton price \$0.90                |               |               |               |               |
| EC level (mmhos $\text{cm}^{-1}$ ) | 0.9           | 1.5           | 2.2           | 3             |
| Total                              | \$443,274,771 | \$375,608,518 | \$304,758,898 | \$249,579,827 |
| Average NPV/50.8 ha                | \$816,344     | \$691,728     | \$561,250     | \$485,426     |
| Average irrigation water (m/ha)    | 0.19          | 0.15          | 0.10          | 0.07          |
| NPV/ha                             | \$16,285      | \$13,797      | \$11,194      | \$9,166       |

### 3.6.4 Design D: Capacity 25% Area at a Time

This design was also for the restricted instantaneous irrigation supply. In this design, the irrigation system was divided into four areas (Figure 3d). At one time, only one area would be irrigated. This reduced the water demand leading to a further reduction in pipeline size as compared to other designs. Water demand of 800 gpm (3028 lpm) per pivot for this design requires a total 108,600 gallons (411,096 liters) of water per minute to irrigate a section. Main pipelines of 36 to 84 inches (0.9 to 2.1 m), lateral pipelines of 12 to 24 inches (0.3 to 0.6 m), and final pipelines of 6 to 10 inches (0.15 to 0.25 m) were used in this design. The annualized fixed cost at a four percent discount rate for this design was \$550 per ha (Table 7), which is approximately 44% less than that of design A and 19% less than that of designs B and C.

Table 7. Annual Fixed Costs of Design D Irrigation System at Different Discount Rates.

| Cost                                 | Cost/ha (4%) | Cost/ha (5%) | Cost/ha (6%) | Cost/ha (8%) |
|--------------------------------------|--------------|--------------|--------------|--------------|
| Pipe cost                            | \$412        | \$487        | \$563        | \$726        |
| Cost of centrifugal pumps and motors | \$7          | \$7          | \$7          | \$10         |
| Cost of valves                       | \$7          | \$10         | \$10         | \$12         |
| Cost of pivots                       | \$124        | \$146        | \$168        | \$217        |
| Total                                | \$550        | \$650        | \$748        | \$965        |

With an annualized fixed cost of \$550 per ha and total variable cost of \$1,359 per ha, the irrigation system was feasible for the cotton price of 65 cents per pound (454 g) or more. The aggregate NPVs per ha for the non-scheduled irrigation system at 65, 75, and 90 cents were \$1,314, \$7,415, and \$17,008, respectively at 1.5 mmhos  $\text{cm}^{-1}$  EC level (Table 8). When the EC level of the irrigation water was decreased from 1.5 to 0.9 mmhos  $\text{cm}^{-1}$  at 60 cents, the NPV increased by more than 100%, and the average optimum quantity of irrigation water increased by 22%. The NPV increased by 28% and average optimum quantity of irrigation water increased by 25% at 75 cents. At the same EC level and cotton price of 90 cents, both the NPV and the average optimal quantity of irrigation water increased by 21%. Increasing the EC level to 3 from 1.5 mmhos  $\text{cm}^{-1}$  decreased the NPV by 39% (for 90-cent cotton), 53% (for 75-cent cotton), and 193% (for 65-cent cotton). Similarly, the average optimum quantity of irrigation water decreased by approximately 54% for cotton prices of 75 and 90 cents per pound (454 g). The NPV for the area was negative at an EC level of 3 mmhos  $\text{cm}^{-1}$  and a cotton price of 65 cents per pound (454 g), indicating that the design D irrigation system was unfeasible at higher EC (2.2 or more) level and lower cotton prices (less than 65 cents).

Scheduling may require less water at each point in time so that the smaller pipes would be enough to meet the demand (Pereira, Calejo, Lamaddalena, Douieb, & Bounoua., 2003). Efficient irrigation scheduling and modifying irrigation system not only help to conserve water but also avoid excessive energy use, reducing the irrigation costs (Morris & Grubinger, 2015). Improved delivery scheduling is a feasible solution for better crop irrigation management (Zaccaria et al., 2010). In this study, irrigation scheduling reduced the size of pipeline, lowered the cost of the irrigation system, and ultimately increased net returns of irrigation systems. As expected, higher salinity level lowered the net returns of irrigation systems, consistent with the findings of a previous study (Tayfur et al., 1996). The soil salinity response functions had negative relation with the amount of irrigation water (Choi, 2011).

Table 8. Aggregate NPV of Irrigated Cotton for Design D at Cotton Price Of \$0.65, \$0.75, and \$0.90 per Pound (454 G) at Different Electrical Conductivity (EC) Levels.

| Cotton price \$0.65                |               |               |               |               |
|------------------------------------|---------------|---------------|---------------|---------------|
| EC level (mmhos $\text{cm}^{-1}$ ) | 0.9           | 1.5           | 2.2           | 3             |
| Total                              | \$75,327,627  | \$35,827,977  | \$(3993223)   | \$(34052596)  |
| Average NPV/50.8 ha                | \$138,725     | \$65,982      | \$(7354)      | \$(62712)     |
| Average irrigation water (m/ha)    | 0.16          | 0.12          | 0             | 0             |
| NPV/ha                             | \$2,766       | \$1,314       | \$(146)       | \$(1,233)     |
| Cotton price \$ 0.75               |               |               |               |               |
| EC level (mmhos $\text{cm}^{-1}$ ) | 0.9           | 1.5           | 2.2           | 3             |
| Total                              | \$259,850,367 | \$201,911,965 | \$140,963,134 | \$93,314,077  |
| Average NPV/50.8 ha                | \$478,546     | \$371,845     | \$259,601     | \$171,849     |
| Average irrigation water (m/ha)    | 0.19          | 0.15          | 0.11          | 0.07          |
| NPV/ha                             | \$9,544       | \$7,415       | \$5,175       | \$3,426       |
| Cotton price \$ 0.90               |               |               |               |               |
| EC level (mmhos $\text{cm}^{-1}$ ) | 0.9           | 1.5           | 2.2           | 3             |
| Total                              | \$550,210,680 | \$463,049,407 | \$367,823,753 | \$291,094,555 |
| Average NPV/50.8 ha                | \$1,013,279   | \$852,761     | \$677,392     | \$536,086     |
| Average irrigation water (m/ha)    | 0.22          | 0.18          | 0.13          | 0.08          |
| NPV/ha                             | \$20,212      | \$17,008      | \$13,508      | \$10,690      |

#### 4. Summary and Conclusions

A combination of GIS and simulation models was used to identify irrigable areas, to develop the irrigation

system, and to determine the cost-benefit of the irrigation systems in this study. The sizing of the pipeline involved a tradeoff between annual energy cost and pipeline cost. Total pipeline cost increases with increasing diameter of pipeline, but the energy required for pumping water through the pipe decreased with increasing pipe diameter. Pipe sizes were iteratively increased or decreased to determine the optimum cost of the irrigation system. Four design with different irrigation scheduling were evaluated in this study.

The total cost (fixed cost plus variable cost) of the Design A irrigation system (irrigation without scheduling) was approximately \$950 per acre (\$2,345 per ha) at 1.5 mmhos  $\text{cm}^{-1}$  EC level (Appendix A). At this cost and EC level, NPV was feasible for the cotton lint price of 75 cents or more per pound (454 g). Both Design B (irrigate alternately to the north and south of the laterals of the Design A) and Design C (scheduled to irrigate two areas alternatively) were feasible above cotton price of 70 cents for 0.9, 1.5, 2.2, and 3 mmhos  $\text{cm}^{-1}$  EC levels. At cotton price of 70 cents, the full and partial pivots in Design B and C were feasible till the EC level of 2.2 mmhos  $\text{cm}^{-1}$ . The total cost of the Design D (scheduled to irrigate one area at a time of four areas) irrigation system was approximately \$773 per acre (\$1,909 per ha) (Appendix A). The NPV was feasible at a cotton lint price of 65 cents per pound (454 g) at this cost and EC level of 0.9 and 1.5 mmhos  $\text{cm}^{-1}$ . However, the NPV for 2.2 and 3 mmhos  $\text{cm}^{-1}$  EC levels was feasible at prices higher than 65 cents for Design D. The sensitivity analysis for different salinity levels and different cotton prices showed that the NPV, average and total optimum irrigation increased linearly with increasing cotton prices. Increase in salinity decreased the yield of cotton (Razzouk and Whittington, 1990), and that decreased the net returns of the irrigation system.

The cost of water flowing through a pipe increased as the diameter of pipe increased. Design A had larger pipelines but scheduling water supply as in Designs B, C, and D allowed the use of smaller more cost effective pipes, which ultimately reduced the irrigation cost, increased the net returns, and lowered the breakeven price of cotton. Although there are several methods to control salinity levels, both salinity and cotton prices are out of the control of the individual agricultural operator. Thus, this study endorses irrigation scheduling as a tool for water conservation with effective irrigation development and management.

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Appendix A. Total annual fixed and variable costs at 4% discount rate for four different designs of irrigation system.

|                                 | Design A | Design B | Design C | Design D |
|---------------------------------|----------|----------|----------|----------|
| Annual fixed costs/ha           |          |          |          |          |
| Cost of pipe and earthwork      | \$847    | \$553    | \$531    | \$412    |
| Cost of pumps and motors        | \$15     | \$7      | \$10     | \$7      |
| Cost of pivot irrigation system | \$124    | \$124    | \$124    | \$124    |
| Cost of valves                  |          | \$7      | \$7      | \$7      |
| Annual variable cost/ha         |          |          |          |          |
| Non-irrigation variable cost    | \$1,235  | \$1,235  | \$1,235  | \$1,235  |
| Pumping cost                    | \$124    | \$124    | \$124    | \$124    |
| Total cost                      | \$2,345  | \$2,050  | \$2,031  | \$1,909  |

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